BNL-NUREG-38934

CONF-8610135--39

OPERATIONAL SAFETY RELIABILITY RESEARCH*

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BNL-NUREG--38934

TI87 003230

ABSTRACT

Operating reactor events such as the TMI accident and the Salem automatic-trip failures raised the concern that during a plant's operating lifetime the reliability of systems could degrade from the design level that was considered in the licensing process. To address this concern, NRC is sponsoring the Operational Safety Reliability Research project. The objectives of this project are to identify the essential tasks of a reliability program and to evaluate the effectiveness and attributes of such a reliability program applicable to maintaining an acceptable level of safety during the operating lifetime at the plant.

Achieving high availability of safety systems involves both controlling the configuration of safety systems so that sufficient safety equipment is always available and providing safety systems that function reliably when challenged.

This research found that some if not most reliability program tasks are presently performed by many utilities without formal reliability programs. The differences are that reliability technology allows prediction of potential problems before they result in deteriorated reliability; a reliability program identifies reliability technology that can be used to perform these tasks so that preestablished reliability targets are met; a reliability program provides techniques for monitoring equipment performance, and alerting when pre-defined reliability targets, consistent with safety goals, are not met by actual equipment performance; and a reliability program involves a discipline by which each task is performed in a way that is consistent with the risk from the problem, thus focusing resources on risk important problems.

1. INTRODUCTION

The purpose of this paper is to describe, relative to reactor safety, what a reliability program is, what it can do, the status of reliability technology, and the research team's assessment of the attributes and effectiveness of a successful reliability program.

*This paper is based on work done under auspices of the U.S. Nuclear Regulatory Commission as part of the Operational Safety Reliability Research Project and as reported in NUREG/CR-4618. The project team was A. Azarm, J. Boccio, J. Carbonaro, R. Hall, and C. Ruger for BNL and E. Lofgren, E. Dougherty, J. Fragola, and W. Vesely for SAIC.

Operating reactor events such as the TMI accident and the Salem automatic-trip failures raised the concern that during a plant's operating lifetime the reliability of systems important to safety might degrade from the designed level that was considered in the licensing process, Generic Issue II-C-4.

To address this concern, organizations such as NRC, DOE, and EPRI sponsored surveys of reliability techniques that have proven successful in aerospace and commercial-aviation industries. NRC-sponsored studies included a Rome Air Development Center survey of Air Force reliability techniques, applications by NASA Kennedy Space Center of system assurance analysis, and an Argonne National Laboratory project to synthesize previous results into an interim reliability program.

In May 1985, Brookhaven National Laboratory (BNL) based on the above studies began the evaluation which is the subject of this paper. The objectives of this project are to identify the essential tasks of a reliability program and to evaluate the effectiveness and attributes of a reliability program applicable to maintaining an acceptable level of safety during the operating lifetime of a nuclear power plant.

This project emphasized reliability programs applicable to operating nuclear reactors. Use of these programs in the design phase would also facilitate meeting design safety objectives for nuclear reactors, but the project reported herein does not treat this subject. The decision to omit the design phase was based on the need to have a manageable short-term scope and the fact that new design work is currently limited.

As an example, Figure 1 shows a top level work breakdown structure that illustrates the role of an operational reliability program in achieving an acceptably low core-melt frequency for the lifetime of a given plant. As illustrated in this figure, achieving a low core-melt frequency involves achieving both a low frequency of challenges to safety systems and a high availability of safety systems. Achieving high availability of safety systems involves both controlling the configuration of safety systems so that sufficient safety equipment is always available and providing safety systems that function reliably when challenged.

As illustrated at the bottom of Figure 1, reliability programs should play a central role in minimizing challenges and in providing safety system reliability when challenged. In addition, reliability technology can help operators to perform configuration-control functions. Thus the role of a reliability program is to provide a method for achieving and maintaining an operational safety goal. A parallel example could be constructed at the plant release or societal risk level.

The objective of such a program is to assure that reliability is maintained for equipment that is performing within the set goals and to improve the reliability of equipment that is not performing within goals, or is experiencing preventable failures.

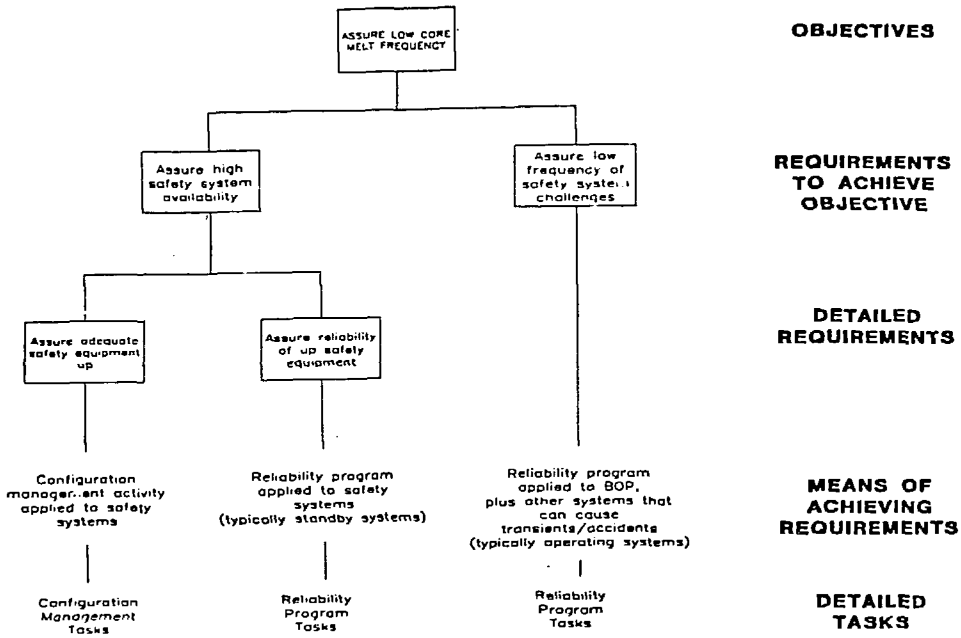

Figure 1. Top-level work breakdown structure for reliability program role in assuring low core-melt frequency.

Some if not most reliability program tasks are presently performed by many utilities without formal programs. However, the program identifies technology that can be used to perform these tasks so that pre-established performance targets are met. Also, the technology allows prediction of potential problems before they result in deteriorated safety. A reliability program provides techniques for monitoring equipment performance and alerting when the pre-defined reliability targets, consistent with safety goals, are not met by actual equipment performance. The developed reliability program involves a discipline by which each task is performed to a level that is consistent with the risk from the problem, thus focusing limited resources on risk important problems.

This research was based in part on reviews of current needs and practices and on a field application as listed below.

- Case studies that included a survey of utilities that have adopted reliability programs, to obtain their experience actually using these programs.

- Review of generic safety issues, abnormal occurrences and precursor events to obtain an indication of the potential impact that adoption of reliability programs by the industry would have on these safety issues.

- A trial application of reliability program technology to the Trojan Emergency Power System.

2. STRUCTURE OF A RELIABILITY PROGRAM

This section explains the elements of a reliability program and how it works. There is no one optimum way of setting up a program, but certain tasks and structure will generally exist, as described in the following subsection.

There are logically definable characteristics which a reliability program must have if it is to accomplish its objectives. Obviously, the program must provide means for recognizing a reliability problem (and, conversely, recognizing when equipment reliability is satisfactory, so that NRC and plant resources are not inappropriately applied to non-problems). The program must also be capable of anticipating, or predicting, potential reliability problems based on evaluations that show design or testing inadequacies, vulnerability to common cause, and observed non-catastrophic deterioration in equipment. If a reliability problem is predicted or diagnosed, the program should provide a means to prioritize it, to correct it in a time frame commensurate with its priority, to assure that the corrective actions have been applied, and to close out the problem when assured of effective corrective action. To summarize, the top-level tasks performed by a reliability program to accomplish the stated objective are:

- problem prediction and recognition,
- problem prioritization and correction, and
- problem close-out.

Application of these top-level tasks constitute a closed-loop process in the sense that as reliability problems are predicted or detected, corrected, and closed out, the emphasis returns to the problem detection task to assure that the corrective action has been effective. This closed-loop process is illustrated in Figure 2. Referring to the figure, problem detection is accomplished by two types of processes: a problem prediction (or prognostic) process, and a problem recognition (or diagnostic) process. Once a problem has been detected, it is prioritized and corrected on a schedule commensurate with its priority. Problem closeout assures that the corrective action applied has been effective. After problem closeout, normal monitoring of equipment performance ensues, assuring that the problem does not recur, and that other reliability problems do not appear.

To more explicitly define the reliability program process, a closed loop process is shown in Figure 3 and described below.

<u>Task: Assess Reliability in Design and Operations</u>

This task represents evaluation of equipment and operations to determine if conditions exist that may result in eventual deterioration of reliability, or that may allow cost effective improvements to reliability or availability. This task uses applicable technology to perform a prognostic function, in the sense that potential problems are uncovered before they manifest them selves in deteriorated reliability of equipment or systems.

Actual work elements, or subtasks necessary to perform this task include the collection of plant-specific and industry wide information, the establishment of reliability targets, and the review of design and operations for reliability adequacy.

Information, particularly industry wide, is collected from INPO, NRC data studies, and manufacturers advisories that may harbinger potential performance problems at the plant, or that may indicate particular assessments that should be performed to ascertain if potential reliability problems exist. Reliability targets are derived to be consistent with top-level safety goals or with other standards of performance such as historical operating performance, industry standards, or experience with equipment of the same general type in similar applications. Since the targets must be consistent with top-level safety goals, the first requirement is to specify the top-level goal, or performance target. The working targets are defined to be consistent with this safety goal or performance target. Finally, design and procedure possibly impacting risk are assessed for adequacy.

<u>Task: Monitor Reliability Performance</u>

The work embodied in this task is to monitor the reliability performance of equipment. This monitoring process includes both reliability monitoring (e.g., the direct monitoring of failure frequency, outage rate, etc.), and condition monitoring (e.g., monitoring conditions that are related to failure, such as acoustic vibration spectral densities, degraded and incipient conditions, etc.). This plant-specific information can be used directly to detect or predict reliability problems, or can be combined with industry-wide information to provide a larger data base for the same purpose.

An assessment is made of requirements for monitoring the equipment, which includes an assessment of dominant failure modes for the equipment, failure frequency, equipment engineering conditions that can be monitored and that are related to equipment failure modes, repair frequency, etc. Also, engineering requirements for setting demand test intervals are considered. Based on these requirements, an equipment surveillance schedule is devised which will suit both the purposes of monitoring the equipment to detect any reliability problems in a timely fashion, and testing the equipment to assure an acceptable probability of its being in an operating condition. This schedule is reviewed to be consistent with any technical specifications that may apply to equipment testing frequency. The result is the surveillance schedule for the equipment, including (for standby equipment) demand test frequency, the frequency of any visual or tear-down inspections, and any condition monitoring schemes including the frequency with which the monitoring should be conducted. Lastly, this task includes the operational activities of actually performing the monitoring activity, and assuring that information from the monitoring activity is input to an appropriate data base.

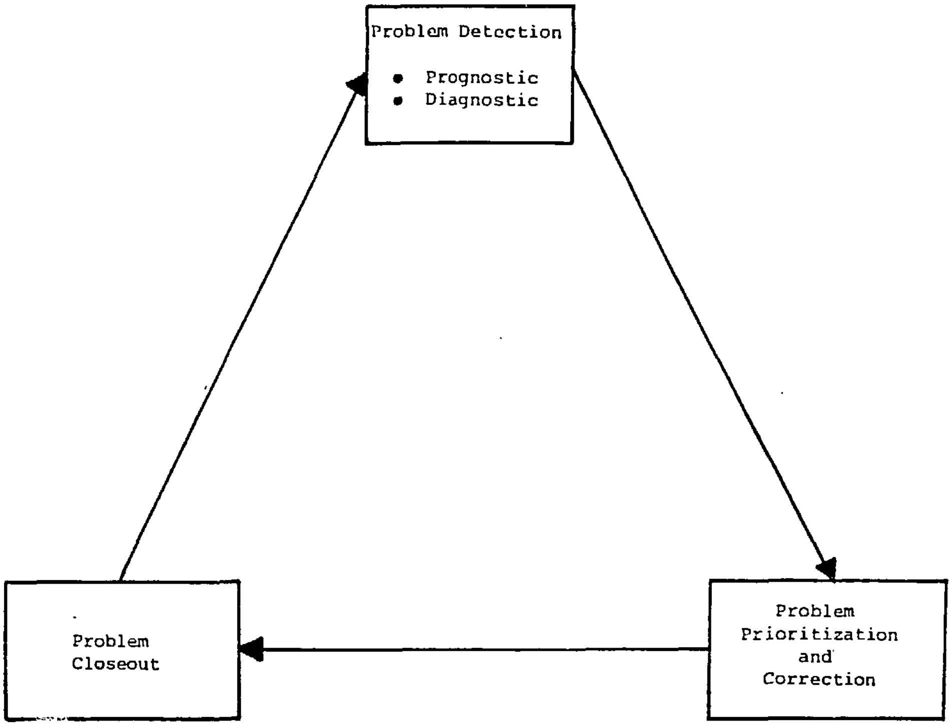

Figure 2. Reliability program objective. Maintain acceptably low likelihood of core melt frequency throughout plant lifetime.

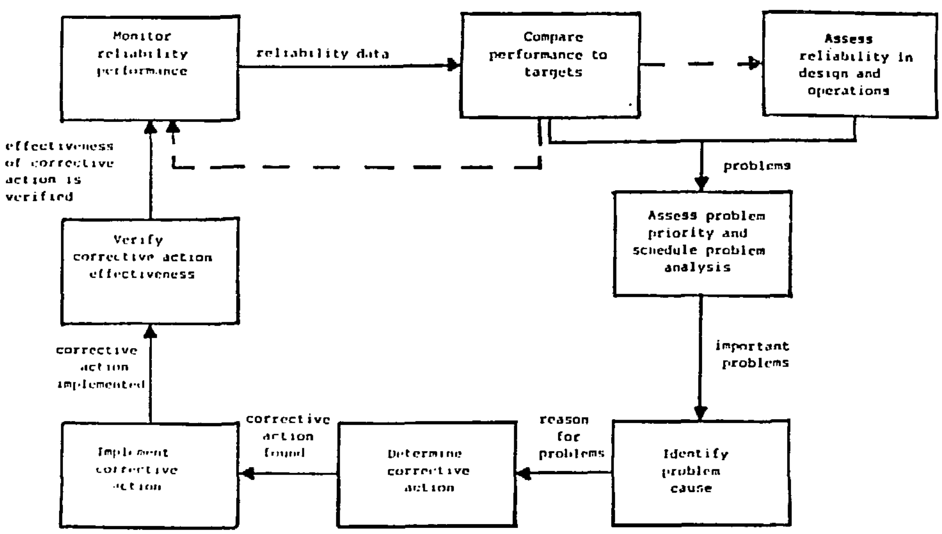

Figure 3. Reliability program process.

Task: Compare Performance to Targets

The work defined by this task is to compare the actual reliability performance of equipment as measured by the previous task to a specified target performance for the equipment. This is the process of comparing actual measures of performance indicators to alert levels. (The alert levels can be derived directly from reliability targets, and, since the reliability targets are consistent with the safety goal, the alert levels also will be consistent with the safety goal). If a reliability problem is indicated, then the succeeding tasks in the reliability program process are performed. If no problem is indicated, then routine monitoring of the equipment performance continues.

Task: Assess Problem Priority

The problem prioritization task provides the technology to focus attention on reliability problems that have the greatest adverse impact on risk. The role of this task is to prioritize reliability problems as they arise, and to prioritize reliability related changes to design and operations.

When an alert has been violated indicating that a reliability problem has been discovered, the problem is characterized according to the risk importance of the equipment, severity of the problem, and prognosis for correcting the problem without causing plant evolutions that may themselves be risk significant. The priority of the problem is obtained by a consideration of these factors. Scheduling of the problem depends on the priority, and on the backlog of problems requiring attention and resources.

First, equipment importances are estimated, and it may be convenient to partition equipment by importance into "bins" or categories. The equipment's importance to risk depends on its role in preserving a safe configuration of the plant. (There are a variety of techniques for assessing equipment importance, ranging from formal analysis techniques such as PRA, to engineering judgements by knowledgeable plant personnel.) Next, severity of the problem is assessed. For instance, it could be prudent to delay repair of an incipient or degraded (i.e., non-catastrophic) component failure until the next scheduled downtime to avoid the impact on risk from removing the equipment from service. Similarly, it may be less risky to delay a redesign or reconfiguration until the next scheduled downtime if there is a chance of this action causing a transient. Such decisions involve risk tradeoffs that should be explicitly considered. Finally, an assessment is made of other circumstances that could impact the problem priority. For instance, the importance of an auxiliary feedwater turbine pump may change significantly if the plant derives power from an unstable grid and has currently been experiencing emergency power diesel generator problems. The priority of the reliability problem is assessed based on the foregoing considerations, and problem analysis is scheduled accordingly.

Task: Identify Problem Cause

After the reliability problem has been prioritized, the next task in the reliability program process is to identify the cause of the problem to a depth commensurate with its importance, and sufficient to be able to devise an effective corrective action. Information for judging the depth at which to pursue the problem cause analysis includes engineering judgment on the part of plant personnel, a knowledge of the priority of the problem from the previous task, and any information that can be obtained from the way the problem was detected. Based on this information there should be a set of formal or informal guidelines for specifying the depth to which the cause analysis should progress. The cause analysis, possibly involving engineering root cause investigations, will then be conducted to the specified depth.

This task differs from what is currently done by plants without reliability programs in that the additional information obtained through use of reliability technology assesses the effort that should be put into cause analysis and aids in specifying the type of cause analysis to use. Thus, performance of this task as part of a reliability program will assure that the depth of the cause investigation will be consistent with the risk-relevance of the problem.

Task: Determine Corrective Action

This task is also currently performed by plants without reliability programs. As with the previous task, reliability technology will supply additional information so that corrective actions can be determined in a more systematic, effective way.

Information concerning the nature of the reliability problem from the problem detection and problem cause analysis tasks, as well as information from industry wide sources, is used to define (if possible) options for corrective actions. These options are listed and then ranked according to defined corrective action objectives. The actual correction to be applied is chosen from the list based on its projected performance versus the objectives.

Task: Implement Corrective Action

As with the previous two tasks, this task is performed by plants without reliability programs. However, reliability technology assures a more systematic performance of this task, such that the utility and the NRC can be assured that the decided-upon corrective action will indeed be implemented and that the corrective action will either be effective in eliminating the reliability problem, or a new approach will be tried. The technology adds the capability of prioritizing the implementation of the corrective action to achieve the maximum risk benefit and scheduling the corrective action. Even though the problem to be resolved is important, it may be necessary or prudent to delay implementation for one reason or another. If implementing the corrective action requires removing essential equipment from service and if the problem does not result in immediate catastrophic failure, it may be risk beneficial to wait for the next scheduled outage before implementing the corrective action. Although "band-aid" repairs are usually to be avoided, there are times when such repairs may be risk beneficial when compared to alternatives. This determination should be made within the concept of a reliability program, where the risk impacts of the alternatives are systematically identified and assessed.

Finally, criteria for problem closeout including enhanced monitoring where necessary would be defined in terms of reliability or engineering specifications.

Task: Verify Corrective Action Effectiveness

This task represents the feedback feature of a reliability program. Provision is made, in terms of procedures, to verify that the action deemed necessary to correct a high priority reliability problem was indeed implemented, and that this corrective action eliminated the reliability problem. This task provides documentation of problem close-out containing a description of the problem, the corrective action devised to solve it, the result of monitoring during the trial period following implementation of the corrective action, and the resolution of the problem at the end of the trial period (i.e., either the problem is closed out or there is a requirement to modify the corrective action before the problem can be closed-out).

3. TRIAL APPLICATION

In order to gain experience and test the conceptual approaches, a trial application was conducted in cooperation with the Portland General Electric (PGE) Company. The particular system under investigation was the emergency diesel generator system at PGE's Trojan plant. The trial application integrated reliability technology into routine operational activities to help in:

1. controlling and monitoring performance against set goals,

2. recognizing deviations from these goals, prioritizing important deviations and identifying their root cause, and

3. taking corrective actions and tracking the effectiveness of the actions taken.

The primary focus was on the operational activities currently conducted at the Trojan plant to maintain the reliability of the emergency diesel generator system and how insights in enhancing these operational activities can be gleaned from reliability technology.

The methodology used was largely based on the reliability techniques, tasks, and activities outlined in Section 2 of this paper. This was implemented in this application through a four-stage process to seek approaches and develop strategies for improving or maintaining the system reliability. Within this process, the effectiveness of current diesel generator tests was specifically examined to identify problems (or potential problems) and determine their causes.

As will be further described, the current surveillance tests did not detect all failure modes; however some of these failure modes were determined not to be crucial to the operability of the diesel generators. Statistical techniques were employed to systematically address the objectives of condition monitoring in detecting abnormal behavior of these components.

Accordingly, the trial application process utilized addressed the three basic top-level tasks of a reliability program (Figure 2) in that it accomplished the objectives of reducing the frequency of transients, controlling faults that challenge safety systems, and providing assurances that a safety system functions properly when called upon to mitigate abnormal occurrences.

Reliability program tasks, activities, and techniques that have been employed in this study are depicted in Figure 4, which also portrays the process employed to analyze, identify, prioritize, and resolve either recurring or potential Figure 5 further details problem identification, problem resolution, and corrective action implementation tasks.

Reliability block diagrams, failure modes and effects analyses, and fault trees were developed to identify existing faults which may prevent emergency ac power supply in the event of loss of off-site power (LOSP) for a LOSP initiating event, the system boundary not only included the support systems required for performing the desired system function, but also portions of logic systems designed to assess the functional performance of the diesel generator system.

Reliability block diagrams were constructed of each diesel generator subsystem to identify the system success paths. The logical simulation of functional failures at the system and train level was provided by constructing fault trees at the subsystem level and obtaining cutsets at the train/system level. In addition to constructing and analyzing the fault trees/block diagrams, failure modes and effects analyses were employed to verify this "top/down" approach as well as to identify failure effect and assess the adequacy of tests to discover component failures. Using existing data (generic or plant specific), major components of the system were prioritized to indicate the potential consequence of an undetected failure.

With this information, a four stage approach can be undertaken in order to eventually develop a reliability program plan for the emergency ac power system. The steps considered necessary to develop a system-specific reliability program plan include the following:

System Analysis - This stage identified critical components from system/ train level fault trees.

For each dominant cutset, the possibility of recovery actions was investigated by review of the FMEA sheets and the plant's Off-Normal Instruction (ONI) procedures. The possibility of human-induced common mode failures during test and maintenance was also examined. This process was repeated at the diesel generator train level in order to identify additional critical components. On the basis of insights gleaned from the system/train fault ees, the critical component list was developed. Analysis of plant experience data was also used to supplement this list.

Operational Activity Analysis - This stage identified operational activities that can be used to improve component reliability through (1) rapid detection of failures, (2) timely and proper corrective maintenance, and (3) effective preventive maintenance and condition monitoring schemes.

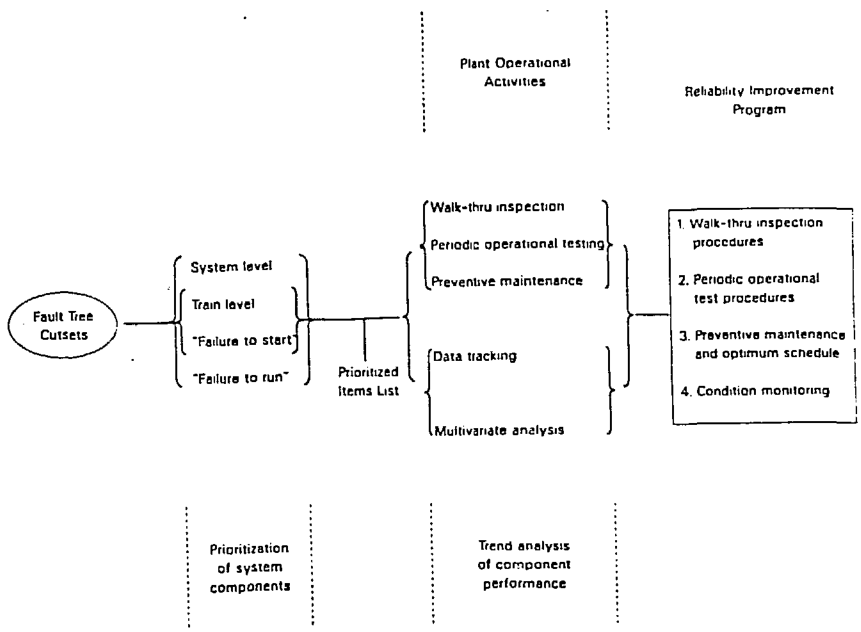

Figure 4. Reliability techniques used to enhance plant operational activities.

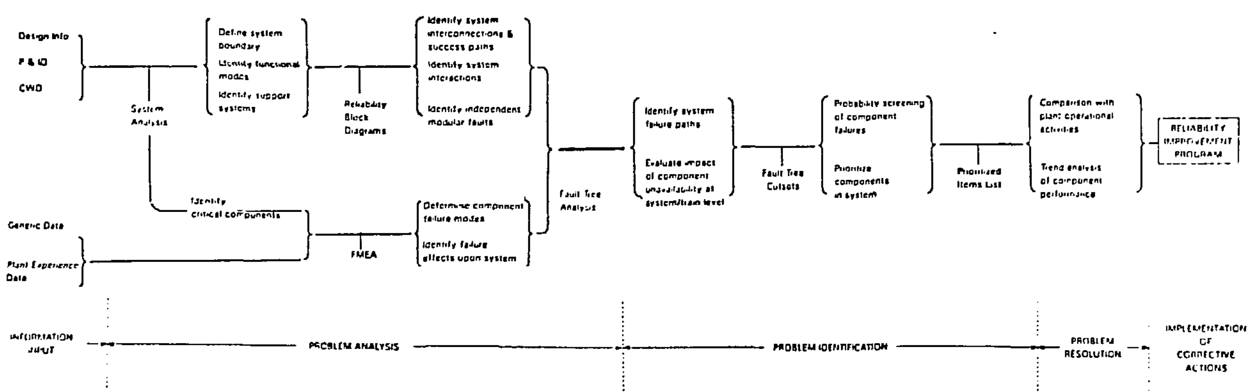

Figure 5. Methods used in prioritizing system components for reliability improvement.

Investigations into timely and proper corrective maintenance activities focused on those controlling measures that could assure performance were performed. The role of preventive maintenance and condition monitoring in detecting critical component degradation on the basis of parameters measured during periodic operational testing and triggering performance of preventive maintenance. Recommendations were developed for these operational activities requiring that (1) for each critical component a set of measurable parameters is defined for a condition monitoring scheme and (2) a refueling outage program and schedule be developed to help detect degraded components.

Reliability Improvement Analysis - The effectiveness of recommendations made in the previous two stages that impact component level reliability enhancement were quantitatively analyzed, and the improvements in reliability that accrue for the diesel generator set and for the entire emergency power system were investigated.

Reliability Performance Analysis - The analysis conducted thus far concentrated on those operational activities which, when implemented, could improve system reliability. This stage, which has not been yet undertaken will concentrate on how to effectively monitor risk and reliability performance. This stage of the overall process identifies two types of indicators: performance indicators and effectiveness measures. Performance indicators determine the reliability of the emergency ac power system; effectiveness measures determine the outcome of the operational activities in achieving reliability performance.

Components that contribute to unavailability of the emergency ac power system were identified on the bases of the plant-specific data analysis and fault tree analysis. Plant-specific data were analyzed from available maintenance records, while the system fault tree model analysis utilized a generic data base for quantification.

The diesel generator experience data for the Trojan nuclear plant were obtained by analyzing maintenance work requests from 1983, 1984 and the first 5 months of 1985. A total of 91 maintenance records were examined and each diesel generator failure was categorized by severity, engine condition at the time of fault detection (standby or running), stress cause, repair category, and effect upon the system (immediate or long term). The severity of a diesel generator failure was ranked according to three degrees: (1) catastrophic, (2) degraded, and (3) incipient. The results presented indicate that catastrophic failures are largely caused by failures in electrical components. Degraded and incipient failures are dominated by faults in mechanical components.

The fault tree model of the Trojan emergency ac power system (EPS) provided the basis for analyzing EPS failures at various levels of system unavailability. The multi-level analysis was used to identify the dominant component failures at four levels: (1) the unavailability of the emergency ac power system, (2) the unavailability of one train of emergency ac power, (3) the failure of one tandem unit to start, and (4) the failure of one tandem unit to run (or operate) after a successful start. This included a critical component methodology and truncation values. The resulting integrated list of critical components based on the fault tree analysis is given in Table 1.

The identification of critical components that cause system unavailability on the basis of integrating fault tree evaluation with plant-specific data analysis shows a more complete mix of "active" and "passive" components that may fail the system. About 30% of these components are electrical while the rest are mechanical components.

The list was used to systematically analyze the adequacy of current operational reliability activities at Trojan and to identify areas where component reliability can potentially be improved. Strategies for reliability enhancement were developed for implementation considerations. The list also aided in reviewing surveillance test requirements and prevention versus corrective maintenance strategies.

Table 1

Integrated List of Critical Components

1. Field flashing circuit
2. Generator excitation circuit
3. Voltage regulator (automatic/manual)
4. Diesel generator "Start/Run" control circuit
5. Circuit breaker 152-108 closing coil
6. Generator lockout relay (186-1D1, 186-1D2)
7. Generator stator winding
8. Service water/jacket water heater exchanger
9. Service water motor-operated valve
10. Main lube oil pump strainer
11. Lube oil scavenging pump strainer
12. Air compressor unloader
13. Jacket water thermostatic control valve
14. Engine main bearings
15. Camshaft/timing gear
16. Generator bearing/coupling
17. Generator slip-rings and brushes
18. Crankshaft-to-piston connecting rod
19. Lube oil scavenging pump
20. Main lube oil pump
21. Engine jacket water pump
22. Crankshaft
23. Fuel oil day tank outlet valve
24. Lube oil cooler
25. Turbocharger aftercooler
26. Engine crankcase pressure instrument
27. Expansion tank
28. Annunciator
29. Engine speed control switch
30. Fuel oil transfer pump breaker
31. Voltage regulator selector switch

Quantitative analysis has shown that the overall system reliability of the Trojan emergency diesel generators is high (96.7%); however the detailed analysis of current operational activities to maintain this reliability indicates areas requiring improvement. The specific areas are walk-through inspection, periodic operational testing, and preventive maintenance for critical components that were prioritized from plant experience data, fault tree analysis and FMEA. The detailed results of this trial application are described in Wong, S.M., et al, "Trial Application of Reliability Technology to Emergency Diesel Generators at Trojan," BNL Technical Report A-3282, April 1986.

4. SUMMARY OF CONCLUSIONS

In this subsection, the major findings and conclusions developed from the project to date are summarized, under separate headings.

Reliability Program Tasks and Structure

Eight reliability tasks were identified as important for accomplishing the objective of assuring low core-melt frequency for the plant lifetime. Several of the tasks (Reliability Monitoring, Comparison of Achieved Reliability to Targets, Assessment of Reliability in Design and Operations, Problem Prioritization) are not performed by plants unless they have adopted systematic use of reliability technology. Reliability technology currently exists to perform each of this latter set of tasks, although projected developments in the technology through continued research would result in even more effective performance of these tasks.

Performance Tracking and Alerts

Risk-based performance tracking and alerts were developed and demonstrated on a small scale pilot basis in this project. The performance tracking methods can be developed for use by both an individual plant (at the component, train or system level), or by the NRC (at the plant level). When developed, the measures and alerts can be chosen to be consistent with a safety goal.

Test Adequacy and Efficiency Evaluations

A variety of techniques was demonstrated that had the objectives of illustrating impact on reliability of test inadequacy and inefficiency, and illustrating techniques to evaluate and specify surveillance of standby equipment that would avoid inadequate tests. The demonstrations were conducted as a trial application on the emergency diesel generator system at the Trojan nuclear power plant.

It was found that the reliability of the hypothetical system would degrade over time if the redundant trains were tested simultaneously rather than individually. Thus, the results of such testing inadequacies are similar to the results from equipment aging, a gradual decrease in equipment reliability with time.

A fault tree and FMEA approach, applied to the Trojan diesels and supporting subsystems, demonstrated that test adequacy can be verified or predicted by an analytical approach. In this analysis, the most important (from the standpoint of reliability) cutsets were identified. Surveillance was proposed that would assure that failures of the elements of these cutsets could be detected in a timely way.

Optimum testing intervals were demonstrated for the Trojan diesels by partitioning catastrophic and non-catastrophic diesel failures into standby stress related and demand stress related categories. This data analysis permits deriving optimum demand test intervals for the diesel generator trains, in the sense that test intervals can be chosen that will minimize diesel unavailability.

Maintenance Effectiveness Measure

A preliminary approach for identification of an effectiveness measure for the preventive maintenance program was developed through evaluating a component's reliability during periodic test as a function of various preventive maintenance strategies. It was found that even though reliability of the tested component increased as the preventive maintenance policies improved, component reliability would not be an appropriate measure for evaluating effectiveness due to response time lag and the fact that component reliability is not an independent parameter sensitive only to preventive maintenance. The measure which is more directly related to these policies was identified as the ratio of the number of repairs of degraded failures to the total number of repairs.

Reliability Program Role in Resolving Safety Issues

Generic safety issues, abnormal occurrences, and precursors were evaluated to determine if implementation of reliability technology would be effective in resolving or preventing them. A number of the safety issues were judged to be addressable by use of reliability technology as embodied in a reliability program.

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