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THE SAFETY OF LWR POWER PLANTS
FINAL REPORT - PART I

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THE IDENTIFICATION OF THE IMPACTS OF
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FINAL REPORT - PART I

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TABLE OF CONTENTS

Part I

<u>Section</u>		<u>Page</u>
1.0	INTRODUCTION	1
2.0	DATA COLLECTION	3
	2.1 Data Sources Evaluation	3
	2.2 Technical Literature Review	9
	2.3 Information Quantification and Classification	10
	2.4 Compilation of Field M&T Data	11
3.0	DATA ANALYSIS	27
	3.1 Data Collation	27
	3.2 Data Clustering	27
	3.3 Analysis of M&T Events by Pattern Recognition	37
	3.4 Statistical Analysis of M&T Frequencies	44
	3.5 General Analysis of Results	58
	3.6 Indirect Root Causes	65
	3.6.1 Operator Errors	65
	3.6.2 Plant Location	67
	3.6.3 Administrative Errors	67
	3.6.4 Financial Conditions	70
	3.6.5 M&T Problems in Identical Plants	70
4.0	MAINTENANCE AND TESTING PROBLEM MITIGATION	76
	4.1 Design Considerations for Maintenance and Testing	77
	4.2 Data Study	78
	4.3 Error Prone Situations	79
	4.4 Recommendation Feasibility	79
	4.5 Procedure for Developing Testing Error Reduction Recommendations	80
	4.6 Sample Maintenance and Testing Recommendations	81
	4.7 Categorization of Maintenance and Testing Recommendations	82
	4.7.1 On Test Station Coordination Errors	82
	4.7.2 Test Station -- Control Room Coordination Errors	83
	4.7.3 Shift to Shift Coordination Errors -- Control Room	83
	4.7.4 Shift to Shift Coordination Errors -- On Test Station	84

Table of Contents (cont.)

<u>Section</u>	<u>Page</u>
4.7.5 Administrative -- Preparation for Testing . . .	85
4.7.6 Administrative -- Preparation for Maintenance .	85
4.7.7 Administrative -- Technical Specifications . .	86
4.7.8 Administrative -- Training	87
4.8 Approaches to Reduction of Maintenance and Testing Problems	88
4.8.1 Organization	88
4.8.2 Administration	89
4.8.3 Training	90
4.8.4 Quality Assurance	91
4.8.5 Technical Specifications	91
4.9 M&T Problems Causing Outages/Transients	92
5.0 RECOMMENDATIONS	95
5.1 Human Factors	95
5.1.1 Objective	95
5.1.2 Program Description	95
5.1.3 Background and Justification	101
5.1.4 Statement of Work	107
5.1.5 Schedule	111
5.2 Administration and Procedures	113
5.2.1 Objectives	113
5.2.2 Program Description	113
5.2.3 Background and Justification	121
5.2.4 Statement of Work	132
5.2.5 Schedule	135
5.3 Monitoring, Diagnostics, and Trouble-Shooting Tools .	136
5.3.1 Objective	136
5.3.2 Program Description	136
5.3.3 Background and Justification	136
5.3.3.1 Quality Assurance	136
5.3.3.2 Performance Monitoring Data System . .	137
5.3.3.3 Performance Monitoring	138
5.3.3.4 Diagnostics and Trouble-Shooting . . .	141
5.3.3.4.1 Utilization of CRT	142
5.3.3.4.2 Noise Diagnostics	143

Table of Contents (cont.)

<u>Section</u>	<u>Page</u>
5.3.3.4.3 Interactive Continuous Monitoring of Reactor Safety Functions	143
5.3.3.4.4 Changes in Safety Controls and Instrumentation	146
5.3.4 Statement of Work	147
5.3.5 Schedule	152
5.4 Technical Specifications	153
5.4.1 Objective	153
5.4.2 Program Description	153
5.4.3 Background and Justification	154
5.4.4 Statement of Work	155
5.4.5 Schedule	156
5.5 Development of Methodologies to Improve Performance of M&T Tasks	157
5.5.1 Objective	157
5.5.2 Program Description	157
5.5.3 Background and Justification	158
5.5.3.1 Pattern Recognition	158
5.5.3.2 Scheduling	158
5.5.3.3 M&T Simulation	162
5.5.4 Statement of Work	163
5.5.5 Schedule	167

CONTENTS
Part II

APPENDIX A:	Overview of Literature Relating to Radiation Exposure and Operating Experience
APPENDIX B:	Details of LWR-MTC3 Classification System
APPENDIX C:	Histograms for Individual BWR Facilities Depicting Frequency of M&T Mode and Frequency of Systems and Components Involved with M&T Problems
APPENDIX D:	Histograms for Individual PWR Facilities Depicting Frequency of M&T Mode and Frequency of Systems and Components Involved with M&T Problems
APPENDIX E:	Fortran Program for M&T Data Clustering

LIST OF TABLES

<u>Number</u>		<u>Page</u>
2.1	Comparison of Available Data Banks for Nuclear Power Plant Operations	6
2.2	Classification System, LWR-MTC3	12
2.3	Facilities Classified for LWR-MTC3	17
2.4	LWR-MTC3 Output from DATACHEC	23
2.5	Sample of Input Data	24
2.6	Sample of Output Data	25
2.7	Sample of Line Summary	26
3.1	Forms of Data Collation for M&T Events	28
3.2	Sample of Collated Data	30
3.3	Clusters of M&T Modes	32
3.4	Frequency of Generic M&T Problems	36
3.5	Systems Involved in M&T Events	38
3.6	Systems Involved in Generic M&T Problems for PWR's	39
3.7	Systems Involved in Generic M&T Problems for BWR's	40
3.8	Most Frequent Components Involved in Generic Mode Categories	41
3.9	Frequency of M&T Events by M&T Mode Clusters	45
3.10	Code Listing of Facilities	48
3.11	Code Listing of Category or Cause of Action	49
3.12	Code Listing of Systems in a Reactor	49
3.13	Code Listing of All Components Involved in the M&T Events	50
3.14	Components Most Frequently Involvd in the Systems During M&T Events	51
3.15	Components Specifically Involved in the Systems of the Reactor Type During M&T Events	51
3.16	Components Generically Involved in the Various Systems During M&T Events	52
3.17	Components Generically Involved in the Reactor Type	55
3.18	Components Generically Involved in Each System	56
3.19	Components Generically Involved in Systems of PWR	59
3.20	Components Generically Involved in Systems of BWR	60
3.21	M&T Problems in 12 BWR's (1972-1977)	63
3.22	M&T Problems in 11 PWR's (1972-1977)	64

LIST OF FIGURES

<u>Number</u>		<u>Page</u>
2.1	Sample Code Sheet	16
2.2	A Block Diagram Showing Procedures to Make a Data Bank on LER's to Retrieve Particular Data	20
2.3	Data Check for Source Document and Data Retrieval System Flow Chart	21
2.4	Data Check for Source Document and Data Retrieval System Flow Chart (Continuation)	22
3.1	Example Histogram	35
3.2	Correlation Between Operator Errors and M&T Events Per Plant	66
3.3	Number of Operator Errors (OE) and M&T Events Per Plant Versus Time for Plant in Commercial Operation	66
3.4	Correlation Between OE and M&T Events Per Plant Per Year In Various Size Ranges	68
3.5	Correlation Between M&T Events in 26 LWR's and Distance From High Population Centers	69
3.6	Correlation Between Population Near Plant and M&T Events in 26 LWR's	69
3.7	M&T Events as Function of the Ratio Between Cost Allocations for Maintenance and Operation	71
3.8	Correlation Between M&T Events in 14 Plants and Rate of Return	72
3.9	Kewaunee	74
3.10	Prairie Island-1	74
3.11	Quad Cities-2	75
3.12	Dresden-2	75
5.1	Power Plant Availability and Performance Optimization Program Flow Chart	108

1.0 INTRODUCTION

The present study was designed to identify the impact of maintenance and testing (M&T) upon the safety of LWR power plants. The study involved data extraction from various sources reporting safety-related and operation-related nuclear power plant experience. Primary sources reviewed, including Licensee Event Reports (LER's) submitted to the NRC, revealed that only ten percent of events reported could be identified as M&T problems.

The collected data were collated in a manner that would allow identification of principal types of problems which are associated with the performance of M&T tasks in LWR power plants. Because of the incompleteness, coarseness, and relative infrequency of the data, these instances could not be analyzed by truly quantified, parametric procedures. However, frequencies of occurrence of events and their general endemic nature were analyzed using data clustering and pattern recognition techniques, as well as chi-square analyses for sparse contingency tables.

The results of these analyses identified seven major categories of M&T error modes which were related to individual facilities and reactor type. Data review indicated that few M&T problems were directly related to procedural inadequacies, with the majority of events being attributable to human error. Components most frequently involved in M&T events were determined to be valves and switches. Based upon the results of these analyses, several indirect root causes for M&T events were examined, including relationships with operator errors, plant location, administrative errors, financial condition of utilities, and M&T problems in identical plants.

Following the identification of specific causes and types of M&T problems, solutions were recommended to mitigate these problems. Recommendations ranged from complete redesigns of hardware, such as valves and switches, to improved human relations and communications between management and labor.

Finally, these recommendations were formalized in the concluding section of the study in an effort to identify programmatic approaches for the in-depth analysis of problems which are associated with the performance of M&T tasks. Recommendations which were made for subsequent phases of the LWR Safety Technology Program, including possible implementation approaches, addressed five major categories. These categories involved programmatic studies in human factors; administration and procedures; monitoring, diagnostics and trouble-shooting tools; technical specifications; and methodologies for M&T task improvement.

The findings of this study indicate that the implementation of many of these recommended programs may contribute significantly to the reduction of specific M&T problems, as well as to the overall improvement in LWR safety technology.

2.0 DATA COLLECTION

2.1 DATA SOURCES EVALUATION

Field data on maintenance and testing (M&T) errors can be extracted from several available Occurrences Information Sources (OIS) which report, with varying degrees of emphasis and amount of detail, operation experiences of light water reactor (LWR) nuclear power plants. These OIS include:

- Nuclear Regulatory Commission (NRC) - Licensee Event Reports (LER's) supplemented by details found in letters from the licensees to the NRC.
- Reports from the Nuclear Safety Information Center (NSIC) which publishes periodical selected summaries in the journal of Nuclear Safety.
- NRC Rainbow Books; such as
 - NUREG-0020, Operating Units Status Reports (OUSR) (Gray Book)
 - NUREG-0366, Nuclear Power Plant Operating Experience (Green Book)
- File of Evaluated and Event Data (FEED) which has been compiled by Science Applications, Inc. (SAI) using detailed information supplied by utility companies.
- Nuclear Power Reliability Data Systems (NPRDS) which are compiled by the nuclear utility companies based on operation experience.
- Special studies by the Electric Power Research Institute (EPRI); such as
 - NP-842; Refueling Outage Trends in Light Water Reactors
 - NP-801; ATWS: A Reappraisal, Part III; Frequency of Anticipated Transients

●● NP-755; Major Outage Trends in Light Water Reactors

These sources are in addition to the human error data bank developed by the Nuclear Safety Research Group (NSRG) at Iowa State University (ISU), which utilizes LER's for 23 LWR power plants from 1972 through 1978.

For information on radiation exposure of M&T personnel, four main sources are available from the nuclear power plants, namely;

- WASH-1311, A Compilation of Occupational Radiation Exposure from Light Water Cooled Nuclear Power Plants 1969-1973.
- NUREG-0109, Occupational Radiation Exposure of Light Water Cooled Power Reactors, 1969-1975.
- Compilation and Analysis of Data on Occupational Radiation Exposure Experienced at Operating Nuclear Power Plants (Atomic Industrial Forum, 1974).
- Plant Personnel Exposure Records (PPER).

Useful information on M&T problems based on field experience may also be found in "On Line With Verna," which is published regularly in Nuclear News.

An extensive effort has been devoted in this program to review and evaluate these available information sources to determine the most appropriate sources for collection of accurate data relevant to M&T. The quality of the information sources has been evaluated on the basis of several considerations, including

- a. Completeness: This refers to the relative fraction of events contained in the data base compared with the total number of events which actually occurred at each plant in the data base for each year included.
- b. Accuracy: In some cases the data recorded in data files are incorrectly labeled or categorized and, therefore, bias the results unless each entry can be verified.
- c. Level of Detail: The level of detail reported in each data entry varies considerably from plant to plant and source to source. The significant features of the data we are interested in are the plant, the date, the

component/system involved if applicable, the failure mode, the impact on the component/system involved, the number of components affected, the type and causes of the maintenance or testing problem, the radiological exposure and further description of the problem.

Table 2.1 gives a summary of the content of the available sources and their limitations.

Although the intention of this work is to conduct only a scoping study in which a representative sample of data is to be collected to identify and analyze M&T problems and to help provide recommendations for mitigation of such problems, no single source has been found to be adequate by itself. Reasons for this inadequacy are:

- Reports include terse details which are not amenable to direct quantification.
- Summary reports such as LER's are often vague and often lack necessary information for extracting hard numerical data.
- No single source provides information on both M&T events and related exposure.

In comparison of various information sources, it was difficult to cross reference some of the events. This was due to the difference in the identification numbers used to label each event. Also, some events reported in one source were either omitted in other sources or were described from a different view. Furthermore, a discrepancy has been observed between report and event dates among the various sources. Such cross checking, however, is found to be necessary to identify root causes of M&T problems.

Data on exposure is very scarce in all the sources except in plant personnel exposure records (PPER). Obtaining data requires visitation to each plant and review of their records. However, plant personnel exposure records are found to be useful in several aspects, including

- Classification of PPER's by M&T tasks and job functions.
- Identification of critical tasks and job functions during which the highest annual exposure occurs.

Table 2.1 Comparison of Available Data Banks for Nuclear Power Plant Operations

Source	Content	Description	Features Related To Maintenance And Testing
Plant Dockets	Usually contains complete description of event, cause, effect(s), and location of occurrence. Volumes of material from plants' conception to present operating status.	Inexhaustible amount of work is necessary for data acquisition because of the documentation length and wordiness.	Contains comprehensive information, but the time necessary for extraction is prohibitive. Includes data on encountered radiation exposures.
Atomic Energy Commission AEC-Operating Experience Reports (Assumed by Nuclear Regulatory Commission in 1974. NUREG-Operating Experience Reports)	Listing of operational events leading to plant outage, contains discrete times of outage, 20 words or less description, cause, major system and component(s) involved. Also contains half-page summary of yearly highlights by plant, including availability and capacity factors.	Event cause is given by only a one word description. System identification is general. Component involved is listed. Effect of event (other than leading to outage) is neglected. Type of outage and duration is included. Human factors can be inferred but are not always stated.	Minimum amount of information related to events other than those with outage consequences. Yearly highlights may include maintenance and testing data. Does not include exposure information.
Nuclear Safety (Published by Nuclear Safety Information Center-NSIC)	Quarterly journal containing: 1. A summary of operating U.S. power reactors, 2. Selected safety related events for journal period, and 3. Events resulting in reactor shutdown and their causes.	1. Taken from NRC-Operating Units Status Report. 2. Gives one sentence descriptions of the occurrence, the cause, and the component/system involved. Also includes one page description of selected events. 3. Short, two line summary of event, cause, component and system involved. Includes the event date.	Summary tables not applicable, however short articles periodically available on specific events. Radiation exposure only considered in a limited number of essay articles.
NRC-Operating Units Status Report (NRC-Grey Book)	Monthly publication which gives operational data-by facility, for month of report, and by year-to-date. Gives abbreviated list of reports received from the Licensee and shutdown/reduction information including: duration, reason, cause and method of shutdown, system and components involved, and any corrective action that was taken.	Basically includes good operations data but is overly terse in descriptive account of events.	Only lists events which resulted in outage. Extremely brief description. Dose levels reported if greater than technical specifications but description absent.
NSIC-Nuclear Reactor Operating Experience Reports	Compilation of abnormal occurrences from 1959 to present. Very little data from 1960-1968 (less than 50 events). Includes 50-100 word summaries with associated keywords for computer retrieval.	Little consistency in reporting of events, especially pre-1972. Events often vague as to the human involvement. System identification is often too general. Event effect(s) often missing. Easily attainable in either document or tape form.	Contains most of the reportable events after 1971. Descriptions are often vague and LWR event categorization experience is necessary for useful data extraction. Radiation exposure dose only given if greater than technical specifications.
NRC-Licensee Event Reports (LER's)	Monthly reports or compilation of events from 1969 to present. Includes a standardized format sorted by: facility name; system, component and date. Gives brief description of event and cause, and delineates between human and equipment error.	Pre-1972 data, although formulated, is overly terse in description. Human error is not always delineated as being operator, maintenance, etc. Overall, best source of abnormal occurrences.	Best source of readily available data for safety related events. System categorization is too broad. Dose levels usually available only if greater than technical specifications.

Table 2.1 Comparison of Available Data Banks for Nuclear Power Plant Operations (cont)

Source	Content	Description	Features Related To Maintenance And Testing
Licensee Letters to NRC	Basically same as LER's, except an additional event description is often available with schematic representation.	Available only on microfiche, and therefore extremely time consuming for data extraction. Event descriptive schematic when included is useful for determination of occurrence location. There does not appear to be any requirements on letter content other than LER content.	Similar to LER's
NPPRS Nuclear Plant Reliability Data System	Quarterly reports which include: (1) Data similar to LER's; (2) Component failure reports; and (3) System reliability summaries including operation statistics, failure counts, times for repair, and the number of surveillance tests performed during the reporting period.	Computer coded system dependent upon utility cooperation for data input. Initiated in 1974. Component description and failure mode is good, however system delineation is too general. The system is suitable for computer calculated reliability and failure statistics, however to date, the source is incomplete.	Appears to be a good data source especially for statistical analysis, however several facilities have not supplied input data. Does not address radiation exposure.
EPRI			
NP-R01	Compilation of data completed in 1978 which includes plant name, date of transient occurrence, outage time, type of transient, and the source of the scram signal.	Data is collected directly from the utilities and therefore dependent upon their response. Categorization limited to outages and is very general in cause delineation. Good source for basic utility information but not apropos as an LWR incident bank.	Basically useful only for an error count of those events which led to an outage. Maintenance and testing event description is absent. Do not address radiation exposure.
NP-755	Includes plant availability, outage trends by component and system, and descriptive impacts of major outages.		
NP-R42	Summary of refueling outage trends, including impacts, characteristics, and critical path analysis.		
File of Evaluated and Event Data (FEED) (Science Applications, Inc., 1977)	Contains a compilation of data which includes event data, evaluated data, and plant descriptive data. The format includes plant name, month and year of occurrence, data type code and mnemonic codes which describe plant type, failure cause, plant status, system and components, and short description of occurrence.	FORTTRAN program for the CDC 7600 computer. Data available for only 12 plants up to 1977. Descriptions very generally in most cases and usually fail to relate cause to event.	Compilation of available data categorized under one or more of the mnemonic codes provides all data related to those codes which must then be further verified as appropriate to MAT events. One code related directly to maintenance activities, no code directly related to testing. Does not directly address radiation exposure.

Table 2.1 Comparison of Available Data Banks for Nuclear Power Plant Operations (cont)

Source	Content	Description	Features Related to Maintenance and Testing
WASH-1311 A Compilation of Occupational Radiation Exposure from Light Water Cooled Nuclear Power Plants 1969-1973	Reactor licenses provided information pertaining to: 1. The number of reactor plant personnel receiving exposures greater than 100 mrem/year. 2. The total Man-Rem for these personnel. 3. A breakdown of the total exposure by work function (operations, maintenance, refueling, etc.) 4. Average exposures for 1-3.	Data base accumulated from licensee reports and calculations made by the AEC. Information given for those LWR's in commercial operation after 1969 beginning with the first full year of operation and including subsequent years through 1973. Does not include exposure data for specific tasks.	Does not address Maintenance and Testing events. Identifies total exposure during maintenance activities only. Gives comparison between yearly operations and maintenance exposures by percent. Does not give average maintenance exposure.
NUREG-0109 Occupational Radiation Exposure at Light Water Cooled Power Reactors 1969-1975	Contains a compilation of the occupational radiation exposures at LWR's from 1969-1975, for plants with at least one full year of operation. Content similar to WASH-1311 except information on overexposures at commercial power reactors for 1971-1975 is included.	Updated data base from WASH-1311 and licensee reports submitted to NRC. Does not include exposure data for specific tasks.	Same as WASH-1311 except overexposure information included for 1971-1975 given by: • Number of overexposures • Whole body Man-Rem involved • Whole body maximum exposure (rems) • Number of reports of exposure to excessive concentration of radioactive material • Maximum exposure to a specific body part
Compilation and Analysis of Data on Occupational Radiation Exposure Experienced at Operating Nuclear Power Plants (Atomic Industrial Forum, 1974)	Review of occupational radiation exposure at 14 LWR's. Includes variables affecting exposure: • Plant age • Reactor type • Plant size • Nature of work and timing • Plant design Includes exposures from specific sources: • Radwaste systems • Procedures related to fuel handling and refueling • Instrument work • Inservice inspections • Control rod maintenance • Equipment failures • Steam generators • System pumps • Main coolant loops • Valves • Turbines and auxiliary equipment • Demineralizers	Databases accumulated from reportable occurrences plus communication with plant personnel. Includes specific task exposures, total annual plant exposures, and percentages of exposure received during outages. Incomplete data base, but may provide useful comparisons with other data bases, such as LER's.	Does not contain information relative to Maintenance and Testing problems, which are not related to occupational exposures. Identifies the major sources contributing to occupational radiation exposure at 8 BWR's and 6 PWR's from 1969-1973. Compiles occupational radiation exposure associated with these sources during operation and maintenance at these plants. Source does not address Maintenance and Testing events.

- Determination of the optimum manpower utilization to achieve ALARA doses.
- Minimization of overexposure events.
- Examination of plant age--annual exposure relationships.

Information on the impact of M&T problems on plant outage also is sparse. However, some data was found in FEED. Also, it is difficult to get any information on the effect of plant layout design on M&T problems. It seems conceivable that plant visitation, together with available M&T data, would provide such information.

To illustrate the inconsistency in reporting, the following example is given.

The NSRG data retrieval system was employed to retrieve M&T events from NSIC records using NSIC keywords. The number of reported M&T problems amounted to 35% of the reported events for all plants from 1967 to 1978. However, this high percentage was found to be due to including such events as failures or problems identified during M&T, rather than being caused by performance of M&T tasks. Inspection of LER's, FEED, letters to NRC, NPRDS, and NSIC files have shown that only 10% can be identified as M&T problems.

2.2 TECHNICAL LITERATURE REVIEW

A technical literature review was also performed to gather information specific to M&T, especially in relationship to radiation exposures occurring during M&T tasks. A rather limited amount of occupational exposure data is available and is generally quantified in broad terms. An overview of the literature relating to radiation exposures and to operation experience appears in Appendix A. Appendix A also contains a bibliography of sources relating to occupational radiation exposures.

The results of the literature review demonstrated that a major portion of the occupational radiation dose is received during maintenance, inservice inspection, refueling, and nonroutine operations. These activities warrant special attention to layout design. Plant layouts should be reviewed to ensure that provisions have been included to achieve minimum exposures (less than the allowed limits) in these situations.

The literature review also showed that, although the design and operating procedures are such as to limit the dose-rate in normal working areas to the practical minimum, the same criteria cannot necessarily be applied to the maintenance of a plant. There are two main aspects to consider when assessing the radiological conditions associated with plant maintenance, namely;

1. Radiation dose control.
2. Contamination control.

The range of dose rates encountered varies between a few milirems per hour up to tens of rems per hour. Radiation exposure involves either whole body exposure, extremity dose, or a combination of both. The presence of surface contamination can produce high surface dose-rates and may give rise to an airborne hazard if the work causes resuspension.

This gives rise to the need for additional work on exposures related to M&T, especially the review of facility health physics records, for the determination of optimum manpower usage and system/component designs to achieve minimum doses.

2.3 INFORMATION QUANTIFICATION AND CLASSIFICATION

In order to extract useful numerical data from the available information sources and data banks, a classification scheme was developed and a coding sheet was designed for both manual and computer analysis. The LWR maintenance and testing classification (LWR-MTC) was developed by stages and has been devised to assure that the coding is:

- Adequate for evaluation of M&T error distribution.
- Appropriate for quantification of man-machine related M&T occurrences/events.
- Suitable for assessing the causes and consequences of each M&T event including the dose which may have been received by the M&T crew.
- Inclusive in identifying the time scale for each maintenance task.

Content of the classification system (LWR-MTC3) is listed in Table 2.2 and necessary details are given in Appendix B. The coding sheet for LWR-MTC3 is shown in Figure 2.1. The classification system developed was the result of several revisions, some of which took place during the data collection effort due to encountering new relevant information.

The LWR-MTC3 system was used to code M&T events from 1972 through 1978 for 12 BWR's and 11 PWR's. Events were extracted from the NSRG data bank and updated by making use of other sources.

The classified data were reviewed to assure completeness, consistency, and relevance. Review of additional events has shown that no additional information can be gained from further data collection efforts whether in identification of other generic problems or in improving the statistics. However, further collection of data would benefit tremendously in verification of the presence of many of the M&T problems, especially those which are attributed to indirect root causes such as inadequate procedures, management, or finance. The review also emphasized the need for a special data base to be compiled by the utilities for the purpose of improving the performance of the M&T tasks and to avoid the recurrence of problems whether within the same plant or in other plants.

2.4 COMPILATION OF FIELD M&T DATA

Information related to M&T events was extracted from available sources, including the NSRG data bank. Four investigators independently carried out the effort of classification of the information and coded it using LWR-MTC3. The results were then compared to assure consistency and resolve any differences in interpretation. The effort was directed to data extraction and compilation for 12 BWR's and 11 PWR's for the period from January 1972 through July 1978. The facilities are listed in Table 2.3. They were selected in order to allow the analysts to delineate plant age, reactor type, vendor, A/E and size.

Throughout the information classification and data compilation effort, data were continually reviewed to assure completeness, consistency,

Table 2.2 Classification System

LWR - MTC 3

1. Record Identification Number (1 Digit)
Used for addition and deletion of events
2. SRG Identification Number (5 Digits)
3. Control Number (6 Digits)
4. Cross Reference Number (6 Characters)
Characters 1 - 2: LER Report Month
JA - January JL - July
FE - February AG - August
MR - March SP - September
AP - April OC - October
MA - May NO - November
JU - June DE - December
Characters 3 - 5: LER Page Number
5. Facility Identification Number* (3 Digits)
6. Data of Report (6 Digits)
7. Date of Event (6 Digits)
8. Error Mode (2 Characters)
M - Maintenance
P - Procedural Resulting in Significant Maintenance Consequences
(e.g., Exposure)
MT - Maintenance During Testing
OT - Operator During Testing
AT - Administrative During Testing
PT - Procedural During Testing
XT - Other Unknown Personnel During Testing
ST - Inherent System Fault During Testing
ZT - Other Testing
X - Other Leading to Exposure
PM - Event Which is Possibly Due to Inadequate Preventative Maintenance Schedules

Table 2.2 (Cont)

9. M&T Mode* (2 Characters)
10. System Involved* (2 Characters)
11. Effect on System Involved (1 Character)
 - U - Unknown/Not Applicable
 - N - None
 - D - Degraded
 - F - Failed
12. Component Involved* (2 Characters)
13. Number of Components Involved (2 Digits)
14. Effect on Component Involved (1 Character)
 - U - Unknown/Not Applicable
 - N - None
 - D - Degraded
 - F - Failed
15. System Affected* (2 Characters)
16. Effect on Systems Affected (1 Character)
 - U - Unknown/Not Applicable
 - N - None
 - D - Degraded
 - F - Failed
17. Component Affected* (2 Characters)
18. Number of Components Affected (2 Digits)
19. Effect on Component Affected (1 Character)
 - U - Unknown/Not Applicable
 - N - None
 - D - Degraded
 - F - Failed

Table 2.2 (Cont)

20. Failure Mode* (2 Characters)

21 Facility Operational Phase Before Event Occurrence (1 Digit)

- 0 - Startup
- 1 - Power Operation
- 2 - Hot Standby
- 3 - Hot Shutdown
- 4 - Warm Shutdown
- 5 - Cold Shutdown
- 6 - Refueling
- 8 - Shutdown (Unknown Mode)
- 9 - Unknown

22. Facility Operational Phase After Event Occurrence (1 Digit)

- 0 - Startup
- 1 - Power Operation
- 2 - Hot Standby
- 3 - Hot Shutdown
- 4 - Warm Shutdown
- 5 - Cold Shutdown
- 6 - Refueling
- 8 - Shutdown (Unknown Mode)
- 9 - Unknown

23. Duration of Event Consequences; Hours (6 Digits)

- Digit 1 - Thousands of Hours
- Digit 2 - Hundreds of Hours
- Digit 3 - Tens of Hours
- Digit 4 - Hours
- Digit 5 - Tenths of Hours
- Digit 6 - Hundredths of Hours

24. Radiation Release to Environment (3 Characters)

- U - Unknown
- NO - No Release
- RWL - Release Within Limits
- REL - Release Exceeds Limits
- RU - Release, Limits Unknown

(See 20 for Limits when available)

Table 2.2 (Cont)

25. Radiation Exposure

a. (2 Characters)

U - Unknown
NO - No Exposure
XP - Exposure

b. Dose - Millerems (4 Digits)

26. Common Mode/Recurring/Unusual Event (1 Digit)

C - Common Mode Occurrence
R - An Incident Which Recurs at a Particular Facility
X - An Event Which Disables Redundant Trains of a System, Violates
a Significant Safety Technical Specification, or is Extremely
Unusual
- Not Applicable/Unknown

27. Description

A Short Description of the Event Expanding its Characteristics

* Appendix B

Figure 2.1 Sample Code Sheet

Facility Name				Type	Size Mw(t)	A/E	NSSS																			
Name				Date																						
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Facility I.D. Number	Contingency Number	Cross Refer. Number	Facility I.D. Number	Date of Report	Date of Event	Event Name	MAT Name	System Name	Event I.D. Number	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Component Name	Event Duration: Hours	Event Duration: Minutes	Event Duration: Seconds	Event Duration: Milliseconds	Description
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	4																							

Table 2.3. Facilities Classified for LWR-MTC 3

Facility	Facility ID #	Plant Type	Power Level (MWT)	Date of Comm.Op	Plant Age D.O.C.O. to 12/31	NSSS	A/E
Fort Calhoun	064	P	1420	092673	4.26	C-E	Gibbs & Hill
Haddam Neck	073	P	1825	010168	10.00	West	Stone & Webster
Indian Point-1	092	P	615	10-62	12.00	B&W	Utility
Indian Point-2	083	P	2758	08-73	4.42	West	UE&C
Kewaunee	089	P	1650	06-74	3.58	West	Pioneer Services & Engr.
Millstone-2	105	P	2560	122675	2.02	C-E	Bechtel
Oconee-1	116	P	2568	071563	4.46	B&W	DPC & Bechtel
Rancho Seco	144	P	2772	041775	2.71	B&W	Bechtel
Three Mile Island-1	174	P	2535	090274	3.33	B&W	Gilbert Assoc.
Yankee Rowe	192	P	600	0761	16.50	West	Stone & Webster
Zion-1	193	P	3250	123173	4.00	West	Sargent & Lundy
Browns Ferry-1	023	B	3293	080174	3.42	GE	TVA
Brunswick-2	027	B	2436	110375	2.16	GE	Un'td Eng. & Const.
Cooper Station	043	B	2381	070174	3.50	GE	Burns & Roe
Dresden-1	054	B	700	070460	17.49	GE	Bechtel
Duane Arnold	057	B	1593	020175	2.91	GE	Bechtel

cont.

Table 2.3. Facilities Classified for LWR-MTC 3 (cont)

Fitzpatrick	062	B	2436	072975	2.43	GE	Stone & Webster
Hatch-1	058	B	2436	123175	2.00	GE	Southern Services
Humboldt Bay	081	B	220	08-63	14.42	GE	Bechtel
LaCrosse	092	B	165	091369	8.30	Allis Chalmers	Sargent & Lundy
Line Mile Point-1	110	B	1850	12-69	8.08	GE	Utility
Quad Cities-2	143	B	2511	031073	4.81	GE	Sargent & Lundy
Vermont Yankee	180	B	1593	113072	5.08	GE	Ebasco

and relevance. Updating was done whenever a piece of new information was found in any of the information sources, and cross checking was also made among the different sources--especially with respect to identification of root causes.

A visit was made by the research team to the Omaha Public Power District (OPPD) to discuss some of the M&T problems and to seek additional information from plant personnel at Fort Calhoun. The records of the facility were made available for review. Several events specific to the M&T tasks were verified and some ideas were formulated relating to mitigation of M&T problems.

The NSRG data were updated using the additional information. The data were then stored and checked using the NSRG DATACHEC computer program. Of the 3564 events extracted from LER data and retained on computer file, 385 were traceable to maintenance and testing. The LERRETS (LER retrieval system) code, which had been developed earlier by NSRG and then modified to accommodate for M&T events, was then used for additional input to the data bank and for retrieval of data for data collation and analysis. Figures 2.2 through 2.4 present the diagrams for the LERRETS code and the DATACHEC program. The purpose of the LERRETS code is to store LER and other OIS information using various keywords to allow for segregation and retrieval of information of interest; such as maintenance problems associated with relief valves. The code also stores numerical data extracted from various sources and provides various collation of such data. DATACHEC, on the other hand, provides a program to check data consistency--especially when the accumulated data is obtained by more than one investigator.

Table 2.4 presents the LWR-MTC3 output from DATACHEC. Tables 2.5 and 2.6 present a sample of the input and output, respectively. The information is also used for line summaries which are useful in extracting further data and statistics in addition to those in the data files. A sample of the line summaries is given in Table 2.7. A complete compilation of the line summaries is available at SAI-Ames (M&T Line Summary Data, No. 1).

Figure 2.2 A Block Diagram showing Procedures to Make A Data Bank on LER's To Retrieve Particular Data.

Figure 2.4. Data Check for Source Document and Data Retrieval System Flow Chart (Continuation)

Table 2.4. LWR-MTC 3 Output from DATACHEC

LWR-MTC3 Output from DATACHEC 2

No.	Abb. ^a	Content	Col. ^b
First-Line			
1	I	Record identification number	1
2	SRG	SRG identification number	2-6
3	ACCNO	Control number	7-12
4	CRN	Cross reference number	13-18
5	F	Facility identification number	19-21
6	RDATE	Date of report (YY/MM/DD)	22-27
7	EDATE	Date of event (YY/MM/DD)	28-33
8	E	Error mode	34-35
9	MT	M&T mode	36-37
10	S	System involved	38-39
11	E	Effect on system involved	40
12	C	Component involved	41-42
13	N	Number of components involved	43-44
14	E	Effect on component involved	45
15	S	System effected	46-47
16	A	Effect on systems affected	48
17	C	Component effected	49-50
18	N	Number of components effected	51-52
19	A	Effect on component affected	53
20	F	Failure mode	54-55
21	B	Facility operational phase before event occurrence	56
22	A	Facility operational phase after event occurrence	57
23	DRN	Duration of event consequences	58-63
24	REN	Radiation release to environment	64-66
25	REXP	Radiation exposure	67-72
26	M	Common mode/recurring/unusual event	73
27	SER	Record serial number	74-79
28	C	Number of comment lines	80
Second-Line through Tenth-Line		Description ^c	57-129

^aSub-title abbreviation from the computer printout.^bColumn number(s) for the data stored on a disk or a tape.^cThe maximum number of characters in description in 659.

0690	VERMONT YANKEE-1	VERMONT YANKEE NUC. POWER CORP.	0181	0680
0691	SUMNER-1	SOUTH CAROLINA ELECTRIC & GAS CO.	0182	0681
0692	WATERFORD-3	LOUISIANA POWER & LIGHT CO.	0183	0682
0693	WATTS BAR-1	TENNESSEE VALLEY AUTHORITY	0184	0683
0694	WATTS BAR-2	TENNESSEE VALLEY AUTHORITY	0185	0684
0695	ZIMMER-1	CINCINNATI GAS & ELECTRIC CO.	0186	0685
0696	WOLF CREAK-1	KANSAS GAS & ELECTRIC CO.	0187	0686
0697	WPPSS-1	WASH. PUBLIC POWER SUPPLY SYSTEM	0188	0687
0698	WPPSS-2	WASH. PUBLIC POWER SUPPLY SYSTEM	0189	0688
0699	WPPSS-3	WASH. PUBLIC POWER SUPPLY SYSTEM	0190	0689
0700	WPPSS-4	WASH. PUBLIC POWER SUPPLY SYSTEM	0191	0690
0701	WPPSS-5	WASH. PUBLIC POWER SUPPLY SYSTEM	0192	0691
0702	YANKEE-ROWE	YANKEE ATOMIC ELECTRIC CO.	0193	0692
0703	ZION-1	COMMONWEALTH EDISON CO.	0194	0693
0704	ZION-2	COMMONWEALTH EDISON CO.	0195	0694
0705	*****MAX. KEY+1		0196	0000
1201M	MAINTENANCE		0198	1201
1202P	PROCEDURAL IN SIGNIFICANT MAINT.		0199	1202
1203X	OTHER LEADING TO EXPOSURE		0200	1203
1204PM	PREVENTIVE MAINTENANCE		0201	1204
1205AT	ADMINISTRATIVE DURING TESTING		0202	1205
1206MT	MAINTENANCE DURING TESTING		0203	1206
1207OT	OPERATION DURING TESTING		0204	1207
1208PT	PROCEDURAL DURING TESTING		0205	1208
1209ST	INHERENT SYSTEM FAULT DURING TESTING		0206	1209
1210XT	OTHER/UNKNOWN PERSONNEL DURING TESTING		0207	1210
12112T	OTHER TESTING		0208	1211
1212	*****MAX. KEY+1		0209	0000
13AD	ADJUSTMENT, OUT OF		0211	1301
13AR	ADDITION RATE, IMPROPER		0212	1304
13AN	ADJUST, DID NOT		0213	1303
13AM	ADJUSTMENT, MIS-		0214	1302
13AS	ASSEMBLY, IMPROPER		0215	1305
13AD	BUMPED		0216	1307
13BP	BYPASS, DID NOT		0217	1306
13CN	CARELESSNESS/NEGLIGENCE/OVERSIGHT		0218	1319
13CI	CHARGING, IMPROPER		0219	1316
13CD	CLOSED		0220	1313
13CL	CLOSED, LEFT		0221	1317
13CP	CLOSED, LEFT PARTIALLY		0222	1321
13CM	COMMUNICATION		0223	1318
13CE	COMPUTER, INPUT ERROR		0224	1314
13CC	CONNECT, DID NOT/LATCH		0225	1312
13CN	CONNECT, DID NOT RE-		0226	1322
13CU	CONNECTION, DIS-		0227	1315
13CG	CONNECTION, LOOSE		0228	1315
13CT	CONNECTION (OTHER), IMPROPER/LATCHING		0229	1314
13CA	CALCULATION		0230	1310
13CB	CALIBRATION		0231	1311
				

Table 2.5 Sample of Input Data

DESCRIPTION:

AFTER SWITCHING FROM CENTRIFUGAL CHARGING PUMP 1B TO 1A, NO FLOW WAS OBSERVED. PUMP DISCHARGE MANUAL ISOL. VALVE WAS LEFT CLOSED AFTER AN EARLIER HOT SHUTDOWN MAINTENANCE.

NSRG-NO	REPORT DATE	EVENT DATE	F A C I L I T Y	REACTION TYPE
20012	013075	112274	ZION-1	PWR
ERROR MODE-----PROCEDURAL DURING TESTING				
MGT MODE-----PROCEDURE INADEQUACY				
SYSTEM INVOLVED-----CPES				
SYSTEM EFFECT-----DEGRADED				
COMPONENT INVOLVED-----DAMPER				
NO. OF COMP. INVOLVED----02				
COMPONENT EFFECT-----DEGRADED				
EVENT DURATION(HR.)----- 0.00				
RADIATION RELEASE-----RELEASE, LIMITS UNKNOWN				
MODE-----COMMON MODE				
DESCRIPTION:				
DURING RECOMBINER PREOP TASTING, 2 CONTAINMENT PURGE VALVES WERE OPENED, AND AN UNPLANNED RADIOACTIVITY RELEASE OCCURRED: 1.77(E-4) CI TRITIUM AND 4.3 (E-7) CI IODINE. THE OUTLET DAMPERS OF THE PURGE EXHAUST FANS WERE AB				
***** L W R - M T C 3 ***** PAGE 56				

NSRG-NO	REPORT DATE	EVENT DATE	F A C I L I T Y	REACTOR TYPE
20013	030675	022075	ZION-1	PWR
ERROR MODE-----MAINTENANCE				
MGT MODE-----REMOVED FROM SERVICE				
SYSTEM INVOLVED-----PRMS				
SYSTEM EFFECT-----DEGRADED				
COMPONENT INVOLVED-----RADIATION MONITOR				
NO. OF COMP. INVOLVED----02				
COMPONENT EFFECT-----FAILED				
EVENT DURATION(HR.)----- 0.00				
RADIATION RELEASE-----NO RELEASE				
MODE-----NOT APPLICABLE/UNKNOWN				
DESCRIPTION:				
TWO RADIATION MONITORS FOR A COMMON SECTION OF THE EXHAUST FANS IN THE AUX. BLDG. WERE REMOVED FOR REPAIR. THIS WAS AGAINST TECH. SPECS. AND ONLY ONE NEEDED REPAIR.				

NSRG-NO	REPORT DATE	EVENT DATE	F A C I L I T Y	REACTOR TYPE
---------	-------------	------------	-----------------	--------------

Table 2.6 Sample of Output Data

Identification Number	Reference Number	Page Number	Facility I.D. Type	Date	Error Type	System Involved/Affected	Component Involved/Affected	No. of Components Involved	Effect on System	Effect on Component	M&T Mode/Failure Mode	Oper-pre	Oper-post	Duration	Radiation Release	Radiation Exp.	Common Mode/Recurring/Unusual	Description
5006	C33024	295	116P	073173	OT	CCS	Pin Valve	1	D	H	Did Not Remove Failure to Close	U	U	U	No	No		During testing, the component discharge valve outside the containment failed to close on receipt of the ES signal. There was a pin (used to operate the valve manually) in the valve preventing it from closing. To prevent recurrence, all pins have been placed in the custody of the shift supervisor.
5001	085563	298	116P	111673	OT	CSIS	Pump Same	1	N	P	Did Not Check/Test None/Event	U	U	U	No	No		During a maintenance outage, a RB spray pump was disassembled for inspection. After reassembly the pump was not run to verify its operability before restarting the reactor. The work order issued for maintenance was inadequate. Pump-performance was done immediately.
5002	086168	299	116P	113073	M	SCS	Tendon Same	4	N	D	Lubrication Loose	U	U	U	No	No		During inspection for leaking grease caps, tendons were found that had not been greased. They were retensioned.
5003	087010	300	116P	122073	OT	CSIS	Valve Same	1	F	D	Did Not Failure to Fully Close	U	U	.25	No	No	U	During testing on the RB spraysystem, both trains were inadv. removed from service for 15 minutes. After test on BS-1 the suction valve BS-3 was opened (Train 1), then the breaker for the RB spray pump B (Train 2) was racked out. Actually the valve BS-3 was not fully opened. Procedures will be modified to require the operator

Table 2.7 Sample of Line Summary

3.0 DATA ANALYSIS

3.1 DATA COLLATION

The collected data has been stored for ease of retrieval using appropriate keywords. The LERRETS computer facility provided by NSRG was then used to appropriately collate the data according to the outline shown in Table 3.1. This is to allow for diagnosis of the M&T problems and to provide possible correlations among the data sets to find possible root causes and methods for problem mitigation. A sample of collated data is given in Table 3.2. The complete set of collated data is available at SAI-Ames (M&T Data Collation, No. 1).

3.2 DATA CLUSTERING

A large number of M&T modes have been identified during data collection. However, the associated frequencies are small and, hence, it is difficult to draw conclusions on the generic nature or importance of each mode. Therefore, it was determined that specific M&T modes could be clustered into seven major categories, namely;

- I. Acts of omission during or after the completion of maintenance and tests.
- II. Acts of commission resulting in improper maintenance or improper operations during testing.
- III. Improper preventive maintenance activities.
- IV. Inadvertance or carelessness during maintenance and testing.
- V. M&T personnel oversight or inadequacies.
- VI. Administrative or procedural deficiencies.
- VII. Miscellaneous.

Table 3.1 Forms of Data Collation for M&T Events

Column	Item	Content & Description
1	Event I.D. #	
2	Facility I.D. #	Docket No./special code number for the plant
3	Date	Date of event occurrence (Gregorian or Julian)
4	Plant size	MW
5	Type of plant	BWR - PWR
6	Vendor	GE- B&W - W - CE
7	A/E	
8	System/Subsystem involved	An extended version of the system code list provided in WASH-1400 will be used; such as HPCI-WPS-RHR-CIS-LPCI. Given in Appendix B
9	Components involved	
10	Number of components	
11	Type of component	
12	Effect on components	
13	Failure mode	
14	Effect on system/subsystem	
15	Type of maintenance and testing problem	Improper repair-Miscalibration-Improper setting-Left open-Left closed-Misadjustment-Lack of lubrication-Misalignment-Overfilled-Left deenergized-Inadvertent actuation-Misconnection-Improper handling-Negligence-Improper positioning-Inadvertent damage-Improper assembly-Improper replacement-Did not tighten-Installation error

Continued

Table 3.1 Forms of Data Collation for M&T Events (cont)

Column	Item	Content & Description
16	Cause of maintenance or testing problem	Human error - Procedure - Layout (inadequate access) - Design
17	Effect on plant	For example, shutdown
18	Recurring unusual events	
19	Consequence	Radiation release
20	Consequence	Occupational dose
21	Magnitude of exposure	
22	Further Description	
23	Comments	Any peculiarity

Table 3.2 Sample of Collated Data

Maintenance and Testing Reportable Occurrences in Twelve Boiling
Water Reactors from January 1972 through December 1977

M & T Events for Zion - 1 (PWR)

Size (MWt): 3250

Vendor: Westinghouse

A/E: Sargent Lundy

M & T MODE	COMPONENT(S) INVOLVED AND NUMBER OF EVENTS								TOTAL NO. OF EVENTS
	Comp.	No.	Comp.	No.	Comp.	No.	Comp.	No.	
Left closed	Valves	1	Valve, (IV)	1					2
Left in wrong position	Switch, test	1	Breaker	1					2
Left open	Valve	2							2
Misalignment/improper setting	Valve	1							1
Proc. inadequacy	Valve	1							1
Inadv. removed from service	Monitor, radiation	1							1
Misadjustment	Gasket	1	Valve	1					2
Did not stop	Pump	1							1
Removed from service	Valve	1							1
Bumped	Transmitter, pressure	1							1
Lubrication	Valve (IV)	1							1
Did not follow proc.	Heater	1							1
Improper repair	Valve (IV)	1							1

The M&T modes included in each category are listed in Table 3.3. Although some of the categories can be combined, the categorization is made to differentiate human error classes and modes such as omission (I), commission (II), systematic (III), sporadic actions (IV), and random (V). Also, the categories differentiate between error modes that can be directly caused by human action (I, II, IV and V) and M&T modes that can be caused as a result of system deficiencies (VI). Furthermore, M&T modes could be caused by improper maintenance scheduling (III), or other reasons (VII).

For example, Omission M&T modes of category I are characterized by skipping a proper step in performing the M&T task, while in category II commission modes involve improper performance of a proper step. Preventive maintenance in category III is an act performed consistently in the same way, or methodically.

The variability of human error in this case is characterized by a small dispersion pattern offset from a desired norm. Category IV is sporadic in nature since the M&T mode occurs occasionally in scattered instances with a variability which may be statistically represented by a small dispersion pattern centered about a desired norm. Category V is random in nature since the M&T mode involves performance of tasks without deliberation or with the lack of a definite aim. The statistical variability in this case is represented by a large dispersion pattern centered about a desired norm. Administrative and procedural deficiencies of category VI are often treated as system failures rather than human errors. In the miscellaneous category VII, events which cannot be identified as part of the other six categories are lumped together. However, both categories VI and VII may be combined. Although categories V and VI are related to procedures, category V is related more to human ability to properly use the procedures while category VI is related more to problems in the procedures which are extraneous to the human performing M&T tasks.

Since the M&T mode components of each group have inherent similarities, the clustering provided a firm basis for commonality among the various important M&T modes. Frequency of occurrence was the primary consideration in identification of important M&T modes. Radiological exposure

Table 3.3. Clusters of M&T Modes

CATEGORY I Acts of omission during or after the completion of maintenance and tests

Left closed/open	Did not report/record
Left partially closed/open	Did not calibrate
Left energized/deenergized	Did not replace
Left in wrong position	Did not bypass
Left withdrawn	Did not return to service
Did not remove after repair/test	Did not test/check
Did not verify	Did not verify
Did not deenergize/stop	Did not readjust
Did not reconnect	Did not adjust
Did not remove	Did not reset

CATEGORY II Acts of commission resulting in improper maintenance or improper operations during testing

Improper repair	Improper venting
Improper replacement	Deenergized
Improper assembly	Disconnected
Improper installation	Improper welding
Improper grounding	Misalignment/mispositioning/ improper setting
Improper connection	Misadjustment/out of adjustment
Loose/loose connection	Excessive tightening
Did not plug	Removed from service
Improper calibration	Over compensation/over torqued
Removed	Improper testing
Improper readjustment	Improper operation
Lack of repair	Improper withdrawal
Wiring	Improper charging
Erroneous repair	Improperly returned to service

CATEGORY III Improper preventive maintenance activities

Did not clean	Loosened/did not tighten
Lubrication	Sticking/stuck/binding
Lack of lubrication/inadequate lubrication	Open
Painted	Out of adjustment
Plugged	

CATEGORY IV Inadvertance or carelessness during maintenance and testing

Inadvertant actuation	Inadvertantly removed from service
Inadvertant damage	Bumped
Carelessness/negligence	Short circuit
	Inadvertant grounding

Table 3.3. Clusters of M&T Modes (cont.)

CATEGORY V M&T personnel oversight or inadequacies

Procedure violation	Misinterpretation/misunderstanding/
Did not follow procedure	misidentification
Wrong procedure followed	Failure to observe/identify
Lack of experience	Performed wrong test
Procedure unfamiliarity	Misread

CATEGORY VI Administrative or procedural deficiencies

Procedure deficiency	Procedure inadequacy
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CATEGORY VII Miscellaneous

Event	Communication problems
-------	------------------------

and shutdown duration were also considered, but inadequacies in reporting procedures resulted in sparse accumulation of these latter criteria with respect to individual events.

The M&T mode categories were then ordered by drawing histograms for individual facilities and reactor types for the determination of plant specific and generic M&T problems (Example, Figure 3.1). The complete set of histograms for BWRs and PWRs can be found in Appendixes C and D respectively. By visual comparison of the histograms, one can easily identify whether a M&T mode is generic or plant specific. This can be done through graph overlays to determine the commonalities among the M&T modes or systems affected by M&T problems. When a mode, for example, appears in several plants at a comparative frequency, then it is generic; while if the mode appears in association with a specific plant, then it is plant specific. Categories I, II, III, and IV are found to be generic M&T problems; while categories V, VI, and VII are more plant specific type problems.

The M&T modes are characterized for BWR's and PWR's. In both cases a frequency ordering of M&T categories for generic type problems is as follows: II, I, III and IV. This ordering technique by categories also identifies general M&T task involvement by categorizing definitions (i.e., the principal tasks involved in M&T error are due to "acts of commission during maintenance and testing activities." Specific task system/component involvement will be discussed later.

Based upon operations data to date, estimates can be given for the expected frequency (number/plant-year of operation) of generic M&T problems for BWR's and PWR's, as in Table 3.4.

Data review has shown that three percent of the M&T problems are directly related to procedural inadequacies which are plant specific M&T problems. This is expected since M&T procedures and administrative policies do differ from one plant to the other. All other events are due to human error.

Histograms have been developed to show the most frequent systems and components involved with M&T problems. For all general system

Facility 174P Three Mile Island-1 No. of Years 2.64 No. of M&T Events 26

Figure 3.1 Example Histogram

Table 3.4. Frequency of Generic M&T Problems

M&T Category	Number of M&T Events	Frequency of M&T Event (No./Reactor Yr. of Operation)	Reactor Type
II	72	2.05	B
	56	1.75	P
I	67	1.91	B
	47	1.47	P
III	47	1.34	B
	39	1.22	P
IV	11	0.31	B
	8	0.25	P

categorizations, the generic M&T mode categories (II, I, III, IV) account for all or at least the principal contribution to the M&T system related events, for both BWR's and PWR's. Table 3.5 shows a general ordering for the systems involved in M&T problems, and Tables 3.6 and 3.7 give the percentage of system involvement for the generic M&T problems. Comparison of Tables 3.6 and 3.7 show little difference between M&T mode category/system relationship for PWR's and BWR's. A list of system abbreviations used is given in Appendix A.

The results also show a consistency among PWR's and BWR's with respect to the principal components involved in M&T problems. Table 3.8 lists the percentage of individual component involvement for M&T events. It is apparent that valves, switches, breakers and relays are common to most of the generic M&T categories. This may lead to the development of future programs which study available alternatives for optimum efficiency during M&T when utilization of these components is necessary (i.e., components which automatically return to operational positions, component communicability--to "tell" M&T personnel what position the component is in, component simulators, etc.).

3.3 ANALYSIS OF M&T EVENTS BY PATTERN RECOGNITION

A simple and intuitive approach to the general analysis of M&T events in a nuclear power plant is to utilize the concept of pattern classification by distance functions. The representation of input data is by arranging measurements in the form of a measurement or pattern vector:

$$\underline{X} = \begin{matrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{matrix}$$

The most obvious way of establishing a measure of similarity between pattern vectors, which we consider as points in Euclidean space, is by

Table 3.5. Systems Involved in M&T Events

System Involved	Number of M&T Events	Percent of Total M&T Errors	Reactor Type
OCS	34	20	PWR
ECCIS	26	15	PWR
AEPS	25	15	PWR
RPS	18	11	PWR
ASNO	17	10	PWR
IMS	15	9	PWR
MRCS	9	5	PWR
CSRS	9	5	PWR
SNS	9	5	PWR
WPS	<u>3</u>	<u>2</u>	PWR
TOTAL	165 [*]	97 [†]	
ECCIS	47	22	BWR
OCS	41	19	BWR
IMS	31	14	BWR
AEPS	28	13	BWR
RPS	21	10	BWR
ASNO	13	6	BWR
SNS	9	4	BWR
CSRS	8	4	BWR
MRCS	7	3	BWR
WPS	<u>5</u>	<u>2</u>	BWR
TOTAL	210 [#]	96 [†]	

* PWR total for M&T events is 168 (3 events could not be system delineated)

† Total is less than 100% due to unknown systems

BWR total for M&T events is 217 (7 events could not be system delineated)

Table 3.6 Systems Involved in Generic M&T Problems for PWR's

M&T Category	System Involved	Number of M&T Events/Category	Percent of Total M&T Category Events
II	OCS	15	27
	ECCIS	11	20
	RPS	7	13
	AEPS	7	13
	ASNO	6	11
	SNS	3	5
	IMS	3	5
	CSRS	2	4
	MRCS	2	4
	TOTAL	56	
I	IMS	10	21
	ECCIS	7	15
	OCS	7	15
	AEPS	7	15
	ASNO	5	11
	CSRS	5	11
	WPS	2	4
	MRCS	2	4
	RPS	1	2
	Unknown	1	2
	TOTAL	47	
III	OCS	11	28
	AEPS	9	23
	ECCIS	6	15
	ASNO	5	13
	RPS	5	13
	CSRS	1	3
	SNS	1	3
	Unknown	1	3
	TOTAL	39	
IV	RPS	3	38
	OCS	1	13
	ASNO	1	13
	SNS	1	13
	IMS	1	13
	Unknown	1	13
	TOTAL	8	

Table 3.7 Systems Involved in Generic M&T Problems for BWR's

M&T Category	System Involved	Number of M&T Events/Category	Percent of Total M&T Category Events
II	ECCIS	23	32
	OCS	11	15
	AEPS	11	15
	RPS	6	8
	ASNO	6	8
	IMS	6	8
	MRCS	5	7
	WPS	3	4
	Unknown	1	1
	TOTAL	72	
I	IMS	15	22
	OCS	13	19
	ECCIS	12	16
	RPS	9	13
	AEPS	5	7
	ASNO	4	6
	CSRS	3	4
	SNS	2	3
	WPS	1	1
	Unknown	3	3
	TOTAL	67	
III	OCS	14	30
	ECCIS	8	17
	AEPS	7	15
	IMS	6	13
	SNS	4	9
	CSRS	4	9
	ASNO	2	4
	MRCS	1	2
	Unknown	1	2
	TOTAL	47	
IV	AEPS	2	18
	RPS	2	18
	IMS	2	18
	SNS	1	9
	ASNO	1	9
	ESRS	1	9
	MRCS	1	9
	Unknown	1	9
	TOTAL	11	

Table 3.8 Most Frequent Components Involved in Generic M&T Mode Categories

Category	Component	Number of Events/Category	Percent of Category/Events	Reactor Type
I	Valve	19	28	B
	Rad. Monitor	7	10	B
	Breaker	5	7	B
	Cable/Line/Pipe	4	6	B
	Jumper	4	6	B
	Switch/Dial	4	6	B
	Valve	19	40	P
	Switch/Dial	3	6	P
	Breaker	3	6	P
	Pump	3	6	P
	D.G.	3	6	P
II	Switch	25	35	B
	Valve	14	19	B
	D.G.	7	10	B
	Relay	6	8	B
	Valve	16	29	P
	Switch	9	16	P
	Breaker	5	9	P
	Relay	5	9	P
	Wire/Cable/Line	3	5	P
III	Switch	13	28	B
	Valve	12	26	B
	Breaker	4	9	B
	Valve	12	31	P
	Switch	6	15	P
	Relay	4	10	P
	Motor	3	8	P
	Snubber	3	8	P
	Filter/Strainer	2	5	P
IV	Switch	4	36	B
	Cable	3	27	B
	Rad. Monitor	1	9	B
	Valve	1	9	B
	Relay	1	9	B
	Nozzle	1	9	B
	Switch	1	13	P
	Relay	1	13	P
	Rad. Monitor	1	13	P
	Cooler	1	13	P
	Snubber	1	13	P
	Linkage	1	13	P
	Thermostat	1	13	P

determining their proximity. The Euclidean distance between an arbitrary pattern vector $\underline{x}$ and the i th prototype is given by

$$D_i = \underline{x} - \underline{z}_i = (\underline{x} - \underline{z}_i)^t (\underline{x} - \underline{z}_i)$$

where $\underline{z}_i$ is the cluster center (mean vector), and "t" is the transpose of a matrix.

The minimum-distance classifier computes the distance from a pattern $\underline{x}$ of unknown classification to the prototype (cluster center) of each class, and assigns the pattern to the class to which it is closest. In other words, $\underline{x}$ is assigned to class w_i if $D_i < D_j$, for all $j \neq i$. If $D_i > D_j$, $\underline{x}$ is assigned to class w_j .

The pattern recognition procedure presented here is called the K-means algorithm. This algorithm is based on the minimization of a performance index which is defined as the sum of the squared distances from all points in a cluster domain to the cluster center. This procedure consists of the following steps.

Step 1. Choose k initial cluster centers ($\underline{z}_1(1)$, $\underline{z}_2(1)$, ..., $\underline{z}_k(1)$). These are arbitrary and are usually selected as the first k samples of the given sample set.

Step 2. At the k th iterative step, distribute the samples $\{\underline{x}\}$ among the k cluster domains, using the relation,

$$\underline{x} \in S_j(k) \quad \text{if} \quad \|\underline{x} - \underline{z}_j(k)\| < \|\underline{x} - \underline{z}_i(k)\|$$

for all $i=1,2,\dots,k$, $i \neq j$, where $S_j(k)$ denotes the set of samples whose cluster center is $\underline{z}_j(k)$.

Step 3. From the results of Step 2, compute the new cluster centers $\underline{z}_j(k+1)$, $j=1,2,\dots,k$ such that the sum of the squared distances from all points in $S_j(k)$ to the new cluster center $\underline{z}_j(k+1)$ is minimized. In other words, the performance index

$$J_j = \sum_{\underline{x} \in S_j(k)} \|\underline{x} - \underline{z}_j(k+1)\|^2, \quad j=1,2,\dots,k$$

is minimized. The $\underline{z}_j(k+1)$ which minimizes this performance index is simply the sample mean of $S_j(k)$. Therefore, the new cluster center is given by

$$\underline{Z}_j^{(k+1)} = \frac{1}{N_j} \cdot \sum_{x \in S_j(k)} x, \quad j=1,2,\dots,k$$

where N_j is the number of samples in $S_j(k)$. This indicates that the cluster centers are sequentially updated.

Step 4. If $\underline{Z}_j^{(k+1)} = \underline{Z}_j^{(k)}$ for $j=1,2,\dots,k$, the algorithm has converged and the procedure is terminated. Otherwise go to Step 2.

The "k" means algorithm was investigated and developed by Macqueen.* A computer program has been written based on the above algorithm in the FORTRAN language. The program was developed especially to handle the M&T data clustering and is given in Appendix E. The initial cluster centers are taken arbitrarily to be $\underline{Z}_1$ and $\underline{Z}_2$, i.e., $k=2$. A value of $k=2$ was chosen because the set of pattern vectors were divided into two classes; i.e., Class 1 shows the group plants with high frequencies of events for the various modes. Class 2 shows the group of plants with low frequency of events. One can use higher values of k , however, $k=2$ was found appropriate due to the small number of events considered here. Starting values of $\underline{Z}_1$ and $\underline{Z}_2$ are selected arbitrarily by the program. In the present case the first two data inputs are

$\underline{Z}_1 =$	$\underline{Z}_2 =$
2.55	1.41
1.82	1.41
0.36	0.00
0.73	0.70
0.73	0.00
0.36	0.70
0.36	0.00

The program analyzes a set of pattern vectors and divides them into two classes or domains. The eventual result is the cluster centers of the two classes which are obtained from the sample set.

Since the M&T events in a nuclear facility have been broadly divided into seven categories with each category (M&T mode) having the

* In J. T. Tou and R. C. Gonzalez, Pattern Recognition Principles (John Wiley, New York, 1975).

frequency of event per reactor year, we have a sample set of patterns from the various facilities. For example,

Facility A: $X_1 =$ 2.55
1.82
0.36
0.73
0.73
0.36
0.36

where each x_i represents the number of events per reactor year for M&T mode i , where $i = I, II, \dots, VII$. The data for all PWR's analyzed were fed into this program and the output shows the mean vector for the frequency of events per reactor year in each mode. Six of the PWR's were characterized by $Z_1(z)$, and five were characterized by $Z_2(z)$. The results are given in Table 3.9.

3.4 STATISTICAL ANALYSIS OF M&T FREQUENCIES

The main purposes of this analysis are:

- a. To determine if some categories of action are highly associated with particular component failures in various systems. That is, examine interactions among factors.
- b. To increase the precision estimates for the probabilities of specific events for each reactor type.

These objectives are achieved by using the Statistical Analysis System (SAS) and the Biomedical Data Program (BMDP) packaged computer programs which are available commercially to construct contingency tables for the event data. The events are cross-classified by the following four factors:

- a. Reactor type (2 categories)
- b. Category of action leading to the accident (7 categories)
- c. Reactor system (11 categories)
- d. Mechanical or electrical component (up to 54 categories)

Table 3.9 Frequency of M&T Events by M&T Mode Clusters

Cluster Center	PWR								BWR							
	# in class	I	II	III	IV	V	VI	VII	# in class	I	II	III	IV	V	VI	VII
z_1	6	2.34	2.57	1.92	0.30	0.23	0.40	0.12	3	7.0	7.81	3.89	1.13	1.01	0.68	0.62
z_2	5	0.67	0.94	0.64	0.18	0.0	0.14	0.30	9	1.0	1.15	0.86	0.18	0.12	0.11	0

Cluster Center	ALL LWR's							
	# in class	I	II	III	IV	V	VI	VII
z_1	3	7.00	7.81	3.29	1.13	1.01	0.68	0.62
z_2	20	1.32	1.52	1.12	0.21	0.12	0.21	0.11

The number of categories in a four-dimensional table constructed from these four factors could exceed the number of events. Therefore, methods for the analysis of sparse contingency tables are required.

This analysis identifies combinations of factor categories which have relatively high probabilities of occurring. For example, if the failure of a particular component in a certain system is highly associated with omission to perform a certain maintenance job, this method would have a "good" chance of discovering this fact. This method uses the theory of log-linear models to fit models for which the factors act independently or are conditionally independent. Large deviations from the model are found through examination of the residuals in the form of Freeman-Tukey deviates. A table of the percentiles for the standard normal distribution is used to determine when a Freeman-Tukey deviate is large. A large positive residual (Freeman-Tukey deviate) for a particular factor combination suggests that corresponding factor categories have a significant positive association. That is, the probability that this combination of factor categories occurs is relatively high. Patterns of residuals are also examined.

The above procedure acts somewhat like a clustering procedure to identify combinations of event categories with significant associations or interactions. After these types of events are identified, it is possible to fix additional models to the table which account for the special structure in the table caused by the cells corresponding to significant interactions. If a model of this type is found to fit the data well, with relatively few parameters, it would provide more precise estimates of the event probabilities (estimates with smaller variances) than those obtained just using observed counts for individual events. Fitting a model essentially smooths the information provided by this sparse data set across the entire contingency table yielding "better" estimates of the probabilities overall.

As a preliminary step to fulfilling these methodological requirements, the general statistical analysis of all 385 abnormal events pertaining to maintenance and testing in 23 nuclear power plants occurring from 1972 to 1977 was carried out by codifying each event according to the

facility, category or cause of action, system, and component. The data set was then analyzed by the Statistical Analysis System (SAS) program. Each observation is listed out where an event is identified as system-component (syscomp), e.g., 1012 indicates system 1 (AEPS) with component 12 (governor) involved.

$$1012 = 1 (1000) + 12$$

The code listings are given in Tables 3.10 through 3.13.

SAS lists out all 385 events according to syscomp grouping and the frequency of occurrence. It also computes the percentage of each syscomp over all events. The components most frequently involved in a system during maintenance and testing events are provided in Table 3.14.

SAS now lists out each syscomp event according to the frequency in each reactor type--PWR or BWR. It also computes the row and column percentages for cross-classification. The components specifically involved in the various systems of the reactor type during maintenance and testing events are shown in Table 3.15.

SAS now classifies each syscomp event by the cause of action, for example, "acts of omission during maintenance and testing activities" resulting in an abnormal event occurrence. It lists the frequency of events under the seven categories and computes the row and column percentages for cross-classification. The components that are most frequently and likely to be involved in their respective systems under the various causes of action during maintenance and testing are shown in Table 3.16.

The SAS program now analyzes all 385 events for generic or reactor type specific problem by means of an analysis of sparse contingency tables. The methodology or theoretical basis for this form of analysis is described below.

For a 3-way table, the model is given by

$$P_{ijk} = (p_{i++}) (p_{+j+}) (p_{++k})$$

Table 3.10 Code Listing of Facilities

PWR (1)		Years of Operation
1.	Three Mile Island - 1	2.64
2.	Oconee - 1	2.96
3.	Kewaunee - 1	2.97
4.	Indian Point - 2	2.82
5.	Zion - 1	2.75
6.	Fort Calhoun - 1	3.24
7.	Millstone - 2	1.72
8.	Haddam Neck - 1	4.95
9.	Indian Point - 1	1.86
10.	Yankee Rowe	4.79
11.	Rancho Seco - 1	1.51

BWR (2)		
1.	Humbolt Bay	4.31
2.	Nine Mile Point - 1	4.49
3.	La Crosse	3.49
4.	Vermont Yankee	3.89
5.	Brunswick - 2	1.41
6.	Duane Arnold	1.95
7.	Cooper - 1	2.91
8.	Browns Ferry - 1	1.74
9.	Hatch - 1	1.43
10.	Fitzpatrick - 1	1.72
11.	Quad Cities - 1	3.64
12.	Dresden - 1	4.07

Table 3.11 Code Listing of Category or Cause of Action

CATEGORY
1. Omission to perform an action (during or after completion of TEST/REPAIR work).
2. Improper maintenance or operation of component.
3. Preventive maintenance.
4. Inadvertence/carelessness.
5. Personnel.
6. Administrative/procedural errors.
7. Miscellaneous

Table 3.12 Code Listing of Systems in a Reactor

SYSTEM
1. AEPS Auxiliary Electrical Power System
2. RPS Reactor Protection System
3. ECCIS Emergency Core Coolant Injection System
4. MRCS Main Reactor Cooling System
5. CSRS Containment Spray and Recirculation System
6. OCS Other Containment System
7. ASNO Auxiliary System for Normal Operation
8. WPS Radioactive Waste Processing System
9. SNS Secondary/Non-nuclear System
10. IMS Instrumentation and Monitoring System
11. U Unknown

Table 3.13 Code Listing of All Components Involved in the M&T Events

1. Cam	28. Bistable
2. Clutch	29. Blower/Fan
3. Control Rod	30. Breaker
4. Cooler/Chiller	31. Cable
5. Cover Plate	32. Dial
6. Door/Hatch	33. Diode
7. Event (no component involved)	34. Film Badge/Dosimeter
8. Filter or Strainer	35. Fuse
9. Fitting	36. Generator (D.G.)
10. Flange	37. Heat Detector
11. Gasket	38. Heat Element
12. Governor	39. Instrumentation
13. Injector/Injector Rock	40. Jumper
14. Line	41. Lightning Arrester
15. Linkage	42. Meter
16. Nozzle	43. Motor
17. Pipe	44. Motor Starter
18. Pump (Shaft)	45. Potentiometer
19. Shock Absorber/Hydraulic Snubber	46. Radiation Monitor
20. Steam Generator	47. Recorder
21. Tank	48. Relay
22. Tendon	49. Switch
23. Tubing	50. Thermostat
24. Valve	51. Transmitter
25. Alarm	52. Wire
26. Amplifier	53. Light
27. Battery/DC Power Supply	54. Wall
	55. Plug

Table 3.14 Components Most Frequently Involved in the Systems During M&T Events

SYSTEM	COMPONENT	FREQUENCY	PERCENT
AEPS	Relay	9	2.34
RPS	Valve	10	2.60
ECCIS	Switch	27	7.01
MRCS	Valve	7	1.82
CSRS	Valve	6	1.56
OCS	Valve	28	7.27
ASNO	Valve	13	3.38
WPS	Line	2	0.52
SNS	Switch	5	1.30
IMS	Radiation Monitor	15	3.90
U	Event (or film badge)	2	0.52

Table 3.15 Components Specifically Involved in the Systems of the Reactor Type During M&T Events

SYSTEM	PWR	BWR
AEPS	Motor, Relay	Switch
RPS	Valve	Valve
ECCIS	Valve	Switch
MRCS	Valve	Valve
CSRS	Valve	Switch, Valve
OCS	Valve	Valve
ASNO	Valve	Switch
WPS	Line	Line
SNS	Switch	Blower/Fan
IMS	Radiation Monitor	Radiation Monitor
U	Event	Film Badge/Dosimeter

Table 3.16 Components Generically Involved in the Various Systems During M&T Events

CATEGORY SYSTEM	1	2	3	4	5	6	7
AEPS	Generator (D.G.)	Relay	Motor	Switch	Battery	Relay	-
RPS	Valve	Switch	Valve	Cable Instru- menta- tion Thermo- stat	Control Rod	Bistable	-
ECCIS	Valve	Switch	Switch	-	Tank Recorder	Valve	Motor
MRCS	Valve	Valve	Valve	Valve	-	Tubing	Steam Generator
CSRS	Pump (Shaft)	Pump (Shaft)	Switch	Nozzle	-	Tank	-
OCS	Valve	Valve	Valve	Switch	Event	-	Steam Generator
ANSO	Valve	Valve	Valve	Cooler	-	-	-
WPS	Line	Instru- mentation Motor Switch	-	-	Event	-	Alarm
SNS	Event	Switch	Blower/ Fan	Shock Absor- ber/ Snub- ber	Bistable	Heat Detector	Breaker
IMS	Radia- tion Moni- tor	Switch	Valve	Radia- tion Moni- tor	Radia- tion Monitor	Recorder	Radiation Monitor
U	Film Badge/ Dosi- meter	Valve	Relay Door	Cable	-	-	Event

where i represents the reactor type, $i = 1, 2$

j represents the category of action, $j = 1, 2, \dots, 7$

k represents the system-component, $k = 1, 2, \dots, 385$

The expected frequency of an event is $n_{+++} p_{ijk}$ where n_{+++} is the total number of events in the sample set.

The parameters $\{p_{i++}; i = 1, 2\}$, $\{p_{+j+}; j = 1, \dots, 7\}$ and $\{p_{++k}; k = 1, \dots, 385\}$ are estimated by

$$\hat{p}_{i++} = \frac{n_{i++}}{n_{+++}}, \quad n_{i++} = \text{row total}$$

$$\hat{p}_{+j+} = \frac{n_{+j+}}{n_{+++}}, \quad n_{+j+} = \text{column total}$$

$$\hat{p}_{++k} = \frac{n_{++k}}{n_{+++}}, \quad n_{++k} = \text{layer total}$$

The estimates for the expected frequencies under the model of independence are

$$n_{+++} \hat{p}_{ijk} = n_{+++} (\hat{p}_{i++}) (\hat{p}_{+j+}) (\hat{p}_{++k})$$

To test the hypothesis that the model of independence fits well, the Pearson chi-square statistic is computed:

$$\chi^2 = \sum_i \sum_j \sum_k \frac{(n_{ijk} - \text{expected value})^2}{\text{expected value}}$$

The contribution from one cell in the table is

$$\frac{(n_{ijk} - n_{+++} \hat{p}_{ijk})^2}{n_{+++} \hat{p}_{ijk}}$$

This behaves approximately as a chi-square distribution with one degree of freedom, or

$$\sqrt{\frac{(\text{observed value} - \text{expected value})^2}{\text{expected value}}}$$

is approximately standard normal, if the true expected frequencies are "large", i.e., greater or equal to 5. But $n_{+++} \hat{p}_{ijk} \geq 1$ is acceptable.

A particular cell fits the independence model if

$$\frac{(\text{observed} - \text{expected})^2}{\text{expected}} \sim \text{large}.$$

This can be compared to the percentile of a $\chi^2_{(1df)}$, where 1df indicates one degree of freedom.

SAS computes the expected frequency and the chi-square values for each cell of observation. A large chi-square value (≥ 1) indicates that cell to be generic or specific to the controlling variable. The components that are generically involved in a system during maintenance and testing for a particular reactor type are shown in Table 3.17.

SAS now analyzes each syscomp event under the various categories of action by sparse contingency table. The components generically involved in each system of all LWR's are displayed on Table 3.18. The numbers within the parentheses indicate the causes of action.

In AEPS, components such as filter, motor, and instrumentation are affected by improper preventive maintenance. A switch may be carelessly operated on. For RPS; relays, switches, cables, etc. are involved in M&T events due to inadvertance or carelessness on the part of personnel. The components involved in the ECCIS are valves, filters, switches, motor, etc. The generic problem here is again preventive maintenance acts. In MRCS, the components involved are switch, steam generator, and turbine. In CSRS, the pump and breaker are involved due to omission to perform an action after test/repair work. For OCS, improper preventive maintenance error modes involved shock absorbers, valves, breakers, and tendons. Switches and a door are involved due to omission to perform an action. For ASNO, improper maintenance involved breakers and motors. In WPS, a line (pipe) was involved due to omission to perform an action. In SNS, switches and shock absorbers were involved due to carelessness. Valves and bistable were involved due to administrative or procedural errors.

Table 3.17. Components Generically Involved in the Reactor Type

SYSTEM	PWR	$\frac{2}{X}$	BWR	$\frac{2}{X}$
AEPS	Motor	3.6	Motor Starter	1.0
RPS	-		Switch	1.0
ECCIS	Switch	2.8	Switch	2.2
MRCS	-		-	
CSRS	-		-	
OCS	Shock Absorber	4.4	Event	1.4
ASNO	Valve	3.3	Valve	2.6
WPS	-		-	
SNS	-		-	
IMS	Recorder	1.5	-	
U	Event	1.5		

Table 3.18 Components Generically Involved in Each System

SYSTEM \ χ^2 VALUES	2-5	5-10	> 10
AEPS	Filter (3) Diesel Generator (1) Instrumentation (1) Motor (3,6) Switch (4,6)		Relay (6)
RPS	Valve (1) Breaker (3) Relay (4)	Bistable (6) Switch (4)	Control Rod (5) Cable (4) Instrumentation (4) Jumper (5) Potentiometer (5) Thermostat (4)
ECCIS	Filter (3) Pump (5) Valve (6) Motor Starter (3) Jumper (1) Relay (2) Switch (1)	Switch (2)	Tank (5) Motor (4) Recorder (5)
MRCS	Switch (2)		Steam Generator (7) Tubing (6)
CSRS	Pump (1) Breaker (1) Motor (3)	Switch (3)	Tank (6)
OCS	Door (1) Shock Absorber (3) Tendon (3) Valve (3) Switch (1,2)	Breaker (3)	Event (5) Filter (5) Steam Generator (7)
ASNO	Filter (3) Breaker (2) Motor (2) Switch (4)		Cooler (4)
WPS	Line (1)		Event (5) Alarm (7)

cont.

Table 3.18 Components Generically Involved in Each System (cont)

SNS	Switch (4)	Shock Absorber (4) Blower/Fan (3) Heat Element (5)	Valve (6) Bistable (5) Breaker (4) Heat Detector (6)
IMS	Valve (1) Amplifier (3) Breaker (1) Cable (4) Meter (3) Radiation Monitor (1,4)	Event (1)	Recorder (6)
U	Door (3) Film Badge (1) Relay (3)		Event (7) Alarm (7) Cable (4)

For IMS, valves and breakers were involved when there was an omission to perform an action. The radiation monitor was involved due to carelessness.

SAS then analyzed each syscomp event under the various categories of action by reactor type (PWR and BWR). Tables 3.19 and 3.20 show the components generically involved during maintenance and testing or systems for PWR's or BWR's, respectively. The numbers within the parentheses indicate the cause of action leading to an abnormal event occurrence.

3.5 GENERAL ANALYSIS OF RESULTS

Of the 3564 events extracted from LER data (23 LWR's from January 1972, or date of commercial operation, whichever is latest, through December 1977) and retained on computer file, only 385 were traceable to maintenance and testing. Yet these errors are highly significant for several reasons.

1. They pre-program further system failures, some of which could result in safety problems.
2. They can seriously compound, multiply, and magnify the results of operator error by providing misinformation or no information at times when such information is critical.

Problems in maintenance and testing work can be the result of many factors, including: personnel problems, operator ignorance, neglect, deliberate omission of tedious work, deliberate commission of a fault, and random incidents resulting from inadequate skill or practice. The following preliminary statements are made at this time regarding maintenance and testing problems attributable to plant personnel:

1. The problematic patterns do not appear to be the result of inadequate job skills or knowledge. What was done wrong or left undone could have been done correctly.
2. Maintenance and testing problems primarily involve valves and switches. The most common errors involve leaving a valve or switch in the wrong position, failure to properly lubricate a valve, faulty repair of a valve, or misadjustment of a valve or switch. They are common types of errors found in nearly all kinds of maintenance and testing work in many industries.

Table 3.19 Components Generically Involved in Systems of PWR

SYSTEM \ χ^2 VALUES	2-5	> 5
AEPS	Filter (3) Battery (2) Diesel Generator (1) Motor (3,6) Relay (6)	
RPS	Breaker (3)	Bistable (6) Instrumentation (4) Potentiometer (5) Relay (4) Thermostat (4)
ECCIS	Filter (3) Pipe (3)	Tank (5)
MRCS	Valve (1)	Steam Generator (7)
CSRS		Tank (6)
OCS	Clutch (3) Shock Absorber (3) Tendon (3) Switch (4)	Steam Generator (7)
ASNO		Cooler (4)
WPS		Alarm (7)
SNS		Shock Absorber (4) Valve (5) Breaker (7) Heat Detector (6) Heat Element (5)
IMS	Radiation Monitor (4)	Recorder (6)
U	Relay (3)	Event (7)

Table 3.20 Components Generically Involved in Systems of BWR

SYSTEM \ χ^2 VALUES	2-5	> 5	SYSTEM \ χ^2 VALUES	2-5	> 5
AEPS	Instrumentation (3) Relay (4) Switch (4)	Battery (3) Relay (6) Switch (6)	* IMS	Cable (4) Motor (3) Radiation Monitor (7) Switch (2)	
RPS	Switch (4)	Control Rod (5) Valve (1) Cable (4) Jumper (5)	U	Door (3) Film Badge (1)	Alarm (7) Cable (4)
ECCIS	Valve (6) Jumper (1) Motor Starter (3) Switch (1)	Pump (5) Motor (7) Recorder (5) Switch (2)			
MRCS	Switch (2)				
CSRS	Motor (3)	Nozzle (4) Switch (3)			
OCS	Valve (3) Fuse (1) Switch (2)	Event (5) Breaker (3)			
ASNO	Filter (3) Motor (2) Switch (4)				
UPS		Event (5)			
SNS	Shock Absorber (3)	Valve (6) Bistable (5) Blower (3) Switch (4)			
IMS	Event (1) Amplifier (3) Breaker (1) *				

3. There appears to be no clear pattern of problems by system. Some patterns and repeatability are evident with subsystem and component--as with valves and switches, left in wrong position, misadjusted, etc.
4. A similar pattern exists in maintenance (M), maintenance during test (MT), and preventative maintenance (PM). since M and PM patterns and frequencies are basically similar, time pressure may not be a problem.
5. In PM, most errors (37/61 counted in sample) involved omission of an operation or element of the maintenance task. Another 13/61 involved misadjustment, misalignment, etc. Another 8 involved lubrication.

The evidence supporting these five observations, and especially that supporting observation number 2, points to common classifications of problems known as:

- Adjustment errors
- Forgetting errors

It also appears that M&T problems tend to involve minor or supportive elements in the work sequence--matters likely to be forgotten. Such problems are all too common in everyday life--leaving a light on, leaving keys in the car, etc. The reasons that these kinds of problems occur frequently in most maintenance and testing work are that:

1. Inadequate cues exist to point to their exclusion or incorrect completion.
2. No check or test of the component or subsystem is made immediately following the maintenance operation in question.
3. The worker is usually unaware of his error and, hence, does not correct himself.
4. Low frequency of maintenance and testing tasks does not permit adequate practice to produce automatic sequencing of small events in the work process.
5. Management controls and incentives are lacking to make the maintenance/testing person specifically responsible for given subsystems and their operation.

6. Poor work habits in performing basic tasks such as lubricating, tightening, etc. may have developed.

It should be emphasized that the maintenance/testing worker is probably, in nearly all cases, unaware that he committed the errors in question. He/She would be surprised to have them pointed out.

A sub-analysis of the 385 maintenance and testing problems in both BWR and PWR plants was performed. In 12 BWR plants a total of 217 M&T problems were listed covering the period 1972-1977, and classified as shown in Table 3.21. Of 62 types of LER events for BWR's classified according to type of problems and component, the first eight accounted for 50 percent of the total. These errors involved such components as: switches, valves, fuses, pumps, recorders, batteries, motors, relays, breakers, governors, and monitors.

In the case of the 11 PWR plants, a total of 168 problems were listed for the period 1972-1977. Categories listed with the highest frequencies are listed in Table 3.22. For PWR M&T problems, the first 11 categories accounted for 55.9 percent of all recorded errors. These typically involved valves, relays, switches, motors, pumps, doors, breakers, and governors.

In both BWR and PWR plants, M&T problems appear to be concentrated statistically within certain hardware classifications. It is likely that initial research on the problem can be concentrated in these areas. For example, valves were involved with a larger portion of M&T problems which totaled 132. Generally, most M&T problems in LWR plants occurred in those rated at more than 1500 Mwt.

A comparison of M&T event frequencies by NSSS vendor shows that the number of events per reactor year of operation are 5.25 for Combustion Engineering, 3 for General Electric, 2.7 for Babcock and Wilcox, 2 for Westinghouse, and 1.81 for Allis Chalmers. The large frequency for CE may be attributed to the fact that only two plants have been selected for data analysis.

Table 3.21 M&T Problems in 12 BWRs (1972-1977)

PROBLEM	NUMBER OF EVENTS	CUMULATIVE %
1. Did not clean	21	
2. Misadjustment	21	
3. Did not test/check	<u>20</u>	
Subtotal	62	28.7%
4. Misalignment/improper setting	15	
5. Lubrication	9	
6. Did not tighten	<u>8</u>	
Subtotal	32	43.5%
7. Procedure violation	7	
8. Left closed	<u>7</u>	
Total, first 8	108	50.0%
TOTAL, all BWR M&T problems	217	

Table 3.22 M&T Problems in 11 PWRs (1972-1977)

ERROR	NUMBER	CUMULATIVE %
1. Lubrication	12	
2. Misposition/improper setting	12	
3. Did not clean	<u>11</u>	
Subtotal	35	20.6%
4. Procedure violation	10	
5. Did not test/check	10	
6. Procedure inadequacy	9	
7. Left closed	7	
8. Left open	<u>7</u>	
Subtotal	43	45.9%
9. Misadjustment	7	
10. Did not tighten	5	
11. Did not clean	<u>5</u>	
Subtotal	17	55.9%
TOTAL, all PWR M&T problems	168	

3.6 INDIRECT ROOT CAUSES

The review of M&T data and the peculiarities of the events in some plants suggested that management attitude towards M&T is an indirect cause of the problems which occur during the performance of M&T tasks. Consequently, the data is collated in a manner that allows examination of various measures which may indicate deficiencies in management policies or possible leniency in organization and administration of M&T tasks. Some of the measures considered are discussed below.

3.6.1 Operator Errors

One may expect that the operating personnel at a plant are well trained, as indicated by RO and SRO scores on NRC examinations. If this is the case, then the maintenance and testing personnel will also be well trained and vice versa. Thus, a close correlation may exist between operator errors and M&T events.

An investigation was made of a possible correlation existing between the number of operator errors (OE) reported (based on line summaries found in Operator Errors Summaries 1972-1977 by Sabri and Husseiny, October, 1978), and the number of maintenance and testing (M&T) events occurring in each plant. There was no discernible correlation found. Next, a comparison of the percentage of OE's (i.e., the percentage of OE's to the total number of OE's and M&T events) to the percentage of M&T events occurring in each facility again showed no correlation. After this, a comparison was made of the number of OE's occurring in each plant type (BWR's and PWR's) per year to the number of M&T events per year. There was a good indication of a linear relationship between OE's to M&T errors (Figure 3.2), suggesting that the linear relationship may be the result of the increase in the number of new plants beginning commercial operation during each year. The data were then normalized to account for this by dividing the number of OE's and the number of M&T events by the number of plants in commercial operation for each year. The linear correlation between OE's and the number of M&T events was still indicated as shown in Figure 3.3.

Figure 3.2 Correlation between operator errors and M&T events per plant.

Figure 3.3 Number of operator errors (OE) and M&T events per plant versus time for plants in commercial operation.

The data were examined further by comparing the number of OE's/plant/year to the number of M&T events/plant/year for those plants in a particular power level range (i.e., three curves: one for those plants with thermal power levels below 1500 MW, one for those between 1500 and 2500 MW, and one for those greater than 2500 MW). There was, again, good correlation within each group and there was also evidence of learning experience as time progressed, as shown in Figure 3.4.

3.6.2 Plant Location

There may be a difference in M&T practices between nuclear power plants located in a large, urban, labor pool area with strong labor union personnel and plants in a more rural location with less jobs available for skilled craftsmen. In some locations a craftsman would perhaps take more pride and responsibility in his work than in other locations. Those hypotheses may be examined by making correlations between M&T events and the nature of the surrounding population areas.

An investigation was made of a possible correlation between the number of M&T events occurring within each facility and its distance from the nearest high population center (Figure 3.5). The trend indicated greater numbers of M&T events reported for those facilities within about ten miles of, or greater than about 30 miles from a high population area. Also, an investigation was made of the correlation between the number of M&T events reported by a facility and the population of the local area near the facility; Figure 3.6. The information gathered here indicated that fewer M&T events occur in those facilities where the local population ranges between 15,000 to 30,000 people.

3.6.3 Administrative Errors

An attempt to find a correlation between the number of M&T events in a facility and the number relating to administrative error types (i.e., administrative during testing/maintenance) failed to show any such correlation existed.

Figure 3.4 Correlation between OE and M&T events per plant per year in various size ranges.

Figure 3.5 Correlation Between M&T Events In 26 LWRs and Distance From High Population Centers.

Figure 3.6 Correlation Between Population Near Plant and M&T Events in 26 LWRs.

3.6.4 Financial Conditions

The financial conditions of a utility company are expected to have impact on the performance of the plant. One may suspect that the utility companies receiving adequate rates are likely to do a more complete job on maintenance than those who have to cut corners some place in order to be able to give the stockholders a return on their investment. To verify these assumptions, correlations are made between the financial conditions of the utilities and the M&T events occurring in their plants.

An investigation was made into the financial well-being of nine utilities to try and determine any correlation between the fraction of the utility's operating expenses applied toward maintenance and the average number of M&T events reported for each plant owned by the utility. The general trend (figure 3.7) indicated that the average number of M&T events per plant for each utility decreases as the ratio of maintenance expenses to operating expenses increased. Additionally, a comparison was made between the average number of M&T events per plant for each utility and the return on each dollar invested by the utility's stockholders, as shown in Figure 3.8. The general trend indicates that the average number of M&T events/plant increases as the return on each dollar invested increases. It should be noted, however, that the information on maintenance expenses, operating expenses, and earnings per share are based upon the utility as a whole, rather than on the portions of the expenses and earnings representative of each plant.

3.6.5 M&T Problems in Identical Plants

During the investigation of possible root causes for M&T errors, a comparison of M&T events for four facilities was made. The four plants consisted of two BWR's which had the same NSSS and A-E, were in the same range of power level, and had approximately the same length of commercial operation experience. The two PWR facilities were similar to each other in the same areas mentioned for BWR's. In each of the four plants, human error was the primary contributor to the total error population, with

Figure 3.7 M&T Events As Function of the Ratio Between Cost Allocations for Maintenance and Operation

Figure 3.8 Correlation Between M&T Events in 14 Plants and Rate of Return

maintenance problems comprising the majority of the human error.

In three of the four plants, the principal problem was incorrect maintenance on mechanical components. Maintenance problems with electrical devices were the principal contributor to the error population for the fourth plant.

Also, an investigation was made as the system type (primary, secondary, electrical supply/logic control systems) most frequently involved in each facility's M&T errors. In three of the plants the primary systems were most often involved. Secondary systems were most often involved in the fourth plant.

Figures 3.9 through 3.12 show data for Kewaunee, Prairie Island-1, Quad Cities-2, and Dresden-2, respectively. The graphs display M&T and operator errors as a function of years of operation, and the average values normalized over the years of operation of each plant type (PWR and BWR). The results show that the average M&T event frequency dominates the average operator error frequency in the four cases considered here.

Figure 3.9 Kewaunee

M&T Avg. = Average No. of M&T Events/Year
For 12 PWRs.

OE Avg. = Average No. of Operator Errors/Year
For 12 PWRs.

Figure 3.10 Prairie Island-1

Figure 3.11 Quad Cities-2

M&T Avg. = Average No. of M&T Events/Year
For 13 BWRs.

OE Avg. = Average No. of Operator Errors/
Year for 13 BWRs.

Figure 3.12 Dresden-2

4.0 MAINTENANCE AND TESTING PROBLEM MITIGATION

Following the identification of specific causes of maintenance and testing problems, several solutions can be recommended.

These range from complete redesigns of hardware such as valves and switches to improved human relations and communications between management and labor. In some cases a combination of several methods may be desirable. A partial list of mitigation methods includes:

1. Basic redesign of hardware.
2. Additions of features to hardware to improve human awareness of its status, such as: basic appearance, marking, alignment, shape and color coding, etc.
3. Improved training of maintenance and testing personnel using:
 - a. Programmed instruction
 - b. Simulators
 - c. Working models of hardware
4. Information check lists for use in maintenance and testing.
5. Hardware tests immediately following maintenance and testing.
6. Automanual control with or without prediction of future states of the system.
7. Management practices, including:
 - a. Assignment of responsibility.
 - b. Use of incentives, feedback, performance evaluation.
 - c. Human relations.
8. Applied work simplification involving:
 - a. Displays or control appearance.
 - b. Diagnostics, decision making in maintenance and testing, trouble-shooting techniques.

- c. Controls and tools, including force or position feedback.
 - d. Work area designs.
 - e. New, improved tools.
9. Control of the work environment including protection and work stress reduction.

4.1 DESIGN CONSIDERATIONS FOR MAINTENANCE AND TESTING

This section specifically addresses the review of Licensee Event Reports and other data, resolving generic problem categories into a set of problem mitigation recommendations. In future phases of study recommendations can be priority listed in order to balance the estimated cost of implementation versus potential benefit gained in the reduction of plant outage time. The characterization of these parameters would, of necessity, be qualitative estimates. A possible follow-on program can quantitatively estimate such parameters through the use of reliability techniques.

Nuclear power generating facilities, similar to any large process system plant, are designed to optimize:

1. Safety
2. Operability - Reliability
3. Maintainability

Safety is the most dominant factor in the design and construction of nuclear power generation facilities. Operability, by needs of investment, becomes the second most dominant factor. For example, many of the current NSSS designs offer extensive control systems to improve the operability and availability of their product. Design for test and maintenance, therefore, is considered when other constraints allow. Deviation from this practice can be noticed only where particular maintainability concerns have or could lead to safety concerns, such as testing the Reactor Protection System. Consequently, these systems have significantly better capabilities for maintenance and testing.

4.2 DATA STUDY

The aim of this study is to reduce the occurrences of maintenance and testing problems which should have a direct result of reducing the Licensee Event Report entries for maintenance and testing. To accomplish this goal, this study has examined the different types of problems to ensure the proper focus on problem types which are large contributors to the data base. To illustrate, M&T problems can be categorized in many ways, however, an instructive categorization is:

1. Random errors. These are errors that are not predictable and virtually impossible to analyze from any data base. Examples of such errors are the inadvertant actuation of a system while cleaning a control board, or the shorting of a circuit by dropping a tool into an open cabinet while conducting tests.
2. Systematic. These are errors that systematically occur as a result of a design error. Examples of such errors are the changing of the position of the wrong type of control rod because control handles are identical, or activation of the wrong pump because the layout of the controls for its system is reversed left-right orientation from other systems.
3. Sporadic. These are errors that occur on an infrequent basis, generally by trained personnel. A data base of such errors can be developed and generic test and maintenance errors can be categorized. Most test and maintenance errors fall into this category; therefore, a data base can be studied for error types and recommendations proposed for error reduction.

Specifically, the Licensee Event Reports have been studied and several generic problem categories for maintenance and testing sporadic errors have been developed:

1. Errors of Omission
2. Errors of Commission
3. Errors of Actions Taken out of Sequence
4. Errors of Improper Timing
5. Errors of Coordination

4.3 ERROR PRONE SITUATIONS

To extract specific recommendations for reduction of maintenance and testing errors from these generic error categories requires reentering the data base and searching for specific errors within a category. Following this procedure, a set of recommendations has been developed. An example of the procedure used is presented in Section 4.5 and a sampling of the recommendations is presented in Section 4.6. Section 4.7 attempts to categorize the recommendations and provides some discussion of them.

Such a recategorization of the recommendations of Section 4.7 is listed below. Detailed discussions of each category with suggestions of achievable objectives are included in Section 4.8.

- A. Organization
- B. Administration
- C. Training
- D. Quality Assurance
- E. Technical Specifications

4.4 RECOMMENDATION FEASIBILITY

As mentioned previously a qualitative cost-benefit analysis may be performed on each of the recommendations. This qualitative analysis should provide guidance on the potential for each to optimize the design and operation of nuclear power generating stations. A more quantitative study can be performed which would:

1. Reevaluate current maintenance and testing intervals to ensure optimization between maintenance or testing and system outage time.
2. Evaluate performance shaping factors for each maintenance and testing duty.
3. Develop man-machine interface coefficients.

4. Evaluate, quantitatively, coupled actions that can lead to errors such as technician calibrating two or more channels of instrumentation incorrectly.
5. Combine this information into a formula such as:
$$[\text{Optimization System Reliability} = \text{Optimized Maintenance and Testing Intervals} \times \text{Human Reliability} \times \text{Including Performance Shaping Factors} \times \text{Man-Machine Interface Coefficient}]$$

Such a formulation can provide a quantitative basis to judge relative magnitudes of optimized benefits for estimated costs for each recommendation.

4.5 PROCEDURE FOR DEVELOPING TESTING ERROR REDUCTION RECOMMENDATIONS

1. On Test Station Coordination
 - Incorrect, post test, switch line-up
 - Miscalibration
 - Manipulative error
 - Omission error
2. Test Station to Control Room Coordination
 - Reactor operator unaware of testing, progress, or completion
 - Too many channels in test
 - Testing with inadequate equipment availability
3. Shift to Shift Coordination
 - Incomplete tests
 - Reactor operator unaware of test in progress
 - Technician continues test at incorrect step
 - Reactor operator believes completed test is in progress
4. Administrative
 - Procedures do not reflect current hardware modifications
 - Out-of-spec calibration equipment
 - Improperly maintained logs
 - Control Room
 - Instrument Shop
 - Improper equipment tag-out

4.6 SAMPLE MAINTENANCE AND TESTING RECOMMENDATIONS

1. Reformat testing procedures, avoiding two steps in one entry. Intersperse switch line-up checks, include a final switch line-up.
2. Establish two-man test teams. One man tests the equipment while the other one reads the procedure and records appropriate readings.
3. Require permission to be granted by the Control Room Operator prior to placing equipment in test.
4. Establish and update "Equipment in Test" Status Boards. Test completion should be acknowledged by the Control Room Operator by a signature on the test procedure.
5. Establish a shift engineer to coordinate Control Room responsibility for testing and maintenance.
6. Establish a formal Control Room watch relief including status of all test and maintenance in progress. Require reliefs in the Control Room to be accompanied by a formal watch relief.
7. Develop administrative guidelines for equipment allowed to be placed in test simultaneous with equipment maintenance. Update guidelines as equipment outages restrict operational flexibility.
8. Restrict shift change of technicians while testing is in progress or prepare appropriate administrative guidelines to preclude incomplete or inaccurate turnover of testing status.
9. Formalize a periodic calibration system for all test equipment and primary standards.
10. Examine work packages on safety related equipment to assure that they are complete and complete.
11. Provide manufacturer's technical manuals at maintenance locations in the event work package instructions are not sufficient.
12. Require wire removal forms or diagrams when removing or replacing wiring. Two-man signature should be required.
13. Provide sufficient welder preparation by using mock-ups.
14. Require non-safety related equipment whose failure could cause challenges to safety equipment to have operability technical specifications.

15. Develop training programs and establish industry certification for I&C technicians and auxiliary operators.
16. Place more emphasis in Reactor Operator training on the role of the Control Room Operator during test and maintenance operations.

4.7 CATEGORIZATION OF MAINTENANCE AND TESTING RECOMMENDATIONS

4.7.1 On Test Station Coordination Errors

1. Reformat testing procedures, avoiding two steps in one entry. Intersperse switch line-up checks, include final switch line-up.
2. Establish two-man test teams. One man tests the equipment while the other reads the procedure and records appropriate readings.

Discussion

Frequent testing errors have been noted during equipment calibration procedures when a technician overlooks a step in the procedure or fails to return test switches to a proper line-up. Errors resulting from procedural omissions or misalignments can cause inadvertent reactor trips when other equipment is in test or out for maintenance. Many of these errors come from familiarity with procedures, biasing the technician not to explicitly follow each written step. Also, steps are easily omitted when the technician is constantly shifting his attention between a procedure and the equipment. A two-man test team would provide an independent check that each step is completed satisfactorily. Reformatted procedures provide a more efficient tool for the procedure user. Elimination of two steps from any one entry limits the possible impact of any line entry omission. Switch line-up checks interspersed during the test provides added assurance that the proper equipment is being tested and the proper test signals are being used. The final switch line-up checks ensure that the equipment is not left in "test" after test completion.

4.7.2 Test Station -- Control Room Coordination Errors

3. Require permission to be granted by the control room operator prior to placing equipment in test.
4. Establish and update "Equipment in Test" status boards. Test completion should be acknowledged by the control room operator by signature on the test procedure.
5. Establish a shift engineer to coordinate control room responsibility for testing and maintenance.

Discussion

The most frequent types of errors, which are major contributors to the overall test and maintenance error rates, are coordination errors between test and station and the control room. For example, a technician places an instrument in test as scheduled. The control room operator is unaware of the test either by forgetting or some other reason. The test signals give control room alarms and the operator takes action which may affect plant operability based upon the test signal.

Theoretically, every error of coordination can be eliminated by better communication. Consequently the primary recommendations are aimed at establishing systems of communication between the test technician and the control room operator to ensure awareness of testing which is beginning, in progress, or completed. The secondary recommendation of establishing a shift engineer to coordinate may not be a suitable solution if communication is not improved. A shift engineer for test and maintenance can be an effective asset especially if a facility presently has the staffing to perform this function.

4.7.3 Shift to Shift Coordination Errors -- Control Room

6. Establish a formal control room watch relief including status of all test and maintenance in progress. Require reliefs in the control room to be accompanied by a formal watch relief.
7. Develop administrative guidelines for equipment allowed to be placed in test simultaneous with equipment maintenance. Update

guidelines as equipment outages restrict operational flexibility.

Discussion

As a follow on to the evaluation of coordination errors between the control room operator and the test technicians, these recommendations focus on providing better tools for the operator (or shift test and maintenance engineer) to maintain continuity of plant status relative to scheduled tests and maintenance. Specifically, a formal watch relief in the control room can reduce the possibility of important tests or maintenance being unknown to a short term relief watch person. In addition, administrative guidelines which list equipment allowed to be tested or maintained for the prevailing plant status will relieve the shift personnel of such decisions. For example, if one train of an Emergency Core Cooling System (ECCS) was being maintained as allowed by technical specifications, it would not be appropriate to conduct ECCS testing, especially testing on the maintained system. Although this example seems somewhat obvious; nevertheless, only minor coordination errors between the control room and test technicians can lead to circumstances causing reactor types.

4.7.4 Shift to Shift Coordination Errors -- On Test Station

8. Restrict shift change of technicians while testing is in progress or prepare appropriate administrative guidelines to preclude incomplete or inaccurate turnover of testing status.

Discussion

Using the same rationale as for recommendations 5 and 6, this recommendation is directed at reducing the possibility of coordination errors among test technicians. It is recognized that some test procedures require extensive test time. To restrict shift change may make test scheduling difficult or even impossible; consequently, formal administration guidelines may be the most appropriate method of accomplishing this coordination. An

example of such an error is in a test condition without supervision. This recommendation also minimizes the possibility that a watch relief will continue a test procedure at an improper step.

4.7.5 Administrative -- Preparation For Testing

9. Formalize a periodic calibration program for all test equipment and primary standards.

Discussion

Miscalibration of plant instrumentation can be due to improperly calibrated test equipment. For example, plant pressure instrumentation may be checked by an uncalibrated voltmeter; thus, even though the calibration procedure is correctly followed, the result is nevertheless an out-of-specification plant pressure instrument. The same sequence of events can occur when performing instrumentation checks with primary standards. Using the same plant instrument as an example, the pressure sensing device may be calibrated by a primary standard pressure cell. Without calibration of the primary standard cell prior to instrument calibration, the plant pressure instrument may be miscalibrated.

Most nuclear power generating facility owners have established calibration programs; however, these programs may not be formalized with an internal quality assurance program. This recommendation focuses on the formalization and reproducibility of such a program such that with minor modifications it can be made generically applicable to any nuclear product line, similar to the standard technical specifications.

4.7.6 Administrative -- Preparation For Maintenance

10. Examine work packages on safety related equipment to assure they are correct and complete.
11. Provide manufacturer's technical manuals at maintenance locations in the event work package instructions are not sufficient.
12. Require wire removal forms and diagrams when removing or replacing wiring. Two-man signature procedure should be required.

13. Provide sufficient welder preparation by using mock-ups.

Discussion

Common maintenance errors occur due to improper component installation, repair, or assembly during maintenance periods. Examples are such errors as valves installed backwards, improper type of valve packing used, incorrect assembly of pumps, and improper replacement of wiring. All of these and many more errors can be minimized by comprehensive maintenance preparation. Often maintenance packages are assembled by maintenance departments and are not thoroughly reviewed for accuracy and completeness by the actual performers of maintenance. Manufacturer technical manuals are either not consulted in developing the maintenance packages, or if consulted, they are not extensively used. Further, if manufacturer's technical manuals are available on job sites, there will be less incentive for the maintenance personnel to not consult them when in doubt.

Welding preparation is conducted through a series of qualification welds. Welding of mock-ups for particularly difficult welds can be of great value when compared to the possibility of grinding out a weld and rewelding.

Particularly troublesome errors arise from improperly rewiring equipment that has been maintained. Two-man control of wire identification will minimize this potential. The first person removes the wires, tags the wires, and identifies the wires on a form or diagram. The second person checks the completeness of the wire removal, tagging, and identifications.

4.7.7 Administrative -- Technical Specifications

14. Require non-safety related equipment whose failure could cause challenges to safety equipment to have operability technical specifications.

Discussion

Nuclear power generating facilities are generally designed to accommodate transients and accidents without the use of non-safety systems

and components. Also, the failure of these non-safety components should not create a safety problem since safety systems exist to accomodate the effects of their failure. However, excessive reliance upon safety systems to mitigate the consequences of non-safety equipment failures, lowers the overall reliability of the safety systems. Another way to view this is that the probability of system or componet failure on a "per challenge" basis would predict more potential failures given more challenges.

An example of such a situation is the need for a safety related feedwater system to be actuated to supply feedwater to pressurized water reactor steam generators during loss of feedwater events. Such loss of feedwater events can be caused by failures of components such as non-safety components, condensate pumps, air ejectors, feed system valving, or control air systems.

In an effort to reduce such challengers, some minimum quality assurance and technical specification requirements should be placed on these non-safety system and components.

4.7.8 Administrative -- Training

15. Develop training programs and establish industry certification for I&C technicians and auxiliary operators.
16. Place more emphasis in Reactor Operator training on the role of the Control Room Operator during test and maintenance operations.

Discussion

These recommendations are directed toward developing formal training programs in areas of test and maintenance where they presently do not exist. Specifically, I&C technicians and auxiliary operators often receive a minimum of formal training; however, these individuals can greatly influence the operability and safety of plant systems and components. Training is needed not only in the necessary technical disciplines but also in the areas of overall plant response. These individuals should be thoroughly

aware of the probable consequences of their errors.

Control Room Operators are trained and tested on the operational aspects of plant control; however, the most challenging control and coordination circumstances occur during testing and maintenance periods when these activities must be coordinated with other plant operations. Formal training programs should be established by each facility owner. Simulator classrooms may provide a tool to standarize such training.

4.8 APPROACHES TO REDUCTION OF MAINTENANCE AND TESTING PROBLEMS

4.8.1 Organization

1. Review existing site organizational structures (including on shift structures) to define the extent of integration of site maintenance and operations departments.
2. Conduct a literature survey and discuss with management consultants. Draft an optimized site organizational structure.
3. Review the draft structure with sample utility management for feedback.
4. Recommend organizational modifications to optimize maintenance and operations functions as well as reduce coordination errors between and within branches of the site organizations.

Discussion

The proposal was directed toward reviewing site organizational structures from a board perspective and eventually a narrow perspective. Future efforts should fine-tune organization structures to avoid coordination errors. As shown previously, errors of coordination tend to dominate the maintenance and testing error data base. Often these errors would not have occurred had the on shift or staff organizations been more flexible. Often tension exists between maintenance personnel and shift personnel. This can be due in part to each group reporting within separate branches of a site organization. This tension can be a factor affecting poor communication between the maintenance and testing activities and the control room.

Poor communications can lead to the control room operator being unaware of the proper status of the plant systems. For example, a maintenance activity is started on the condensate system. The control room operator is not informed of this activity because it is a "simple procedure". Inadvertently suction pressure is lost to the feedwater system causing a loss of feed flow transient. The operator could waste precious minutes attempting to regain the normal feed flow instead of using back-up systems to control the event not realizing that the maintenance activity has contributed to the loss of normal feedwater flow and is preventing its restoration.

4.8.2 Administration

1. Survey existing methods for generation and execution of testing procedures and schedules including interfaces with the operations department and the operating shift on which a test is scheduled to be performed.
2. Survey existing methods for generation and execution of maintenance work packages, including interfaces with operations department and the operating shift on which the scheduled maintenance is to be performed.
3. Recommend generic administrative guidance on improved interfaces to reduce errors of coordination during maintenance and testing.

Discussion

Coordination errors not only originate, as previously discussed, from organizational reasons but also from administrative difficulties. Attempts should be made to insure optimum communication within operating shifts, within maintenance departments, and between them. Although it is realized that generic administrative guidance may not be equally applicable to all facilities, it is valuable to set standards for interfaces between both operations and maintenance departments. Many examples can be cited of particular incidents caused by poor interface relations. One such example is a plant transient caused by testing conducted concurrent with maintenance. Although these concurrent activities in themselves did not

cause the transient, a single human error during testing resulted in a complete loss of feedwater transient rather than a simple reactor trip. This situation may have been prevented by more optimized administrative procedures limiting testing during the maintenance activities.

4.8.3 Training

1. Survey training programs for I&C technicians and auxiliary operators.
2. Survey the extent to which test and maintenance is a part of formal reactor operator training simulators and plant sites.
3. Based upon the investigations of interfaces between maintenance and operations departments, outline a recommended test and maintenance training content for formalized training programs for auxiliary operations, I&C technicians, and reactor operators. Recommended items could be categorized as 1) utility unique -- those to be conducted at the plant site, and 2) generic -- those that can be conducted in simulator programs.

Discussion

Recent events at the Three Mile Island-2 Nuclear Power Station have focused renewed attention on the need for training, not only for control room operators, but also I&C technicians, auxiliary operations, and even site management. The above approach should first review the current training status of test and maintenance personnel, then examine current constraints on training such as facilities, union restrictions, regulations, etc. Review should include the level of training that control room operators receive from simulators and utility programs. The program should incorporate acceptable U.S. NRC qualification requirements for reactor operators and senior reactor operators.

The results of this program should be a key factor in providing generic guidance for training to utilities and simulators. Such training should be valuable in reducing errors such as improper installation of equipment, improper test sequences, and improper equipment repair. It also

should be a key element in training the control room operators in coordination of testing and maintenance activities with plant operators, whether during power generation or outages.

4.8.4 Quality Assurance

1. Survey organizational and content of site quality assurance programs with regard to maintenance and testing.
2. Review operations and maintenance department procedures on systems and components whose failure could cause plant safety system challenges.
3. Review interfaces between maintenance and operations departments and recommend areas where additional quality assurance programs may be needed.
4. Review maintenance and testing coordination aspects of site administration and recommend areas where additional quality assurance programs may be used.

Discussion

Although it is recognized that extensive quality assurance programs may be in place in site organizations; nevertheless, these programs may be directed toward equipment qualification traceability. The quality assurance needs, suggested in this analysis, are procedure and record controls dealing principally with reductions in human errors relative to testing and maintenance. An easily cited example of errors which can be reduced through such quality assurance programs are instrument miscalibrations due to use of uncalibrated test equipment. These errors not only affect single and multiple channels of instrumentation, but also have potential impact on instrumentation of a variety of types.

4.8.5 Technical Specifications

1. Review present standard NRC Technical Specifications for typical PWR and BWR product lines.
2. Review system design bases for which the above technical specifications are applied.

3. Examine the functional requirements of these systems compared to other systems or components that do not have technical specifications.
4. Conduct failure mode effects analyses for these system networks under normal transients and accident conditions.
5. Determine if single component or system failures not presently under technical specifications can cause plant safety systems operations.
6. Perform reliability analysis on these system networks to determine suitable technical specifications if necessary to optimize safety system availability.

Discussion

Programs may be directed toward providing technical specifications for systems and components presently not under technical specifications whose failure would require safety system operation to mitigate the effects of the resulting transient. The proposed technical specifications would be optimized component or system availability and testability.

The results of this program would be central in reducing the total challenge rate to plant safeguard systems principally designed for mitigation of accident conditions. An example of potentially needed technical specifications is the non-safety feed and condensate systems which rely on the auxiliary feedwater system in pressurized water reactors for maintenance of cooling.

4.9 M&T PROBLEMS CAUSING OUTAGES/TRANSIENTS

The review of FEED relative to the impact of M&T problems on outages resulted in the following observations. A corrective action is suggested in each case.

1. More equipment should be housed in waterproof or dustproof housings or in such a way as to not be flooded by water. In several cases, pump failures or valve failures in which a significant amount of water was released have resulted in flooding of other nearby equipment. In other instances, sealed units containing electrical contact switches and

other electro-mechanical devices sealed against dust and grit are cleaned regularly manually or chemically.

2. Some standby valving should be regularly maintained to the point of refitting possible sticking parts with a greater frequency.
3. Transient causing events often are a result of mishaps involving maintenance of on-line equipment or equipment whose state is commonly monitored by safety instrumentation. Efforts should be made to separate equipment as far as possible, i.e., separate monitor circuits for different safety functions and to reorganize procedures in order to prevent trips.
4. Relief valves popping open is a major cause of trips and maintenance outages. An onsite method of testing relief valves before insertion in the system should be identified. Maintenance procedures should be changed to take advantage of early indicators of possible failures such as high downstream temperatures.
5. Larger reservoirs or more positive oil level indicators for RCP's and other large pumps may be advisable. In some instances a low oil level indicator gave inconsistent readings and in others the incorrect level was identified only as a result of checking. The potential is for multiple RCP problems though not necessarily simultaneous. Regular flushings and refueling may be advisable, depending on NSSS supplier recommendations.

It is not clear in some cases whether the large amount of retorquing of bolts and replacement of nuts, etc. is a function of the tendency of equipment to vibrate excessively, is a result of poor torquing procedures during previous maintenance or is a result of normal wear. The instances where significant maintenance of this type is done should be examined to define equipment where possible design changes or procedure changes would eliminate this problem.

6. A potentially large number of scrams are caused by operator errors as a result of performing normal plant operation and monitoring functions. Examples of this type of personnel error include opening or closing the wrong valve on a piece of equipment, out of sequence instructions and incorrect performance of operating adjustment (missetting pump speeds). While a high state of operation training would help mitigate these problems, analysis and design effort should be put into

reduction of the capacity for incorrect actions. As such research goals in order of priority are:

- determination of a set of operator responses, most frequently done incorrectly
- redesign of equipment most especially the O.R. control equipment to assist in guiding operator through cooperative action sequences and lock out of related equipment during adjustment operation
- diagnosis of which equipment malfunctions are most likely to result in a safety signal to scram

7. A significant number of cases of equipment outages such as recirculation pumps being allowed to run low on lubricant are being reported. Apparently it is a policy in some cases to run equipment until an alarm sounds at which time the reactor is shutdown or slowed and lubricant is added. This is taxing on the equipment and with a single failure in the alarm system this could result in a recirculation pump seizure which is a severe transient. A means of mitigation of this tendency, without resorting to more frequent servicing should be found. Such fixes as reserve tanks or enlarged oil reservoirs and other changes which would allow lubrication during operation with a larger lubricant capacity are suggest, but a thorough analysis of the problem is required to fully implement a workable solution.
8. We should perhaps be reviewing the whole concept of how to maintain a standby safety system. How much maintenance is required? Is there a way to redesign systems to require less maintenance or to allow single integrated maintenance efforts (components required maintenance times need to be similar)?
9. A large number of scrams resulting from personnel errors involving reintegration of monitoring equipment into a running system are reported. Those instances should be investigated to determine if there was truly an incorrect procedure or action sequence used or if the system as designed is overly sensitive to minor electrical transients and fluctuations in transmitter readings. In cases where there is truly a personnel error involved, revised procedure based on existing plant designs should be devised possibly with the implementation of verbal procedures checkout routines. In the case where the scram is really a result of the inherent sensitivity of the system, an analysis should be undertaken to determine possible changes in circuit and equipment design which would prevent circuit transients without compromising the sensitivity of transient sensed signals.

5.0 RECOMMENDATIONS

In this section programmatic approaches are identified for in-depth analysis of M&T problems caused by the performance of M&T tasks. Recommendations are made for the implementation of methods to reduce M&T problems, as well as reduce their resultant consequences.

The recommendations made for subsequent phases of the LWR Safety Technology Program are divided into five major categories:

- Human Factors
- Administration and Procedures
- Monitoring, Diagnostics, and Trouble-Shooting Tools
- Technical Specifications
- Methodologies for M&T Task Improvement

The states of recommended development are such that each major category is suitable for individual analysis. However, complementary research is suggested for optimization of time and money required for successful completion of the proposed works.

5.1 HUMAN FACTORS

5.1.1 Objective

The objective of this program is to assess the impact of plant design on the occurrence of M&T problems and to provide commercially viable mitigation methods for such problems.

5.1.2 Program Description

The human factor program encompasses the evaluation of the layout design of operating plants to identify problematic areas which may

affect the performance of M&T tasks. Such studies would require field evaluation of some representative plants, identification of areas of possible changes, provision of redesign procedure for new plants, and conduct of cost/benefit analysis for suggested changes.

The program would include prioritizing the types of M&T problems by considering both frequency and a weighted severity index, the latter being based on LWR plant safety. Priorities in conducting studies on specific subsystems or components can be established based on the ranked values of combined frequency and severity. Based on these priorities, selected plants can be visited. Maintenance and testing operations would include on-the-job studies, surveys, and interviews with maintenance and testing workers, management, and possibly others, such as technicians and controllers, to obtain a better understanding of the nature of maintenance and testing work and of M&T problems.

Based on actual studies of job performance and work stresses, it would be possible to identify specific areas of hardware design and work design which need to be improved through application of known solutions or which need to be researched through additional studies. Program goals, objectives, and criteria can then be established, along with an overall weighted model expressing frequency, severity, potential for improvement through applications of known concepts, probability of success, and cost.

The sequence of activities to be covered during the performance of this program are as follows:

- Definition of maintenance and testing problems by plant type, subsystem, and components. This is followed by frequency and severity of priorities in studying given classes of problems.
- Based on ranked priorities, visit representative high maintenance and testing frequency BWR and PWR plants.

To be studied at plants:

- a. Job performance - a study of maintenance and testing workers on-the-job and an assessment of the need for job performance aids, human factors in work

design, work simplification, coded control positions, tools, and work methods. Activities can be logged by researchers or plant personnel.

b. Environmental stress - including,

- Heat stress
- Knowledge of exposure to radiation
- Cramped workspace, heights
- Physical effort - biomechanical stress
- Time schedules
- Noise stresses

Stresses and problems may be related.

- Identify areas of work design which are involved as causative or contributing factors with respect to M&T problems.

Examples of potential methods of achieving improvement in dealing with specific problems are:

a. Standardization of design for given types of subsystems serving similar functions.

b. Work simplification, including improving:

- Feedback from hardware by position, color, and shape coding.
- Providing components that only go on the right way.
- Coded sheets to check off maintenance and testing steps.
- A way to check performance of subsystem at completion of maintenance and testing job.
- Visible lubricants.
- Torque or force metered instruments to assure correct tension in setting valves, seals, etc.

c. Automanual control to show predicted outcome of the results of maintenance and testing when the system is put into operation.

- Establish goals or objectives, factors or criteria based on comparison and evaluation of the steps listed above.
- Develop a preliminary tradeoff model with recommendations for further development of a model for prioritizing improvement needs, recognizing frequency, severity, probability of improvement (reduction of frequency and severity), likelihood of success in research, acceptance of results, and cost.

- Conduct cost/benefit analysis for detailed studies of high priority M&T improvement methods towards implementation in practice.
- Perform research towards implementation of the most cost effective items which would have the highest impact on utility with respect to economical benefits.

The basic components of the redesign activities are as follows:

- Establishing Quantified Goals and Objectives: An aggressive and obtainable goal for new plants may be established and integrated into the total design process. San Diego Gas and Electric established a goal for Sundersert Nuclear Plant of 90% Availability and 80% Capacity Factor. These goals require advance planning and specification, coupled with continuing design evaluation. For plants already operating or nearing operation, less aggressive interim goals might be appropriate. The goals may be established upon prior plant performance, industry experience, and overall system requirements. For a plant with a lower performance record, a gradual increase to high availability operation with interim goals and performance feedback is recommended.
- Performance Measurement and Data Base: The overall program of plant performance improvement must rely on timely and accurate data to keep all participants aware of performance and to allow accurate feedback for performance improvements. By coupling the data base requirements to on-line performance as determined by plant personnel, the availability goal can be made more visible and the effects of plant problems and service requirements on availability more readily apparent. One option is to track plant availability and capacity factor on the plant process computer so that performance data can be available at the start of each shift. The critical plant data, such as actual power level, outage time, outage cause, time to repair, time to return to power, and system performance demands can be input to the process computer for on-site data evaluation and transmission to home-office data base systems. The total data base should be constructed so that all performance is related to a known contributor. This would assume that test and maintenance errors are identified and logged for improvement. This will aid in the process of ranking critical systems and components, and will assure feedback to determine the effect of actions taken. In addition, plant demand should be monitored so that actual performance ratios can be maintained.

- Simplified Block Diagram of Plant: The block diagram is a simple tool to aid in the definition of sources of performance loss and their effects on the plant. Areas of system interaction and dependency can be shown and quantified. Significant (> 1%) availability losses should be broken down into component parts and the interrelationship shown. This allows the complex system with significant impact to be identified for further modeling. The block diagram is a useful tool for feedback and definition of data acquisition needs.
- Role of Industry Experience: Utilities' records reflect somewhat unique performance experiences, possibly due to variations in system demand, regional productivity, and training methods. Where insufficient data exists (a likely occurrence for many systems), the industry experience should be used, with actual utility experience factored into any decision regarding action to improve performance. In addition, the areas of poor power plant performance relative to industry experience can be identified as prime targets for performance improvement.
- Criticality Ranking: The predetermined effect or potential effect of various systems on availability and capacity factor can guide the availability engineering staff in their effort to maximize plant performance. This can be implemented by determining the relationship of each systems overall production, that is, the ability of a system failure to cause an outage or to cause a loss in capacity, and by determining the ability of systems in terms of their criticality to the overall operation. Perhaps the best choice for a criticality parameter is the allocated unreliability in dollars per year:

$$\text{Allocated Unreliability} = \frac{\text{MTTR}}{\text{MTTR} + \text{MTBF}} A + B \times C \times D$$

A = Cost of Outage Activity

B = Cost of Replacement Power

C = Capacity Factor

D = Plant Rating

MTBF = Mean Time Between Failures

MTTR = Mean Time To Repair

- Options Assessment: The decision to proceed with a plant improvement cannot be made without careful assessment of the possible alternative ways to achieve the improvement. Methods such as redesign, repair, increased spare parts inventory, replacement, revised procedures, and monitoring should be considered so that the optimum corrective action can be identified.

- Economic Analysis:** The goal of performance improvement can be best achieved by focusing attention on critical contributors to lost revenue for which improvement is likely to be achievable. By ranking the contributors and allocating availability loss to each, by weighting each with a likelihood of improvement and magnitude of improvement, and by determining the cost of the modifications required, it is possible to establish a weighted cost benefit ratio. That is, by converting both performance and actions to achieve improvements to revenue, it is possible to establish a rate of return for effort expended as a second ranking criterion. For example, if a 2% availability loss on a 600 MWe plant is caused by excessive main turbine generator test and maintenance, then an evaluation of the improvement utility would include:

Plant Rating	-- 600 MWe
T-G Availability Loss	-- 2%
Average Capacity Factor	-- 76%
Industry Experience with T-G	-- 1.5% unavailability
Cost of Detailed Analysis	-- \$40K (once)
Projected Cost of Improved Monitoring/Maintenance	-- \$50K/once, \$5K/year
Likelihood of Successful Improvement	-- 75%
Magnitude of Successful Improvement	-- 0.5% (to industry avg)
Age of Plant	-- 10 years
Service Life of Plant	-- 40 years
Remaining Life of Plant	-- 30 years
Cost of Replacement Power	-- \$15/MWe hour

Payback = (Revenue Return/Cost of Program)

$$\begin{aligned}
 &= \frac{(.76) \left(\frac{.005}{\text{yr}} \right) (.75) (600 \text{ MWe}) (8760 \text{ hr}) \left(\frac{\$15}{\text{MWe hr}} \right)}{\frac{\$40\text{K}^*}{30 \text{ yrs}} + \frac{\$50\text{K}}{30 \text{ yrs}} + \frac{\$5\text{K/yr}}{30 \text{ yrs}}} \\
 &= \frac{225\text{K/yr}}{8\text{K/yr}} = 28.1
 \end{aligned}$$

* This value should be computed on the basis of fixed carrying charges on a projected cost basis converted to the present worth of the year of evaluation. This has been modified for simplicity.

- Feedback and Testing of Economic Decisions: Once a decision is made to proceed with a specified improvement program, the results should be measured to confirm the attained effect. In the preceding example, a 28 to 1 payback is calculated. Actual performance measurements will aid in the determination of the accuracy of the chosen analytical method and validity of the improvement. In addition, performance feedback will enhance the ability to determine additional action to be taken.

5.1.3 Background and Justification

As stated previously, of 3564 LER's on file, only 385 were traceable to maintenance and testing. Yet these errors are highly significant for several reasons:

- They pre-program further system failures, some of which would result in safety problems.
- They can seriously compound, multiply, and magnify the results of operator error by providing misinformation or no information at times when such information is critical.

Presently, available theory based on experiments conducted with military personnel suggest that when the human operator is presented with failure of the system to respond or with misinformation regarding the status of the system he is controlling, human error rate doubles for each occurrence of such failure to bring the system under control. Thus, if the operator chance error probability was 20%, it would double to 40% and then to 80%, following two unsuccessful attempts to communicate with and/or control the system. Since maintenance errors increase the probability of such events, they should be eliminated whenever possible.

The review of the M&T data available has led to several conclusions, namely;

- The problematic patterns do not appear to be the result of inadequate job skills or knowledge. What was done wrong or left undone could have been done correctly.
- There appears to be no clear pattern of problems by system. Some patterns and repeatability are evident with subsystem and component--as with valves and switches left in wrong position, misadjusted, etc.

- A similar pattern exists in maintenance (M), maintenance during test (MT), and preventative maintenance (PM). Since M and PM patterns and frequencies are basically similar, time pressure may not be a problem unless time pressure is common to both M and PM.
- In PM, most errors (37/61 counted in sample) involves omission of an operation or element of the maintenance task. Another 13/61 involved misadjustment, misalignment, etc. Another 8 involved lubrication.
- Maintenance and testing problems primarily involve valves and switches. The most common errors involve leaving a valve or switch in the wrong position, failure to properly lubricate a valve, faulty repair of a valve, or misadjustment of a valve or switch. They are common types of errors found in nearly all kinds of maintenance and testing work in many industries. In fact, a high percentage of human errors which have occurred during plant operation or test and maintenance have been related to valves. The details of such events emphasize the need to develop practical methods to mitigate valve problems which may affect LWR safety based on identification of the root causes of such problems.

It should be emphasized that the maintenance and testing worker is probably, in nearly all cases, unaware that he committed the errors in question. Thus, the identification of specific causes of maintenance and testing problems is valuable in providing several solutions to M&T problems including complete redesigns of some hardware such as valves and switches. In some cases, a combination of several design modifications may be desirable. A partial list of mitigation methods as related to human factors includes:

- Basic redesign of hardware.
- Additions of features to hardware to improve human awareness of its status, such as: basic appearance, marking, alignment, shape and color coding, etc.
- Hardware tests immediately following maintenance and testing.
- Automanual control with or without prediction of future states of the system.

- Applied work simplification involving:
 - a. Displays or control appearance
 - b. Diagnostics, decision-making in maintenance and testing, trouble-shooting techniques
 - c. Controls and tools, including force or position feedback
 - d. Work area designs
 - e. New improved tools

Recorded data events related to M&T in LWR plants does not give information that would help in layout design modifications which would reduce the impact of M&T problems of LWR plant safety. In addition, some inadequate M&T practices, although of general nature, are not easy to detect through operation information reviews; such as omissions due to unorderly multiple task performance.

The best way of evaluating which plants are going to have the best records, from the standpoint of M&T, is to rely on in-plant visits to evaluate situations and on reports based on those in-plant visits such as the reports of compliance inspectors. Further, observations by persons with some experience in plant operations or knowledge of how things are done within the power plants can yield useful information which can help in layout modifications and changes in current M&T practices.

After a plant is operating, the major impetus is to repair or restore failed components so that power production can resume. Often time is not available for root cause analysis or redesign. It would be helpful if components were designed to enhance maintenance repair and with design goals for Mean Time to Repair (MTTR). Since unavailability is $MTTR / (MTTR + MTBF)$, where MTBF is the Mean Time Between Failures; an improved MTTR would greatly increase availability and safety.

A large number of component failures requiring maintenance downtime are attributable to environmental stress such as dust-clogging lines and shorting contacts, water-filling compartment, and vibration-caused loss of parts. In some cases, the failures can be attributed to infrequent maintenance, such as failures of relays due to dirty contacts. In other cases, failures are attributable to incorrect maintenance, such

as the failure to tighten bolts to manufacturer's torque specifications. Often the tendency for failures to occur is exacerbated by the design of the equipment itself, which may be excessively vulnerable to environmental stimuli or to small errors in procedure.

To correct maintenance omission by prescription of more frequent maintenance, is to beg the problem entirely since more frequent maintenance may extend equipment outage times and cause increase in the equipment outage frequency, i.e., increase the unwanted trend. Further, the increased maintenance frequency would increase the likelihood for error and commission of secondary errors.

A more accessible approach in some cases is the recommendation of design changes which have the capacity to decrease or not increase maintenance time and still decrease the vulnerability of the equipment to environmental stress and maintenance damage. Of course, simple changes, like addition of dust protection and waterproof housings, are desirable since their implementation cost could be easily justified. But even more comprehensive design changes such as vibration isolation of equipment and redesign to reduce the number of bolts, etc. could be justified on a cost-benefit basis.

A comprehensive program of cost and risk tradeoff studies is recommended to identify potential changes in equipment design which, for some equipment items, would decrease the required frequency of maintenance and, for others, the vulnerability to maintenance errors. The basic value impact methodology used to identify appropriate design changes would utilize:

- Equipment reliability and maintenance outage data.
- Safety implications and risk assessment methodology.
- Equipment design and design costing techniques.
- Current value impact evaluation techniques such as added utility assessments.

For major items of equipment, such as safety pumps, much effort has already been placed on developing safety modifications to reduce maintenance

vulnerability. In some cases, the vulnerability is not that of the vital component, but of its ancillary and support equipment. Such is the case for MSIV's in which the valves are highly invulnerable to tampering, but the control valving is subject to a variety of maintenance errors such as inadvertent crimping of the air bleed lines. These errors are found in FEED and NSRG data, and indicate that the emphasis of a value impact design evaluation should be on the ancillary control equipment and the support equipment for major vital components.

A comprehensive design for maintenance value impact programs should commence with a critical review of available plant operating experience to determine frequencies of certain generic failures and the degree of plant-to-plant generality of these failures. Many such failures endemic to multiple plants have been identified in FEED and NSRG data and include:

- Clogging of contact breakers and other electromechanical elements by grit and dirt.
- Damage by water intrusion or electrical switching and instrumentation components as a result of mechanical equipment failures which result in flooding or water damage.
- Damage to safety relief valves and speciality items, such as snubber assemblies on BWR's through infrequent or incorrect maintenance.
- Damage to pumps and other lubrication requiring equipment, such as diesels, as a result of infrequent lubrication, incomplete instrumentation, failure of level indicators or insufficient reservoir size.
- Damage to mechanical or electromechanical equipment as a result of incorrect maintenance practice or incomplete reassembly of units.
- Damage to mechanical components due to lost or loose bolts as a result of incorrect maintenance practices.
- Damage to mechanical valving as a result of poor maintenance practice or inappropriate frequency of packing refit.

These instances cannot be truly quantified by frequency of occurrence and general endemic nature because of the incompleteness and coarseness of the data. Therefore, it is recommended that a study be

initiated of multiple U.S. LWR's to determine the frequency of particular suspected equipment failures and the required design changes to eliminate them. The emphasis should be on determining frequencies of occurrence, comparative safety impact values, and a concise determination of the event occurrence data. In a sense, the plants are monitored for a period of time to ascertain the "payoff" in terms of decreased safety equipment downtime as a result of particular design changes.

Since it is clear that there will be plant-to-plant differences in the frequency of problems encountered, the analysis might be performed as a measure of the application effect of certain broad and generic changes on overall plant safety. The results of a plant monitoring study can then, using the value impact methodology, be reviewed for suitability of recommended design adjustment.

The conventional design process is a somewhat iterative procedure involving a number of demands or desires for system or component performance. These demands take the form of requirements, recommendations, and constraints. These constraints can be categorized as follows:

Institutional	{ Codes Standards Regulations OSHA
Engineering	{ Feasibility Compatibility Plant/System Interface Requirements Critical Plant
Operation	{ Availability Surveillance Operator Action

Maintenance

Spare Parts
Manpower
Replacement
Changeout

Safety

Reliability
System/Component Effects
Level of Redundancy

Cost

Contractual Considerations
Changeout Versus Repair
Marketability

It is instructive to note that maintainability is a lower tier requirement and, in fact, may sometimes be considered a "nicety." Indeed, a system which fails to meet its performance objective is viewed far differently from a system which is difficult to maintain. Nevertheless, it is the function of the designer to achieve safety and reliability for the systems being designed. This fact has long been recognized and has been reinforced in recent years.

In recent years, developments in the engineering sciences and associated computer applications have greatly enhanced the ability to quantify, track, and maintain established levels of system performance. A number of utilities have established levels as objectives for plant design and performance. In some states the existing utility incentive for good plant performance has been augmented by state mandated incentives for plant availability. An example of state action is Michigan, where the scale established by the Public Service Commission is as follows:

AVAILABILITY	EFFECT ON RATE OF RETURN ON COMMON EQUITY
0% - 70%	-.25%
70.1% - 80%	No Change
80.1% - 85%	+.25%
85.1% - 100%	+.50%

A power plant availability and performance optimization program can be implemented as a way of achieving availability and capacity factor performance consistent with predetermined goals and objectives. Such a program could be applied to plants under construction or in operation. A simplified flow chart is included as Figure 5.1. Designing for maintainability is a key ingredient in such a program.

5.1.4 Statement of Work

TASK 1 -- FIELD EVALUATION

This task would involve three subtasks.

Subtask 1.1 Prioritization of M&T Problems

A priority list would be formed of M&T problems as identified from M&T data base.

Subtask 1.2 Plant Visitation

The objective of plant visits is to study the performance of M&T work and to investigate the design from a human factors point of view. Thus, layout design problems can be identified. Plant visits should be conducted with cooperation from the utilities. The visits would involve examination of accessibility, radiation records, layout design evaluation, and M&T performance observation.

Subtask 1.3 Valves

Among the components to be evaluated are the valves. The logic of valve layout design and operation modes need to be investigated to review the design basis by which the decision is made on whether or not a specific valve is manual, automatic, or automatic-manual. Such review, based upon past experience, would provide design guides or criteria by which the mode of operation of specific valves has to be decided. This effort requires an examination or re-examination of the operation mode

Figure 5.1 Power plant availability and performance optimization program flow chart

with respect to automation versus human actions from the point of view of coordination and reliability in terms of doing the right sequence when needed and passiveness when action is not required or wrong.

Many of the valve problems which result from test and maintenance tasks could be attributed to poor valve layout design, the lack of sequencing in valve operation or scheduling of maintenance and testing, and the lack of standardized valve design or configuration for valves having the same function. The work would include the following phases:

- Examination of valve operation modes
- Evaluation of logic of valve layout
- Evaluation of valve layout design
- Examination of sequencing of valve operations
- Examination of sequencing of valve maintenance and testing
- Design of schedule sequencing of maintenance and testing

Subtask 1.4 Recommendations

The field evaluation results can be used to provide recommendations for design modifications of present plants and possible redesign for newer plants.

TASK 2 DESIGN REVIEW

A design review should be conducted to determine the effects of component design on M&T problems. Consultation with utilities, vendors, architect-engineers, and component manufacturers will yield valuable information about system/component design modifications which have been made. A determination of why specific design changes have been implemented will identify areas relevant to M&T problems. Such a study will also signify systems which have been altered in design most frequently (throughout the history of the vendor and A/E) and identify principal components (with respect to manufacturer) which are most error prone.

A design review program can then be established for analysis of the principal design problems affecting M&T personnel. Recommendations for programs leading to generic as well as plant, vendor, A/E, and manufacturer specific fixes can then be made. Consideration would be given to both present and future system/component designs.

Communication with personnel throughout the nuclear power industry (especially vendors, A/E's, regulatory bodies, and utilities) would then enable the development of optimized design review programs for the initiation of necessary design modifications to be applied to future system/component designs to ensure amenable M&T personnel interaction.

TASK 3 DESIGN FIXES

Recommendations may then be made on layout modification and on appropriate changes in M&T practices. This requires a preliminary assessment and cost/benefit analysis to assure benefits to utility. A cost/benefit analysis or value impact of introducing any changes or design fixes has to be associated with the recommendation. A ranking scale may be used to prioritize the recommended fixes. Personnel for performing this program must have M&T experience, nuclear engineering knowledge, and familiarity with balance-of-plant instrumentation. This is to assure efficient performance of the work. Also, it is necessary to focus on issues which are relevant to plant improvement from the utility point of view and not to tackle any regulatory issues.

TASK 4 REPAIR DATA

Review data to obtain MTTR statistics for classes and individual components. If possible, develop trends or plots of MTTR versus time, say for ten years.

TASK 5 REDESIGN RECOMMENDATIONS

Develop methodology to integrate MTTR objectives into design process. Methods for setting objectives, evaluating alternatives for achieving the objectives, measure results, and improving would be developed.

TASK 6 VALUE IMPACT ANALYSIS

A value impact analysis would be conducted to justify to the utility companies the value of implementing the recommended design changes in operating plants or future plants.

TASK 7 DEMONSTRATION

The redesign (partial or complete) should be tested. In case of partial changes in plant layout, arrangement should be made with a plant to test out the modifications.

5.1.5 Schedule

	80	81	82	83	84	85	86	87	88	89	90
1. Field Evaluation											
1.1 Prioritization	_____										
1.2 Plant Visits		_____									
1.3 Valves		_____									
1.4 Recommendations		_____									
2. Design Review			_____								
3. Design Fixes				_____							
4. Repair Data					_____						
5. Redesign Recommendations						_____					
6. Value Impact							_____				
7. Demonstration								_____			

5.2 ADMINISTRATION AND PROCEDURES

5.2.1 Objective

Enhancement of human performance in carrying out M&T tasks through improvement in procedures, communications, organization, and training for safety assurance in LWR plants.

5.2.2 Program Description

Problems in maintenance and testing work can be the result of many factors including: personnel problems, operator ignorance, neglect, deliberate omission of tedious work, deliberate commission of a fault, and random incidents resulting from inadequate skill or practice.

The basic problems to be addressed in this program are:

- Examination and definition of human error aspects in the maintenance and testing data base.
- Determination through actual job studies and worker surveys in several PWR and BWR plants, of the operational nature of maintenance and testing problems and the factors which cause them.
- Definition of specific areas for improvement in the areas of job designs, work stress reduction, and human resource management.
- The development of cost/benefit models to assist in formulating the needs for specific improvement and the methods of implementation of such improvement.

The program would require plant visits to selected plants, sampling both BWR's and PWR's and representing high maintenance and testing frequencies. Maintenance and testing operations would be studied including on-the-job studies, surveys, and interviews with maintenance and testing workers, management, and possibly others such as technicians and controllers to obtain a better understanding of the nature of maintenance and testing work and of M&T problems.

- On-the-job studies can be performed using standardized job and task analysis procedures. These include both observational and questionnaire techniques and are focused on specific task elements as well as more general job-related skills, abilities, and knowledges. The studies may involve worker perceptions of job difficulties, M&T problems, including "close calls;" management perceptions of job difficulties and major problems, including "close calls;" and job performance. This involves a study of maintenance and testing workers on the job and an assessment of the need for job performance aids, human factors in work design, work simplification, coded control positions, tools, and work methods. Activities can be logged by researchers or plant personnel.
- Perceptions of specific job difficulties encountered by both workers and management can be assessed through the use of semi-structured interviews. The methodology would include the "identification of critical-incidents" which seem to discriminate very good from very poor performance. Specific instances identified in LER's would be used to elicit both factual and attitudinal data from interviews.
- Environmental factors, including physical (e.g., heat, light, noise, effort) and emotional (e.g., fear of exposure to radiation) variables can be studied to determine their impact on work activities.
- Attitude surveys would be administered where feasible. There are a number of surveys in existence which measure objective and subjective descriptions of the organization in terms of such factors as communications systems, reward and recognition structures, work autonomy and variety, and others. These measurement tools enable one to pinpoint areas of both "real" and "perceived" job dissatisfaction which can impact on poor work performance.
- The organizational structure of individual plants would be studied in order to determine:
 - a. Who makes decisions and how.
 - b. What are the management control mechanisms, the operational checks and balances.
 - c. How are the communications and working relations structured for the operations, technical, and maintenance groups.

- d. What are the committees and other formal mechanisms used to monitor and evaluate M&T activities.
- e. What are the divisions of responsibility between various groups.

Such plant visits would allow identification of areas of work which cause M&T problems and potential methods of achieving improvement in dealing with specific problems, such as:

- a. Standardization of maintenance and testing operations (specific job elements, sequences, checks, functional diagrams, simplified diagnostic procedures, etc.)
- b. Training simulators or models to permit practice in disassembling, lubricating, and assembling. These can be worked on during non-service intervals to improve familiarity with basic job elements, correct forces and tensions, etc. (Most errors involve common hardware elements of subsystems.)
- c. Assignment of individual responsibility and accountability to specific hardware subsystem: "These are yours." This will increase both familiarity and motivation.
- d. Measures of maintenance and testing job performance against some criterion.
- e. Improved management including: type of supervision experienced by employees, supervisors' human-relations skills, supervisors' attitudes towards employees, and employee attitude toward self and job.
- f. Programmed instruction to improve learning and routines and eliminate poor habits.
- g. Improved relations and divisions of responsibility between: maintenance personnel, operators, technicians, and management.

Using LWR plant operating experience data on M&T, the following considerations would have very definite correlation to operating efficiency of nuclear power plants, especially considering maintenance and testing activities.

- Does the operating utility have previous experience with nuclear plants? Does the operating facility receive satisfactory inspection reports from NRC?

- Are the operating personnel at the plant well trained as indicated by RO and SRO scores on NRC examinations? (Usually if operating personnel are well trained, the maintenance personnel will also be well trained.)
- Is there an excessive turnover rate of employees? (Perhaps the number of operators licensed per year in a plant life would be indicative of this parameter. Even if turnover at the plant and number of people licensed at the plant is due to the plant being used by the utility as a training facility for other plants, this correlation might still be positive.)
- Are maintenance procedures prepared, produced, and devised under the same criteria as operating procedures?
- Are maintenance procedures followed?
- Does the quality assurance group within the plant exercise a direct field inspection function on maintenance activities?
- Are the maintenance personnel trained?
- Are support personnel, such as painters, plumbers, and steamfitters trained adequately for the maintenance which they may do within the plant?
- Does the reactor operating staff verify that maintenance is performed properly before using the system afterward?
- Is the nuclear power plant in a large urban labor pool area with strong labor union personnel, or is it in a more rural location with less jobs available for skilled craftsmen and, therefore, the craftsmen would perhaps take more pride and responsibility for his work?

A final point, which is worth considering, is to compare the financial condition of the utility company with the performance of the plant. It is suspected that the utility companies receiving adequate rates are likely to do a more complete job on maintenance than those who have minimized expenditures in order to be able to give the stockholders a return on their investment.

Based on the results of the above analyses, method revisions could be suggested, and where possible, operationalized. These suggestions would focus on the areas of (1) optimizing the level of planning and coordination

of M&T tasks, (2) redesigning certain "troublesome" elements of the M&T tasks, (3) providing effective and satisfying management practices, including human relations skills and adequate incentive motivation, (4) improving selection and training of M&T personnel, and (5) developing applicable monitoring and checking systems to assure quality performance. Other important areas of possible revision will no doubt be discovered during the problem identification phase and will be addressed at this stage.

- Planning and coordination errors between test station and the control room have already been identified as the major contributors to overall M&T error rates. Errors of coordination may be eliminated by better communication systems, establishment of two-man test teams, or establishment of formal administrative guidelines. Planning errors might also be minimized by comprehensive preparation packages, determination of optimum M&T schedule frequencies, and providing guidelines to determine priority assignments for maintenance requests.

The work priority assignment on a maintenance request is based on cross-ranking of repair policy and equipment group. The priority number of an M.O. can be changed after it is initially assigned as it progresses through the sequence of reviews. Furthermore, there are alternates to the various responsible officers in the review process of a maintenance request.

A study can be made on the impact of priority assignment on maintenance by having a researcher assigned to the Maintenance section of a nuclear power plant. The person would familiarize himself with all aspects of maintenance procedures and propose guidelines for optimal decision on the review of a maintenance request. Decision analysis on the cross-ranking procedure of designating priority can be examined for the implementation of a maintenance task with respect to safety, outage reduction, and quality assurance.

A second part of the program would include development of a decision analysis methodology and a package suitable for use by the utilities incorporating the management philosophy of the plant.

- Specific "troublesome" elements of the M&T task could be alleviated by job redesigning. For instance, preliminary analysis may suggest certain functions can best be performed using a team concept while others can be improved by giving the worker individual responsibility. Job rotation or job enlargement (or "enrichment") could also provide a means to upgrade job involvement for M&T personnel, and provide improved relations and divisions of responsibility.
- Management practices can have a significant impact on employee behavior. By determining the proper mix of such supervisory factors as consideration for the employee, initiation of task structure, application of appropriate incentives and rewards, use of proper feedback mechanisms, etc., one should be able to improve worker motivation and performance.
- Not only can a thorough job analysis contribute to better selection practices based upon relevant discriminating qualifications, but it can also provide important information concerning the types of elements necessary for effective training programs. For instance, training may be needed not only in the necessary technical disciplines, but also in the areas of overall plant response. Control and coordination circumstances and other areas might best be covered in formal training programs, and in simulator classrooms or by programmed instruction. Specific instructional aids, such as visual displays or CRT systems, might be identified as important features of training which may need development or revision.
- Quality assurance groups within plants might need to be structured differently to exercise their function more effectively. Interfaces between M&T workers and other groups might also require clarification. In addition to technical checking and monitoring devices, information checklists may be found to be useful. Since feedback has been shown to be of major importance in modifying both quantity and quality of performance, visual graphing of performance and more routine performance evaluations might also serve to motivate quality M&T work.

This phase of the program would include cost/benefit analysis for detailed studies of high priority M&T improvement methods towards implementation in practice.

Based on the results, a phase could be included which would perform research toward implementing the most cost effective items identified in the previous phases.

The administration improvement program may include two phases:

- Organization -- This phase is directed toward reviewing organizational structures from a broad perspective and eventually a narrow perspective. It will attempt to fine-tune organization structures to avoid coordination errors. As shown previously, errors of coordination tend to predominate in the test and maintenance error data base. Often times these errors would not have occurred had the on shift or staff organizations been more flexible. Often tension exists between maintenance personnel and shift personnel. This can be due in part to each group reporting within separate branches of a site organization. This tension can be a factor effecting poor communication between the test and maintenance activities and the control room. Poor communications can lead to the control room operator being unaware of the proper status of the plant systems. For example, a maintenance activity is started on the condensate system. The control room operator is not informed of this activity because it is a "simple procedure." Inadvertently, suction pressure is lost to the feedwater system causing a loss of feed flow transient. The operator could waste precious minutes attempting to regain the normal feed flow instead of using back-up systems to control the event, not realizing that the maintenance activity has contributed to the loss of normal feedwater flow and is preventing its restoration.
- Administration -- Coordination errors not only originate, as previously discussed, from organizational reasons but also from administrative difficulties. This proposal is aimed at ensuring optimum communication within operating shifts, within maintenance departments, and between them. Although it is realized that generic administrative guidance may not be equally applicable to all facilities, it is valuable to set standards of interface between both operations and maintenance departments. Many examples can be cited of particular incidents caused by poor interface relations. One such example is a plant transient caused by testing conducted concurrent with maintenance. Although these concurrent activities in themselves did not cause the transient, a single human error during testing resulted in a complete loss of feedwater transient rather than a simple reactor trip. This situation may have been prevented by more optimized administrative procedures limiting testing during the maintenance activities. In

conjunction with the above analyses, research can be conducted to assess areas of manpower availability and review procedure utilized in the selection, placement, and training of NEPP personnel. The purpose of this section is to ensure the quality of M&T work crews.

- Manpower availability studies would assess the adequacy of the needed supply of M&T crews for present and future nuclear power plants and would recommend actions required to insure the availability of trained M&T crews.
- Existing selection criteria would be analyzed to identify and examine predictive variables such as education; training (amount and where trained); experience; scores on NRC licensing and other exams (e.g., intelligence); psychological profiles; biographical data; and other aptitudes and qualifications as available. These data would be analyzed in terms of their relationship to safety and other criteria, as well as to critical human factors associated with the performance of various M&T tasks.
- Training programs, where they exist, would be reviewed for test and maintenance personnel. Critical dimensions of the training programs, sampling both general knowledge variables as well as specific components of simulator training, would be identified. Current constraints on training such as facilities, union restrictions, regulations, etc. would be examined. An analysis of errors and successes in the various aspects of training can lead to delineation of critical elements to be meshed with the requirements identified by job analysis.
- The use of visual display can be studied for utilization in training and actual performance. The effort would be to collect and describe the visual tasks encountered by nuclear power plant personnel, including a comprehensive analysis of the message content and purposes of visual displays. Human information processing research provides the basis for understanding the perceptual and information-processing demands upon the user of graphic displays. Research models and paradigms derived from the literature in reading comprehension and pattern recognition can be used to explore methods to identify, quantify, and manipulate variables associated with graphic comprehension. Errors in perception and comprehension can be determined through actual job studies and operator surveys in order to define specific areas for improvement in the design and teaching of visual displays.

5.2.3 Background and Justification

Analysis of M&T data points to two common M&T problems, namely adjustment errors and forgetting errors. It also appears that M&T problems tend to involve minor supportive elements in the work sequence-- matters likely to be forgotten. Such problems are all too common in everyday life--leaving a light on, leaving keys in the car, etc. The reasons that these kinds of problems occur frequently in most maintenance and testing work are:

- That inadequate cues exist to point to their exclusion or incorrect completion.
- No check or test of the component or subsystem is made immediately following the maintenance operation in question.
- The worker is usually unaware of his error and, hence, does not correct himself.
- Low frequency of maintenance and testing tasks does not permit adequate practice to produce automatic sequencing of small events in the work process.
- Management controls and incentives are lacking to make the maintenance and testing person specifically responsible for given subsystems and their operation.
- Poor work habits in performing basic tasks such as lubricating, tightening, etc. may have developed.

In order to provide realistic diagnostics of the M&T problems and to recommend specific policies to mitigate such problems and their impact on the safety of LWR plants, it is necessary to identify specific indicators that would help understand management attitude and capability in a nuclear power plant. Analysis of data from LER's has shown that management attitudes have a very great effect on the way in which maintenance and testing is done and on the number of reactor shutdowns or interruptions occasioned by improper management. The best available indicator of management attitudes at a plant would be to read LER's. This is not exactly sufficient, since it only indicates that management attitudes are indeed the important thing in determining the effect of maintenance on

reactor operation capability. However, one can determine management attitude very quickly upon arrival at a nuclear power plant by observing housekeeping in the various areas, and the manner in which employees carry out their work. Admittedly, this is a subjective evaluation that one must make upon comparing one nuclear power plant's appearance to another, without looking at records or operating performance. Despite the fact that some of the judgments on criteria indicated below must be subjective to an appreciable extent, several items (given below) should be directly correlated with reactor plant performance, and in particular, with the effects of maintenance and testing on reactor plant performance.

If management's attitude places great emphasis on the overall importance of maintenance, as opposed to meeting technical specifications exclusively, then some of the items below would not necessarily be highly correlated. For example, extensive, well-reviewed maintenance procedures may not be necessary if maintenance personnel have a feeling of responsibility instilled in them by management. Conversely, the existence of the detailed procedures may have no significance if the persons using them do not adhere to these procedures. Furthermore, if higher management personnel are not committed to maintenance as a cost-effective management tool, then the attitude of on-site personnel to maintenance may correspondingly be lax. Also, if upper-management's attitude does not allow personnel at the plant to have a major input into maintenance planning and modifications, then the maintenance group may be considerably less effective.

The first step in this study involves obtaining up-to-date information about the organizational structure of all nuclear electric power plants (on-site) and relevant parts of the operating utility company (off-site). Comparative analyses of the plants and the NRC Regulatory Guides can be made and the results related to various measures of plant effectiveness.

There are a large number of important questions to be asked, with answers sought in additional studies. Some of these are: Who's in charge? Who makes decisions and how? How are the decisions implemented?

What are the management control mechanisms, the checks and balances? How are the communications and working relations structured for the operations, technical, and maintenance groups? What are the committees and other formal mechanisms used in NEPP's to monitor and evaluate the operation of the plants?

More specific studies of the following type would be conducted in the next phase: Who actually is responsible for maintenance activities? Are maintenance procedures prepared, produced, and devised using the same criteria for comprehensiveness as operating procedures? Are maintenance procedures followed? What is the training required and provided for maintenance personnel? Does the quality assurance group within the plant exercise a direct field inspection function on maintenance activities? Does the reactor operating staff verify that maintenance has been performed properly before using the system after maintenance? What is the Quality Assurance Program for each NEPP? How effective is it? What is its working relationship with operations and with maintenance? What are its field inspection functions?

During refueling who has the major authority and responsibility for scheduling activities and carrying them out? How are refueling, test and inspection, and maintenance coordinated during a refueling outage? What can we learn about management and supervision from NEPP's experience during refueling outages?

One of the major problems which is related to organization and administration of M&T tasks is the work coordination among various plant activities. As discussed in Section 4.0, these include:

A. Test Station Coordination

Frequent testing errors have been noted during equipment calibration procedures when a technician overlooks a step in the procedure or fails to return test switches to proper positions. Errors resulting from procedural omissions or misalignments can cause inadvertent reactor trips when other equipment is in test or out for maintenance. Many of these errors come from familiarity with procedures, biasing the technician not to explicitly

follow each written step. Also, steps are easily omitted when the technician is constantly shifting his attention between a procedure and the equipment. A two-man team would provide an independent check that each step is completed satisfactorily. Reformatted procedures provide a more efficient tool for the procedure user. Elimination of two steps from any one entry limits the possible impact of any line entry omission. Switch position checks interspersed during the test provides added assurance that the proper test signals are being used. The final switch position checks ensure that the equipment is not left in "test" after test completion.

Test station coordination requires an effort to reformat testing procedures, avoiding two steps in one entry. Interspersed switch position checks include a final switch line-up. Two-man test teams should be established, with one man testing the equipment while the other reads the procedure and records appropriate readings.

B. Test Station Control Room Coordination

The most frequent types of errors, which are major contributors to the overall test and maintenance error rates, are coordination errors between test station and control room. For example, a technician places an instrument in test as scheduled. The control room operator is unaware of the test either by forgetting or some other reason. The test signals give control room alarms and the operator takes action, which may effect plant operability based upon the test signal.

Theoretically, every error of coordination can be eliminated by better communication. Consequently, the primary recommendations are aimed at establishing systems of communication between the test technician and the control room operator to ensure awareness of testing which is beginning, in progress, or completed. The secondary recommendation, of establishing a shift engineer to coordinate, may not be a suitable solution if communication is not improved. A shift engineer for test and maintenance can be an effective asset especially if a facility presently has the staffing to perform this function.

Control room coordination necessitates the following actions:

- Require permission to be granted by the control room operator prior to placing equipment in test.
- Establish and update "Equipment in Test" status boards. Test completion should be acknowledged by the control room operator by signature on the test procedure.

- Establish a shift engineer to coordinate control room responsibility for testing and maintenance.

C. Shift to Shift Coordination Errors -- Control Room

As a follow-up to the evaluation of coordination errors between the control room operator and the test technicians, these recommendations focus on providing better tools for the operator (or shift test and maintenance engineer) to maintain continuity of plant status relative to scheduled tests and maintenance. Specifically, a formal watch relief in the control room will reduce the possibility of important tests or maintenance being unknown to a short-term relief watch person. In addition, administrative guidelines which list equipment allowed to be tested or maintained for the prevailing plant status, will relieve the shift personnel of such decisions. For example, if one train of an Emergency Core Cooling System (ECCS) was maintained as allowed by technical specifications, it would not be appropriate to conduct ECCS testing, especially testing on the maintained system. Although this example seems somewhat obvious, nevertheless, only minor coordination errors between the control room and test technicians can lead to circumstances causing reactor trips.

Thus, one must:

- Establish a formal control room relief plan including status of all test and maintenance in progress. Require reliefs in the control room to be accompanied by a formal watch-relief.
- Develop administrative guidelines for equipment allowed to be placed in test simultaneous with equipment maintenance. Update guidelines as equipment outages restrict operational flexibility.

D. Shift to Shift Coordination Errors -- On Test Station

Using the same rationale as for recommendations B and C, this recommendation is directed at reducing the possibility of coordination errors among test technicians. It is recognized that some test procedures require extensive test time. To restrict shift change may make test scheduling difficult or even impossible; consequently, formal administration guidelines may be the most appropriate method of accomplishing this coordination. An example of such an error is in a test condition performed without proper supervision. This recommendation also minimizes the possibility that a watch relief will continue a test procedure at an improper step.

In order to do so, one needs to restrict shift change of technicians while testing is in progress or prepare appropriate administrative guidelines to preclude incomplete or inaccurate turnover of testing status.

E. Preparation for Testing

Miscalibration of plant instrumentation can be due to improperly calibrated test equipment. For example, plant pressure instrumentation may be checked by an uncalibrated voltmeter; thus, even though the calibration procedure is correctly followed, the result is nevertheless an out-of-specification plant pressure instrument. The same sequence of events can occur when performing instrumentation checks with primary standards. Using the same plant instrument as an example, the pressure sensing device may be calibrated by a primary standard pressure cell. Without calibration, the plant pressure may be miscalibrated.

Most nuclear power generating facility owners have established calibration systems; however, these systems may not be formalized with an internal quality assurance program. This recommendation focuses on the formalization and reproducibility of such a program that with minor modifications, can be made generically applicable to any nuclear product line, similar to the standard technical specifications.

Thus, it is necessary to formalize a periodic calibration system for all test equipment and primary standards.

F. Preparation for Maintenance

Common maintenance errors occur due to improper component installation, repair, or assembly during maintenance periods. Examples are valves installed backwards, improper type of valve packing used, incorrect assembly of pumps, and improper replacement of wiring. All of these and many more errors can be minimized by comprehensive maintenance preparation. Often maintenance packages are assembled by maintenance departments and are not thoroughly reviewed for accuracy and completeness by the actual performers of maintenance. Manufacturer technical manuals are either not consulted in developing the maintenance packages, or if consulted, are not extensively used. Further, if manufacturer's technical manuals are available on job sites, there will be incentive for the maintenance personnel to consult them when in doubt.

Welding preparation is conducted through a series of qualification welds. Welding of mock-ups for particularly

difficult welds can be of great value when compared to the possibility of grinding out a weld and rewelding.

Particularly troublesome errors arise from improperly rewiring equipment that has been maintained. Two-man control of wire identification will minimize this potential. The first person removes, tags, and identifies the wires on a form or diagram. The second person checks the completeness of the wire removal, tagging, and identifications.

This calls for taking the following steps:

- Examine packages on safety related equipment to assure they are correct and complete.
- Provide manufacturers technical manuals at maintenance locations in the event work package instructions are not sufficient.
- Require wire removal forms and diagrams when removing or replacing wiring. Two-man signature procedure should be required.
- Provide sufficient welder preparation by using mock-ups.

When a request for maintenance due to some system or component failure is initiated, a Maintenance Order (M.O.) form complete with details of desired work description is forwarded to the Shift Supervisor for review. The Shift Supervisor approves the work request and designates the type of outage desired. The M.O. is then submitted to the Supervisor-Operations for work priority assignment. The Technical Supervisor will then technically review and analyze the work request. Any NRC Senior Licensed PRS Member may also perform this Technical Review function.

This technical Review involves job-planning and interfacing with Radiation Protection and Health Physics personnel, as well as Quantify Assurance and Control personnel before setting up the detailed work instructions. After review by the various sections above, the M.O. is then submitted to the Maintenance Supervisor.

The Maintenance Supervisor ensures completeness in the review and designates the appropriate area of responsibility and manpower requirements. The M.O. is then forwarded to the supervisor in charge of the proposed work.

A large number of component failures with safety implications, as identified in FEED, involve failures of safety relief valving by leaking, popping open, and failing to reseal after opening. Failure of safety valves to fully reclose is a design problem which has long existed in the industry, and seal leakage is usually considered to occur over a long period of time and may be considered a wear problem. Situations involving SRV's popping open, however, have been known to occur immediately after installation or overhaul. Since the consequences of an SRV popping open vary in severity, depending on the location of the valve and in all cases result in a required shutdown, the event is a transient and any means of lowering its frequency should be identified and analyzed.

It is possible that the tendency for quick SRV failure by pop-open is a result of inadequacies in the quality of the maintenance procedure much the same as poor performance of an overhauled engine is dependent on the overhaul process. Alternatively, failure may simply be the product of parts wear in parts which are not routinely replaced. A multi-faced analysis of relief valve performance is required which has, as its goal, identifying the interplay between maintenance procedures and defects on overhauled equipment and definition of an improved pre-installation testing program to determine vulnerability of overhauled equipment to failure before installation.

Here, the need is for a review of data or collection of data from operating plants to determine event frequencies, as well as the background data on the events necessary for a refined assessment of cause and effect relationships. This program would emphasize the identification of maintenance procedure changes and appropriate test criteria and test equipment.

A program of this nature could conveniently be extended to include other equipment which exhibit a high frequency of replacement failures, such as certain critical valving and diesel generator components. Following the identification of specific causes of maintenance and testing problems, several types of solutions may be recommended including,

- Improved training of maintenance and testing personnel using:
 - a. Programmed instruction
 - b. Simulators
 - c. Working models of hardware
- Information check lists for use in maintenance and testing.
- Management practices, including:
 - a. Assignment of responsibility
 - b. Use of incentives, feedback, performance evaluation
 - c. Human relations
- Control of the work environment including protection and work stress reduction.

Although identified maintenance and testing problems have been demonstrated primarily to involve valves and switches, the problems observed are largely traceable to human, as opposed to mechanical errors. Thus, changes in the design of equipment and technical specifications may not address the more fundamental problem of how human performance may be improved so that M&T errors are minimized. Many studies in the safety field focus on the relationship between accidents and factors that are, from the standpoint of management, difficult to alter; for example, age, experience level, and personality characteristics of the work force. However, recent advances in the technology of job redesign, as well as more traditionally accepted successful management practices, offer areas to consider in reducing safety-related human errors.

There are major issues relevant to the performance of M&T tasks and which contribute to the M&T problems. One such issue is manpower availability. Several factors may make this of real concern:

- Experienced M&T crew having "utilized" or "consumed" their allotted dose and being "burned."
- As present plants get older, the dose level in certain plant locations that need maintenance is expected to be higher than present levels. Also, the frequency of M&T is expected to be higher for older plants.

- The current trend for tightening nuclear plant security practices (e.g., requiring L-security clearances) may impact the availability of the needed manpower.

A second issue is the selection of M&T personnel. Utility personnel, including operators, maintenance men, engineers and management play a key role in determining the safety of a reactor. They can cause or aggravate accidents through errors or they can prevent or mitigate accidents through their ability to make judgments and to innovate. The difference between two courses of action often depends on training, knowledge, and abilities. This rationale forms the basis for emphasizing personnel selection and training.

The existing selection criteria would first be analyzed. Any predictive variables such as education; training (amount and where trained); experience; scores on NRC licensing and other exams (i.e., intelligence); psychological profiles; and other aptitudes, qualifications, and biographical data would be identified and examined. Criterion variables including performance ratings, salary progression, error and accident rates, absenteeism, etc. would also be identified and examined. Concurrently, validity would be determined and multiple regression analyses developed. In addition, the results of job analysis and job descriptions would be utilized to determine critical human factors associated with various jobs.

Training programs would also be evaluated. Critical dimensions of the training programs, sampling both general knowledge variables, as well as the components of simulator training, would be identified. An analysis of errors and successes of the various aspects of training would lead to delineation of critical elements in need of revision. These elements would also be closely meshed with the critical requirements identified by a thorough job analysis. During the analysis of current methods employed, alternate selection and training devices would be introduced and preliminary evaluation instituted.

A third issue which impacts the performance of M&T tasks is the training of an M&T crew. Currently no license is required and, hence, no formal training is planned. Therefore, a need exists to develop formal training programs in areas of test and maintenance where they presently

do not exist. Specifically, I&C technicians and auxiliary operators often receive a minimum of formal training; however, these individuals can greatly influence the operability and safety of plant systems and components. Training is needed not only in the necessary technical disciplines, but also in the areas of overall plant response. These individuals (especially the maintenance and testing crew) should be thoroughly aware of the probable consequences of their actions.

Control Room Operators are trained and tested on the operational aspects of plant control; however, the most challenging control and coordination circumstances occur during testing and maintenance periods when these activities must be coordinated with other plant operations. Formal training programs should be established by each facility owner. Simulator classrooms may provide a tool to standardize such training.

This program involves work to:

- develop training programs and establish industry certification for I&C technicians and auxiliary operators, and
- place more emphasis in Reactor Operator training on the role of the Control Room Operator during test and maintenance operations.

Review and analysis of reported events from 1972 to date have demonstrated the need for training, not only for control room operators, but also technicians, auxiliary operators, and even site management. The above proposed program will review the current training status of test and maintenance personnel. It will examine current constraints on training such as facilities, union restrictions, regulations, etc. It will also review the level of training that control room operators receive from simulators and utility programs. The program will examine the acceptable U.S. NRC qualification requirements for reactor operators and senior reactor operators.

The results of this program should be a key factor in providing generic guidance for training to utilities and simulators. Such training should be valuable in reducing errors such as improper installation of equipment, improper test sequences, and improper equipment repair. From

this it should be a key element in training the control room operators in coordination of testing and maintenance activities with plant operators, whether during power generation or outages.

A training program can only be effective if developed on the basis of avoiding common M&T problems. A study of methods of mitigation of M&T problems would provide insight into the areas which need to be emphasized. One of those areas is the ability to comprehend graphic displays. Psychological studies in learning have shown that an absent element in many education and training programs is interpretation of graphic displays. The use of graphic displays will be an essential part of any program to improve M&T task performance. M&T and other personnel involved in nuclear power plant operations are confronted with large masses of information which are critical to effective plant operation. The form of presentation of this information presents perceptual and information-processing demands on the user which may be excessive if not appropriately designed and taught.

5.2.4 Statement of Work

TASK 1 FIELD WORK

Selected plants can be visited to collect information on procedures, organization, and M&T work performance. Job design would be analyzed to provide appropriate recommendations for improvement of M&T task performance. This task involves the following subtasks:

Subtask 1.1 Organization

- Review existing site organizational structures (including on shift structures) to define the extent of integration of site maintenance and operations departments.
- Conduct a literature survey and discuss with management consultant. Draft an optimized site organizational structure.
- Review the draft structure with sample utility management for feedback.

- Recommend organizational modifications to optimize maintenance and operations functions, as well as reduce coordination errors between and within branches of the site organizations.

Subtask 1.2 Administration and Procedures

- Survey existing methods for generation and execution of testing procedures and schedules including interfaces with the operations department and the operating shift on which a test is scheduled to be performed.
- Survey existing methods for generation and execution of maintenance work packages, including interfaces with operations department and the operating shift on which the scheduled maintenance is to be performed.
- Recommend generic administrative guidance on improved interfaces to reduce errors of coordination during maintenance and testing.

Subtask 1.3 M&T Task Prioritization and Decisions

- Determine the impact of priority assignment on a maintenance request by supervisory personnel in a nuclear power plant.
- Provide guidelines for an optimal decision on the review of a maintenance request, particularly in relation to safety aspects and outage reduction.

Subtask 1.4 M&T Manpower

- Assess present supply and training practices of the M&T personnel and their compatibility with the near future demands.
- Provide projection of the needed supply of M&T personnel taking into account both the additional work load required for current and new plants.
- Identify special important considerations to be taken into account in training the nuclear M&T crew as compared to M&T personnel for other types of power plants.

Subtask 1.5 Training

- Survey training programs for I&C technicians and auxiliary operations.
- Survey the extent to which test and maintenance is a part of formal reactor operator training simulators and plant sites.
- Based upon the investigations of interfaces between maintenance and operations departments, outline a recommended test and maintenance training content for formalized training programs for auxiliary operations, I&C technicians, and reactor operators. Recommended items may be categorized as (1) utility unique--those to be conducted at the plant site, and (2) generic--those that can be conducted in simulator programs.

TASK 2 PROCEDURE MODIFICATIONS

This task includes design of procedures and management organization to improve current practices in M&T work performance. Emphasis is on coordination, M&T decisions, and sequencing. This task involves three subtasks.

Subtask 2.1 Recommendations

The results from the field visit might be used to provide necessary improvements. The recommendations can be reviewed by utility personnel for possible modifications.

Subtask 2.2 Cost/Benefit Analysis

Recommended changes could be analyzed to assess both of the cost and benefit trade-offs.

Subtask 2.3 Implementation

The recommended modifications can be implemented in a sample LWR plant to test the potential improvement on M&T performance.

TASK 3 TRAINING

Subtask 3.1 Training Program

Based on field studies, a training program can be developed for the M&T crew.

Subtask 3.2 Test of Program

The program would be tested in a sample plant to demonstrate its practicality. The impact of training on M&T performance would be monitored.

5.2.5 Schedule

5.3 MONITORING, DIAGNOSTICS, AND TROUBLE-SHOOTING TOOLS

5.3.1 Objective

The objective of this program is to develop and demonstrate appropriate techniques and devices which can be used in monitoring and diagnosis M&T problems and which can assist in trouble-shooting.

5.3.2 Program Description

This program involves the development, testing, and demonstration of monitoring, diagnostics, and trouble-shooting tools such as:

- Quality assurance.
- Performance monitoring data systems.
- Monitoring devices.
- Diagnostics and trouble-shooting techniques.

The research includes feasibility, design, field testing, cost/benefit analysis and evaluation of acceptability of the proposed schemes, and demonstration. Utility acceptance is an important element in the development of each system/device.

5.3.3 Background and Justitication

5.3.3.1 Quality Assurance

The most frequent generic M&T problem is that involving acts of commission resulting in improper maintenance or improper operations during testing. Examples are improper calibration and misadjustments. The third most frequent generic M&T problem are acts of negligence.

Although it is recognized that extensive quality assurance programs may be in place in site organizations; nevertheless, these programs may be directed toward equipment qualification traceability. The quality assurance needs that are in view in this program are procedure and record

controls dealing principally with reductions in human errors relative to maintenance and testing. An easily cited example of errors which can be reduced through such quality assurance programs are instrument miscalibrations due to use of uncalibrated test equipment. These errors not only affect single and multiple channels of instrumentation, but potential instrumentation of a variety of types.

5.3.3.2 Performance Monitoring Data System

Any effective quality assurance program requires a method to monitor improvement in performance. For that matter, a measure--such as learning or performance improvement--needs to be developed to monitor the effectiveness of any technique or method which is recommended for mitigation of frequent M&T problems. One such measure is the development of a continuously updated data file on M&T events which would provide trends in performance of M&T tasks whether for a specific plant or for a group of plants.

Extraction of M&T data from the various available sources proves to be a very tedious task due to inadequacies inherent in the reports; often because reporting formats have been keyed towards the needs of individual regulatory bodies. A standard M&T report format which is amenable to the needs of the nuclear industry would provide optimization in terms of data usage, and the time required for review. There is no complete data bank which quantifies the effects of maintenance and testing upon the safety of LWR's. Presently, most sources with data applicable to M&T are formulated with specific criteria in mind (examples: M&T events leading to outages and M&T related radiation exposures) to meet the requirements of various regulatory bodies. Each source has placed different reporting criteria upon the appropriate nuclear industries, and as such make it extremely difficult to cross-correlate reported events from the numerous sources. Also, because of the number and variety of sources, it is inappropriately time consuming for M&T event review.

A comprehensive M&T data bank which is founded upon the relevant needs of the nuclear industries would greatly enhance interaction with the bank and stimulate internal facility, vendor, A/E, etc. review of applicable

events. Also, since interaction could conveniently take place amongst appropriate nuclear industries the formulation of "in-house" programs for evaluation of M&T events would be encouraged.

Initial contacts with utility management have shown preliminary acceptance of adopting any recommendations which would be beneficial to the company whether in terms of performance or economical return.

5.3.3.3 Performance Monitoring

The result of the scoping study in which the most frequent M&T problems have been identified has also shown that 37/61 events which have occurred during the performance of preventive maintenance were acts of omission during or after the completion of the task. Generally acts of omission are the second most frequent M&T mode.

Some of the recurring problems in maintenance and testing are:

- Component misidentification
- Taking a component out for test when its backup (redundant member is under repair)
- Use of improper parts
- Improper assembly (e.g., check valve improperly oriented)
- Improper system restoration following test and repair.

Several recurring M&T problems which have been shown to have significant safety impact on reactor operation include defeat of multiple components by leaving components isolated after maintenance and taking components out for test and maintenance when a redundant component is undergoing repair. Both of these failures often involve not only the performance failure in question, but additional failures such as ignoring electronic state signals and incorrect accounting of system and component states.

Other failures, such as improper assembly of components, use of improper parts, and misidentification of components (replacing defective equipment with nonoverhauled components) have in common with the first failure the fact that they can be remedied by a system of positive checks.

Several forms and configurations of positive check systems can be identified depending on the identified system end use. These include positive lock sequence systems, electric sequencing systems, and procedural written checks. Of the three, the most secure is the mechanical lock system, and the least secure is the check form concept; but optimal end uses can be defined for each type of system.

As an example, assume that isolation valving on the auxiliary feed-water system is covered by a positive key sequence system. In this manner, using a single key with matched locks, no second valve can be closed unless all others are in the open position with the key removable from the lock only in this position. Alternatively, the system can be electronically locked such that logically only one lock can be opened at a particular time, the logic being housed locally in a small microprocessing unit.

To examine the function of an electronic sequencing system, it is constructive to reflect on the monitoring system used to control nightwatchmen's routine surveillance functions. Positive check control results by keeping keys at specific locations used to actuate a clock-punched device worn by the watchmen. The dish device indicates not only the frequency of passage but also the time of passage. Technology negates the use of a punch clock or any mechanical device, but a small microprocessor unit can be devised which, when worn by the maintenance person, has a program sequence of events which must be performed in order within allocated time window to effectively signal completion of the procedure to a central monitoring unit.

A program should be initiated to develop positive check systems to control specific maintenance tasks shown to be vulnerable to the use of improper repair or calibration procedures. A preliminary program of data collection and analysis should be used to identify particularly vulnerable repair sequences. Perhaps the utilities themselves can provide direct working knowledge of specific performance problems and other problems which would represent a constraint on the use of such equipment. The program would thus include a problem definition stage, technology selection stage, product development stage, and a field test stage. The last stage is a requirement to insure the ability to measure performance improvements and additive maintenance costs associated with using the system instrument. A small number of

plants would be provided with the system, but the number would be sufficient to generate useful information on the difference in performance between equipped and unequipped plants.

As an example; M&T monitor might consist of a small microcomputer with a permanent memory (Read-Only - ROM) and a recording memory (Random Access Memory - RAM), a display and light pen.

The actual coding of the monitor in its permanent memory would be performed by the Operations Supervisor on a somewhat larger mini or micro-computer supported by various input-output devices. Among these would be a magnetic tape that contains the program and special instructions for recurring tasks.

The technicians would receive a kit which may consist of repair parts, written instructions and the monitor. Upon arriving at the assigned location, the monitor would display or audibly provide the instruction: "Identify Component". Following this instruction, the technician would move the monitor light pen across the component identification code. (This code is similar to the code used for automated inventory control and checkout in grocery stores.) If correct, the display will indicate: "Correct;" otherwise, "Wrong Component, Identify Correct Component." When the correct component is identified the monitor would indicate "Correct, Proceed."

The next instruction might be: "Configure for Test." What occurs next depends upon the task complexity. If it is simple, the next instruction would be: "Verify Test Configuration" and the technician would move the light pen across an LED bar display of configuration status. This code would be read by the light pen and the display would indicate "Test Configuration Correct." This code could carry component identification code to assure against one component being identified and another configured for test. If the test configuration is complex, the monitor could lead the technician through the configuration. One such instruction could be "Close Valve V2105." When this valve is closed, the valve position is indicated by exposing a code plate for reading with the light pen or it may be electronically indicated by

LCD's for light pen reading. After the valve is closed and read with the light pen and verified by the monitor, it displays the next instruction such as "Close Valve V2106." This process continues until the component is correctly configured for removal from service. Maintenance would be performed according to instructions using the tools and parts provided. If the component may be put together improperly configured, this could be avoided by splitting a verification code so that part of the code is on one part and part of the code is on the other part and it is necessary to read both parts in a limited time interval.

If testing is required, a component would be configured for the test which would be verified as before and the reading could be read with the light pen using LCD coded readout. This could also be done with a Heisse guage using a coded disk to supplement the needle indicator.

After M&T operations, the monitor would prompt the technician through restoration procedures to assure the component is restored to service and the restored status would also be recorded by the light pen. Only when restoration is complete will the active light go off in the monitor so if the technician skips any stages or does not complete the procedures a light will show when the monitor is turned on.

When all steps are satisfied, the monitor is turned in. It is read electronically by the operations supervisor using the micro or mini computer used to program the instructions. This computer verifies each step that was recorded by the light pen. It would also record personnel exposure by light pen reading of the dosimeter. It can check the elapsed time between steps for irregularities. Data and status recorded by the monitor can be achieved on magnetic tapes for use in report preparation or operations inspection.

This example of the operations of an M&T monitor is not expected to completely describe the capabilities of such a device, but rather to outline the device potential. A more complete description of the monitor capabilities would result from the studies.

5.3.3.4 Diagnostics and Trouble-Shooting

In spite of efforts in mitigation and monitoring M&T problems,

it is necessary to provide tools for diagnostics of such problems before any serious impact on the components/systems or operation take place. In addition, means to minimize the impact of M&T problems on plant safety and performance should be sought. Several methods have been suggested based on these studies. The recommended tools can be investigated in sequence and a technique can be developed and implemented based on the results of such investigation. The tools are discussed below and are listed according to their potential for acceptance by the utilities.

5.3.3.4.1 Utilization of CRT. Different types of malfunctions in nuclear plants may cause the system to exhibit very similar symptoms. It takes highly experience operators and M&T crew to give the right diagnosis to the correct cause of the malfunction. Reaching the correct decision as to the true source of the malfunction within a short time period and taking the best corrective action can greatly impact plant safety and availability.

Development of CRT Systems to help in diagnosing the root causes of malfunctions is more difficult for systems involving fluids than for systems involving electronic systems. This is due to the fact that the logic is too complex to program. However, if the appropriate set of parameters is selected to be displayed on the CRT, this may provide the operators and the M&T crew with an insight as to where to look first. For example, the sensors to certain important parameters in the plant are connected such that the display of a circle on the CRT indicates the system is functioning properly and a certain deformed shape implies otherwise.

5.3.3.4.2 Noise Diagnostics. Accurate information on the operational state of components in a system is important for control and surveillance of nuclear reactors. The use of noise monitoring devices to characterized the operational state of a particular component has the following advantages over alternative techniques:

- No disturbance to the normal operations of the system
- Easy maintenance
- Predicts incipient component failure
- Cost beneficial to a utility in down-time reduction

For instance, an ultrasonic transducer can be assembled to monitor coolant flow in some piping systems. There is no obstruction of the flow channel, no physical penetration of the pipe wall, and no calibration drift.

The operating principle of the ultrasonic flow meter utilizes the time difference of the travel times of an ultrasonic pulse travelling with and against the direction of the fluid flow. The ultrasonic energy is transmitted at an oblique angle through the wall of the pipe. There is, therefore, no obstruction to the flow and no physical perforation of the pipe.

Experimental research can be conducted on a specific LWR plant utilizing noise monitoring techniques to detect incipient component failure. Ultrasonic devices can be built and tested to determine their campatibility to the system, as well as providing precise information on the operational state of a component. The development of noise monitoring techniques of safety aspects of various mechanical or instrumentation systems can have applications to other non-destructive and surveillance testing systems as well.

5.3.3.4.3 Interactive Continuous Monitoring of Reactor Safety Functions.

Review of the M&T data has illustrated the vulnerability of current nuclear power plants to:

- human error compounded and undetected for significant operating periods of time, and

- design differences between reactors which can create new safety problems or exacerbate existing ones.

These vulnerabilities are not easily remedied by the current design process which relies heavily on single failure criteria and improved equipment reliability. The resiliency of current designs to many common-mode failures is questionable and, as recently seen, little credit can be taken for beneficial human interaction.

During an accident, the reactor is not instantaneously in a binary state, safe or unsafe. Rather, it can be a lengthy process of hours or days before the safety of the core is assured following an accident initiator. During these hours, a useful tool for the operator is a method of identifying a "safe" set of actions on his part.

A number of annunciators and light displays currently exist in reactors which show the status of certain components deemed critical to safe reactor performance. The fact that this represents a passive system for controlling and monitoring the state of some critical reactor systems and the fact that such a system has failed in the past, most notably at Three Mile Island, to prevent neglect of the passive display suggests that any system to perform reactor safety status evaluations should be active or interactive in nature.

In addition to a simple system state determination, an interactive, hard-curved monitoring system would need to be useful for integrating other forms of data, such as reliability data and previous equipment performance, into a realistic representation of the vulnerability of a reactor to a variety of safety-related problems.

Since the system must be positive interactive, it would be most useful to have the unit based on a minicomputer with transducers and monitor system inputs as well as data inputs through the use of tapes. The interactive capacity would exist through the use of key input and CRT-light pen displays.

Probabilistic logic analysis (event trees and fault trees) have been used in the past with some success to determine design vulnerabilities

and relative likelihoods of various failure sequences. In theory, it is feasible to determine a set of event trees and fault trees (such as those of WASH-1400 for the Surry and Peach Bottom 2 plants) specific to the plant or a generic group of plants (such as the B&W PWRs) which can be used to identify incipient safety hazards.

Through the use of microprocessors or small "committed" computers, a set of event trees for various accident initiators (most importantly the transients) can be defined for the plant or generic plant type and hard-wired into an on-line monitoring system. This monitoring system would, in a sense, continuously solve for the probability of completion of each failure event sequence using information such as the state of various equipment, previous plant operating experience and current reliability data. More practically from a safety standpoint, partially complete event sequences (entire system ineffective) and highly probable fault tree top events (systems with a high failure likelihood because of off-line equipment or previous upsets) can be identified.

Using a relatively simple signal processing system with existing or easily added monitoring circuitry, equipment which is failed or in an off-line state and so "logically failed" can be incorporated as component failures in the hard-wired fault trees.

Also, through the use of an updated failure probability data bank which includes reliability data on specific plant equipment plus current, continuous tabulations of initiating events (varying types of transients) experienced throughout the reactor industry and event sequences which are comparatively high risk for the particular plant or its generic plant type can be identified in a timely manner and proper actions taken.

The system would be highly interactive through the use of visual graphics and since it is an active system, the system operator is less vulnerable to the type of detection failures commonly associated with passive displays (such as ignoring panel displays). Also, the operator can be quite cognizant of what the implications of various equipment outages are. The result is that instead of relying only on procedural guidelines, the operator can use decision logic and design information on plant safety

systems, such as system reaction times, to determine safety margins and conditions requiring shutdown. A set of shutdown margin criteria can be incorporated directly in the system which would automatically initiate and control shutdowns.

The same type of monitoring system can be used should a safety incident occur to prescribe optimal reaction paths given design information on the reactor.

Given an accident initiator, the logic acts as an aid in the decision process by identifying all the actions (sequences) available to the operator for achieving a safe plant status.

The system could also provide a quick format for NRC field representatives to check previous reactor expense and current operating status and form regulatory procedures and judgments.

It is recommended that some initial work be done to establish the feasibility of such a system and its relative value impact advantage. The development of an active monitoring system and instrumentation of a single facility should be pursued as an innovative safety program. The necessary hard technology should, for the most part, be purchasable and the remaining major design problems include:

- Identifying adequate fault logic for the plant.
- Designing a realistically workable onsite data collection and integration system.
- Designing ancillary control elements for integration of the active system with present safety controls and instrumentation.

5.3.3.4.4 Changes in Safety Controls and Instrumentation. The number of automatic shutdowns experienced by most reactors is severely increased by inadvertent trips resulting from maintenance of on-line monitoring and control equipment. In many cases the equipment is designed such that the slightest fluctuation on input signals can render a "sensed" instability resulting in an originated scram signal. It is suggested that a

program be initiated to develop options for mitigating excessive scrams which cause added thermal stressing of the system and the opportunity for safety failures.

5.3.4 Statement of Work

TASK 1 DEVELOPMENT OF M&T QUALITY ASSURANCE PROGRAM

A quality assurance program should be developed to assure mitigation of M&T problems, especially those which result from acts of commission and negligence. This task is divided into three subtasks.

Subtask 1.1 Review Studies

The review study should involve

- a. Survey organization and content of site quality assurance programs with regard to test and maintenance.
- b. Review operations and maintenance department procedures on systems and components whose failure could cause a plant safety system challenges.
- c. Review interfaces between maintenance and operations departments and recommend areas where additional quality assurance programs may be needed.
- d. Review maintenance and test coordination aspects of site administration and recommend areas where additional quality assurance programs may be needed.

Subtask 1.2 Development

- a. Develop a comprehensive quality assurance (QA) program for M&T which can be integrated into ongoing programs and which can be accepted by the utility companies.
- b. Conduct a cost/benefit analysis of the M&T QA program.
- c. Provide an implementation plan for the M&T QA program.

Subtask 1.3 Testing

Carry out a field test of the M&T AQ program in a specific utility for a period of six months at least, and provide the results including inputs from the utility management and M&T personnel.

TASK 2 PERFORMANCE MONITORING DATA SYSTEM (PMDS)

A PMDS can be developed and tested to assure the effectiveness of the M&T AQ program and other improvements on M&T task performance. Although the PMDS may be tested in one plant, it should be developed for all the nuclear industry. This task involves the following subtasks:

Subtask 2.1 Design PMDS

An M&T report format which has applicability for convenient usage by the nuclear industries and which is concise in its presentation of appropriate information will be designed. All available data banks with relevance to M&T will be briefly reviewed with the objective of extracting their inherent desirable traits. Several nuclear industries will be consulted for identification of the features deemed necessary for inclusion in an amenable M&T report format. An M&T data and reporting format will be devised which incorporates optimum usage of the desirable features identified from the previous tasks. Utility input will be utilized to ensure the final format is appropriate for their completion.

The PMDS will be designed to allow for continuous computer updating and to assure its viability as a monitoring scheme for M&T performance improvement. Utility acceptability will be examined and a cost/benefit analysis will be conducted.

Subtask 2.2 Development of PMDS

A comprehensive data base of maintenance and testing events (PMDS) which is applicable to the needs of the LWR nuclear industry will be developed in a file which is suitable for inputting new data and outputting performance level according to specific keywords.

Personnel from DOE, nuclear power plant facilities, vendors, architect-engineering firms, and other related nuclear industries will be consulted to determine their opinions on what information should be included in development of the M&T data bank. A brief review of all available M&T information sources will be made for the identification of materials which satisfy the above requirements, and for determination of desired criteria which does not presently exist in available sources. Nuclear industries will be contacted for identification of those which can provide required absent information. Then a comprehensive M&T data bank will be constructed which specifically meets the overall needs of the LWR nuclear community. Applicability and adequacy of the data bank will be stressed. A convenient reporting format for the M&T data bank will then be devised for continual computer updating of the bank.

Subtask 2.3 Updating and Application

The NPDS will be continuously updated and used to monitor changes in performance of M&T tasks.

TASK 3 DEVELOPMENT OF AN M&T PERFORMANCE MONITOR

The objective of this task is to develop a small device approximately the size of a pocket calculator that would serve as a task accuracy prompter and performance monitor to be used by technicians performing maintenance and testing. This task involves the following subtasks:

Subtask 3.1 State-of-the-Art Review

A search of the industrial, research, and patent literature would be conducted to discover ideas or efforts being made for human performance monitoring. Also, specific M&T performance problems will be identified.

Subtask 3.2 Alternate Conceptual Designs

Several alternate conceptual designs will be considered and appropriate technology will be selected.

Subtask 3.3 Monitor Specifications

This effort would be aimed at determining the practical and acceptable level of M&T personnel monitoring and the level of task prompting. Utility and vendor input should be solicited. A cost/benefit analysis will be conducted to assure its commercial viability.

Subtask 3.4 Monitor Prototype

Using the previous background and specifications, a prototype M&T monitor would be constructed and laboratory-tested.

Subtask 3.5 Field Tests

The support of one or more utilities would be solicited to use the M&T monitor of selected critical components and report back on acceptability and needs for monitor improvement.

TASK 4 · DIAGNOSTICS AND TROUBLE-SHOOTING TECHNIQUES

This task is divided into the following subtasks:

Subtask 4.1 Assessment of the Feasibility of Utilizing CRT for "Trouble-Shooting" and M&T Decisions

The practicality of the feasibility of utilizing CRT as a tool to help the M&T crew and reactor operators reach reliable and quick decisions as to the root causes of malfunctions will be evaluated. This may have a profound impact on nuclear plant safety and availability. The work performed in this subtask should involve:

- Assess methods of CRT display of various parameters pertinent to M&T problem diagnosis.
- Synthesize a pattern to maximize the number of information bits displayed on the CRT.
- Develop a conceptual design of CRT.
- Study the feasibility of CRT display.

Subtask 4.2 Malfunction Detection and Diagnostics of Component Failure Due to M&T Problems by Noise Monitoring Techniques

The objectives of this subtask are to examine the feasibility of noise diagnostic techniques to detect malfunction of components in a reactor system which has limited accessibility to maintenance and surveillance testing personnel and to diagnose the degree of abnormality in component functions or operations without disturbing the general state of reactor operation. This would involve design and testing of the system in an operating nuclear power plant.

Subtask 4.3 Feasibility of Interactive Systems for Continuous Monitoring of Safety Functions

Initial work would involve feasibility evaluation of a conceptual interactive system for detection of failure of safety systems caused by M&T problems. A value impact study will also be performed to evaluate the benefits of such system.

Subtask 4.4 Identification of Design Changes in Present Safety Controls and Instrumentation Systems to Mitigate the Potential for Excessive Automatic Shutdowns

Several choices are available including procedural controls and the addition of integrators, comparators to eliminate control system transients. This subtask could be pursued to the level of identifying minor design changes and implementation in a single plant for observation.

Subtask 4.5 Development of a Diagnostic and Trouble-Shooting (DTS) System

The results of Subtasks 4.1 through 4.4 will be used to develop a commercially viable DTS system which would be acceptable to the utility industry. The DTS system may be a combination or a modification of one of the systems investigated in Subtasks 4.1 through 4.4.

Subtask 4.6 Testing of the DTS System

The DTS system designed in Subtask 4.5 will be tested in one of the operating plants. Recommendations will be made of further modifications for use in other plants.

5.3.5 Schedule

	FY										
	80	81	82	83	84	85	86	87	88	89	90
1. M&T Quality Assurance Program											
1.1 Review Studies	_____										
1.2 Development		_____									
1.3 Testing				_____							
2. Performance Monitoring Data System											
2.1 Design	_____										
2.2 Development		_____									
2.3 Updating and Applications					_____						
3. M&T Performance Monitor											
3.1 State-of-the-art Review	_____										
3.2 Alternate Conceptual Designs		_____									
3.3 Monitor Specifications			_____								
3.4 Prototype				_____							
3.5 Field Tests					_____						

	FY										
	80	81	82	83	84	85	86	87	88	89	90
4. Diagnostics & Trouble-Shooting Techniques											
4.1 CRT											
4.2 Noise Techniques											
4.3 Interactive Continuous Monitor System											
4.4 Mitigation of Excessive Shutdowns											
4.5 Development of a Diagnostic and Trouble-Shooting (DTS) System											
4.6 Testing of DTS System											

5.4 TECHNICAL SPECIFICATIONS

5.4.1 Objective

The objectives are the minimization of the impact of M&T problems of non-safety related components on safety equipment via providing operability technical specifications of those components and to improve plant productivity through optimization of plant specifications.

5.4.2 Program Description

This program is partially directed toward providing technical specifications for systems and components presently not under technical specification whose failure would require safety system operation to mitigate the effects of the resulting transient. The proposed technical specifications would optimize component or system availability and testability.

The results of this program will be key in reducing the total challenge rate to plant safeguard systems principally designed for mitigation of accident conditions. An example of potentially needed technical specifications is the non-safety feed and condensate systems which

rely on the auxiliary feedwater system in pressurized water reactors to maintain adequate cooling.

The second part of the program involves optimization of plant safety and productivity (availability) through proper adjustment of technical specifications on allowable safety system outages.

5.4.3 Background and Justification

Nuclear power generating facilities are generally designed to accommodate transients and accidents without the use of non-safety systems and components. Also, failure of these non-safety components should not create a safety problem, since safety systems exist to accommodate the effects of their failure. However, excessive reliance upon safety systems to mitigate the consequences of non-safety equipment failures lowers the overall reliability of the safety system. Another way to view this is that the probability of system or component failure on a "per challenge" basis would predict more potential failures given more challenges.

An example of such a situation is the need for a safety related feedwater system to be actuated to supply feedwater to pressurized water reactor steam generators during loss of feedwater events. Such loss of feedwater events can be caused by failures of components such as non-safety components, condensate pumps, air ejectors, feed system valving, or control air systems.

In an effort to reduce such challenges, some minimum quality assurance and technical specification requirements should be placed on these non-safety system components.

Another important point which is related to M&T is that the single most important effect of M&T on plant safety, as interpreted by WASH-1400, is the unavailability of safety systems to function during test and maintenance operations. This unavailability of safety systems in conjunction with other random component failures may lead to the loss of necessary mitigating systems following an accident initiator.

One of the factors which has a direct influence on the amount of unavailability attributed to test and maintenance is the allowable outage time for any safety system before plant shutdown is required. This requirement is part of the plant technical specifications. However, in virtually no case has there been a detailed justification for the allowed outage time. In particular, a risk assessment approach which evaluates and ranks the various paths to unacceptable consequences as a function of the allowed unavailability of a given safety system may show up some pronounced improvements in plant safety.

The FRANTIC computer code developed at the NRC can be used in the optimization tradeoff. The tradeoff which must be clearly defined in terms of cost/benefit are:

1. The change in risk associated with changes in system unavailability.
2. The change in plant productivity (e.g., capacity factor or availability).

Any plant shutdowns induced by loss of safety systems can be extremely costly (\$500,000/day). As has been shown in other studies, reactor shutdowns due to unavailability of safety systems represent approximately 5% of all the reactor unavailability.

5.4.4 Statement of Work

TASK 1 TECHNICAL SPECIFICATIONS

Subtask 1.1 Review of Technical Specifications

This subtask involves the following work:

- Review present standard Technical Specifications for typical PWR and BWR product lines.
- Review system design bases for which the above technical specifications are applied.
- Examine the functional requirements of these systems from other systems or components that do not have technical specifications.

Subtask 1.2 Failure Analysis

This involves an effort to:

- Conduct failure mode effects analyses for these system networks under normal transients and accident conditions.
- Determine if single component or system failures not presently under technical specification can cause plant safety systems operations.

Subtask 1.3 Optimal Technical Specifications

Perform reliability analysis on these system networks to determine suitable technical specifications if necessary to optimize safety system availability.

TASK 2 OPTIMIZATION

Conduct feasibility study as the amount of plant productivity improvement by optimizing plant technical specifications. This would include a cost/benefit analysis.

TASK 3 TESTING

Review plant technical specification at a selected number of plants on the safety systems which are deemed most promising.

TASK 4 IMPLEMENTATION

Implement changes to technical specifications with a cooperating utility or group of utilities.

5.4.5 Schedule

	FY										
	80	81	82	83	84	85	86	87	88	89	90
1. Tech Specs											
1.1 Review											
1.2 Failure Analysis											
1.3 Optimal Tech Specs											

						FY								
	80	81	82	83	84	85	86	87	88	89	90			
2. Optimization														
3. Testing														
4. Implementation														

5.5 DEVELOPMENT OF METHODOLOGIES TO IMPROVE PERFORMANCE OF M&T TASKS

5.5.1 Objective

The objective of this program is to provide methodologies for simulation, performance optimization and analysis of M&T tasks and associated data which would assist in identification of M&T problems and in their mitigation.

5.5.2 Program Description

This program would include development and application of the following methodologies:

- Pattern recognition and statistical analysis of data on M&T problems.
- M&T schedule optimization
- Simulation of M&T tasks

The methodologies will be centered around the optimization of schedules and task performance periods with the constraints of minimizing radiation exposure and providing high levels of maintainability. The statistical analysis of the data will provide a systematic approach to M&T problem identification.

5.5.3 Background and Justification

5.5.3.1 Pattern Recognition

In the scoping studies (FY79), the data on M&T problems is found to be sparse especially if each problem is considered separately. Thus, an approach has to be developed to identify generic problems and to cluster the event frequencies in order to assess the main causes.

An intuitive approach to the general analysis of component failure in a reactor system is to utilize the concept of cluster techniques or pattern classification by distance functions. If the input M&T data represent the various components that are specific to each system, then a measure of similarity can be established between pattern vectors, which we consider as points in Euclidean space, by determining their proximity.

The data required for this analysis can be retrieved from M&T data banks. Furthermore, the compilation of hardware inventories in the various systems for the reactor type will facilitate convenient analysis by the above methodology.

Various cluster-seeking algorithms that form the basis of a pattern recognition effort could be examined for suitability of implementation. Computer programs can then be developed for the pattern recognition of hardware failure in reactor systems, as well as the classification of causes of action associated with specific component failures.

5.5.3.2 Scheduling

Analysis of M&T frequency with nuclear power plant age has shown that frequency generally decreases with plant age (characteristic of the "learning" process). However, Rancho Seco, which has only been commercially operable for about three years, had a total of only three M&T errors, possibly demonstrating more efficient M&T scheduling and/or administrative control.

Available data does not lend itself to an optimum scheduling analysis, however, it does identify the implementation of scheduling changes

(usually an increase in frequency, though there are instances of scheduling frequency decrease due to component malfunctions from excessive usage).

Plant M&T procedures and schedules can be reviewed for the identification of individual plant practices, and compared with M&T error frequency (available from the present study). This will enable the determination of attributes resulting in optimum scheduling programs. These attributes can be characterized according to plant type, vendor, A/E, and utility for the construction of optimum M&T programs based upon similar characterizations. Past individual system and component performance will be strongly considered to ensure that recommended M&T practices do not become generalized and instead are localized programs with respect to individual systems and components.

Preventive maintenance (PM) schedules will also be thoroughly characterized. It is anticipated that facilities with strong PM programs will exhibit faster learning tendencies, suffer fewer forced outages, and have fewer personnel errors (especially related to maintenance since an excellent PM program would lead to fewer major repair tasks, with a resultant decrease in the frequency of personnel-component interaction).

Equipment maintenance problems focus upon scheduling maintenance actions for LWR plants. Maintenance actions are classified as inspections, which are intended to obtain information about the operational status of system components, and repairs and/or replacements, which are intended to restore the operational status of those components judged to be unsatisfactory. Equipment maintenance problems arise when inspection and repair actions are costly. In scheduling maintenance actions, the inspection and repair costs must be weighted against the benefits expected from prolonged satisfactory operations and improved safe system operation. Repair costs are incurred from parts and component installation. More important, repair procedures in complex industrial equipment often involve extended shutdown periods and the associated costs of production down-time.

Inspection costs are incurred when the operational status of system components cannot easily be determined. For example, equipment components

may be accessible only during shutdown and after safety precautions have been taken. When the existence of hazardous conditions, such as cracks in structural components and excessive rates of corrosion do wear, is not revealed during normal system operation, the level of damage in these components often involves an appreciable expense. This situation is exemplified by the primary reactor coolant system in nuclear reactors. Careful design and strict operating control procedures are employed to limit the possibility of coolant system failure (leakages and/or rupture) due to fatigue crack growth, stress corrosion, or brittle fracture. In addition, periodic inspections are employed as a means of reducing the hazards associated with coolant system failure and the resultant loss of cooling to the reactor. System components are not easily accessible and currently available techniques for crack detection must be adapted to comply with special requirements imposed by the nuclear environment. Thereby, the reactor must be shutdown during the inspection procedures.

In other applications the equipment may have been designed not for continuous operation, but rather for operation under emergency conditions. Emergency conditions frequently lead to high temperatures and/or stresses. System capability to function properly under extreme environmental conditions must be assessed by a testing program. Inspection costs are incurred when verification tests of an operational readiness are conducted. Sometimes the test program, being designed to assess the effects of extreme environmental conditions, imposes additional stresses on equipment components so that the required number of tests (inspections) should be kept at a minimum. Test programs for the verification of leak tightness in containment systems for nuclear reactors illustrate this inspection and repair problem. The containment system is designed to prevent excessive release of radioactive contaminants and is required to perform this function only in the unlikely event that a nuclear accident occurs.

The applications already mentioned illustrate the special features of the nuclear plant which impose stringent requirements on maintenance operations. One arises from the limited accessibility of reactor plant components resulting in increased complexity of inspection procedures. The other involves nuclear safety considerations. To ensure continued safe

operation, reactor safety systems, usually called "engineered safety features" are provided to limit the probability of occurrence or the consequences of accidents in the nuclear reactor. The Emergency Core Cooling System (ECCS), designed to maintain core cooling capability after failure of the Reactor Coolant System is an example of an engineered safety feature. Others are the containment system designed to shut off the nuclear chain reaction whenever one of a number of safety limits is exceeded. Since these safety systems are not operating under normal plant conditions, but only in the case of an emergency, their operational readiness must be verified by periodic testing procedures (inspections).

Literature review and analysis of health physics records have shown that the distribution of cumulative doses (man-rem) among the major work functions of the personnel at power reactor facilities continues to be the major contributor of occupational exposure.

Radioactive doses received during maintenance and testing require further collation for the determination of those specific tasks leading to significant exposures and the frequency of occurrence.

A study may be conducted for the identification of scheduling of strategies leading to the minimization of radiation exposure during M&T tasks. Criteria which might be expected to influence radiation dose rates to M&T personnel include:

- Systems/component design
- Administrative control
- Health physics programs
- Manpower availability
- Facility age
- M&T frequency

These and any other criteria which are determined to be significant can be analyzed amongst facility records for the determination of optimum M&T schedules which can lead to ALARA dose rates.

5.5.3.3 M&T Simulation

A Monte Carlo simulation could provide the following information:

- The probability that an M&T event is due to a specific component type
- Locating the system which has the specific component as part of it
- Location of component
- Impact on component
- Importance allocation
 - If interest is in plant performance, i.e., whether it is going to trip, remain operating at reduced power level, or nothing will happen to the power level; then a certain set of importance (or weight) factors are to be given to each type of event, e.g., a valve in position x in system y is stuck, a weight is given to this mode; if the valve has a different failure mode, a different weight is given; hence, a set of weighting factors are given to each valve position in each system.
 - If interest is in the amount of activity released to the environment; then a completely different set of weighting factors are to be given to the components in specific positions, in every system and for each failure mode.
 - If interest is in the radiation exposure to plant personnel, then the weighting (or importance) factors would be proportional to the length of time the failure would take to repair and the radiation level in the working area, or man-rem; the higher this number is, the higher the weighting factor for the component in that system having that failure mode.

The choice of these weighting factors can be made by using a "sensitivity test procedure, as follows:

- First a number of trails has to be chosen. This is done by continuously picking events until the percentage of the output counters (for the performance levels) to the total event numbers stabilize within a certain confidence limit (e.g. 90%). These runs are made for an assumed set of weight factors.

- Each weighting factor is changed and its effect on the output is noted.
- The "critical" weighting factors, which have the most effect, will be picked up and a better choice can be made based on these factors.
- Quality levels are varied and the effects on the numbers accumulated in the memory locations are monitored and compared with the average numbers of such events that are obtained from the data collected, e.g., out of the 385 events collected (maybe) 3 involved radiation release in excess of x curies; hence, the percentage of radiation release in excess of x curies is $0.78x$. Now, out of the (say) 10,000 events processed above, how many involve radiation release in excess of x curies (assuming we are calculating this case)? If the percentage figure is quite different, then the level is changed (the level represents activity level) or some of the weighting factors are changed. Therefore, a trial and error procedure is carried through, by continuous comparison with actual numbers obtained from the data collected until a reasonable set of choices are obtained.

During M&T, personnel are exposed to radiation. It may be possible to reduce radiation exposure by, e.g., changing the layout of certain components, or extra shielding, etc. Example: a pump to be maintained lies in a high radiation area. If it is moved to a lower radiation area, extra piping and valves may have to be installed. Radiation exposure per maintenance event is decreased but the number of events may increase due to the extra valves and pipes. Hence, changing the position of such pumps all over the plant might lead to an overall increase in total man-rem. The objective would be to look for the portion of such pumps to be changed to give an overall minimum exposure (man-rem).

5.5.4 Statement of Work

TASK 1 GENERAL ANALYSIS OF HARDWARE FAILURE AND M&T PROBLEMS IN LWR POWER PLANTS BASED ON PATTERN RECOGNITION PRINCIPLES

A methodology would be developed to determine the expected frequencies of component failure or M&T problems in a reactor system based on reported events from the nuclear facilities and to classify causes of action that are highly associated with particular component failure or M&T problems

in various systems. The methodology will be developed in the form of a computer program that utilizes as input the field data for M&T problems and component failure. The task will be divided into three subtasks.

Subtask 1.1 Methodology Selection

There are various techniques for clustering and pattern recognition. Thus, appropriate techniques will be selected which are applicable to analysis of M&T and component data. The selected approach may be modified by the use of other statistical methods.

Subtask 1.2 Methodology Development

The methodology will be developed and provided in a format suitable for application. Computer programs will be developed with sample problems.

Subtask 1.3 Application

The methodology will be applied to identify generic component failure and M&T problems.

TASK 2 OPTIMIZATION OF M&T SCHEDULES

An approach for evaluating the effect of inspection and repair actions and maintenance and testing schedules on LWR safety and operation performance will be developed and an optimum M&T schedule frequencies based upon past experience at commercial LWR's will be determined. The optimization will be based upon minimization of radiation exposure, cost and risk to the plant. The task includes the following subtasks:

Subtask 2.1 Model Development

A stochastic model of component deterioration and failure in complex equipment will be developed. The model would enable evaluation of the merits of alternative inspection and repair schedules, and possibly the optimization of the schedule in terms of the cost criterion

selected in a particular application. Emphasis would be upon situations in which the inspection costs are not negligible in comparison with the other cost components (repair costs and failure costs).

Subtask 2.2 Optimization Criteria

Objective functions will be identified based upon minimization of radiation exposure cost and maximization of maintainability for assuring plant safety or risk minimization. Also, appropriate constraints will be identified.

Subtask 2.3 Methodology Development

The methodology will be developed and tested for practical applications to M&T scheduling.

Subtask 2.4 Data Acquisition

Data on current M&T scheduling practices for specific tasks will be gathered from utility companies. Also, the plant exposure records will be reviewed to identify critical M&T tasks. Evaluation of maintenance requirements in each M&T task, as well as sequencing, will be made.

Subtask 2.5 Data Analysis

Correlations will be made between schedules and M&T tasks will be constructed to identify the various elements involved in scheduling.

Subtask 2.6 Optimal Scheduling

An optimal schedule will be developed for a representative plant.

Subtask 2.7 Applications

The optimal M&T schedule will be tested on the selected plant for final evaluation.

TASK 3 M&T SIMULATION

A Monte Carlo Simulation of various M&T tasks will be developed to identify the root causes of M&T problems and their impact of LWR components. The Monte Carlo simulation of M&T events with radiation exposure as the response function (or output) will be formulated. The model is perturbed until an optimum radiation exposure (man-rem) is obtained. This task involves 2 subtasks.

Subtask 3.1 Monte Carlo Simulation

Develop an appropriate Monte Carlo simulation using data sources on M&T events. The data is to be used in calculating the frequency of failure type caused by M&T problems. Determine the root causes, impact on components/systems, and relative importance of M&T problems.

Subtask 3.2 Optimization of M&T Tasks

The following procedures may be used.

- A table of random numbers is generated to represent random failures.
- A number is picked from this table and decisions are made as to what kind of component that has failed, in which system it lies, and what kind of failure it is.
- A rank is given to this event (e.g., 0-10) that represents the man-rem received for this maintenance event when this component is in its present location. Example: a rank of 10 indicates that man-rem received is greater than 20; a rank of 9 is (15-20) man-rem; etc.
- A performance index is calculated that includes all probabilities associated with frequencies of occurrences of such events.
- A large number of events are calculated and a total performance index is obtained.
- The whole procedure is repeated with certain components at different positions and hence different ranking numbers. A different total performance index is obtained. The procedure is repeated until a minimum index is obtained which is going to represent the minimum radiation exposure and the required number of changes necessary.

5.5.5 Schedule

	FY										
	80	81	82	83	84	85	86	87	88	89	90
1. Pattern Recognition											
1.1 Methodology Selection											
1.2 Methodology Development											
1.3 Application											
2. Scheduling											
2.1 Model Development											
2.2 Optimization Criteria											
2.3 Methodology Development											
2.4 Data Aquisition											
2.5 Data Analysis											
2.6 Optimal Scheduling											
2.7 Applications											
3. M&T Simulation											
3.1 Monte Carlo Simulation											
3.2 Optimization of M&T Tasks											

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