Failure-Cause Analysis: Turbine Bearing Systems

Phase I, Development of Data Collection Plan

EPRI CS-1801-SY
Project 1265-3
Summary Report
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Prepared by
Franklin Research Center
Philadelphia, Pennsylvania

ELECTRIC POWER RESEARCH INSTITUTE

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Philadelphia, Pennsylvania

ABSTRACT

This report comprises the summary of the first of a three phase study intended to investigate rotor/bearing/lube system-related failures in large capacity ($\geq$ 300 MW) turbine/generator units. The objectives of Phase I were to: 1) identify and tentatively rank the proximate/root causes of generic problems that result in failures of the rotor/bearing/lube system, 2) determine the nature of the available data and select the appropriate methodologies for both data collection and analysis, and 3) develop the data collection plan to be implemented during Phase II.

These objectives were accomplished by: surveying existing data bases, relevant literature and technical personnel; implementing fault tree methodology to identify potential root causes; establishing an integrated analysis approach to maximize the value of the information available; and finally, structuring a data collection plan based on a mail survey of all utilities having unit capacities greater than 300 MW, on-site visits to selected utilities, and personal interviews with industry experts.

The successful completion of Phase I has established the foundation for the subsequent phases of this study, the goal of which is to formulate recommended, ranked research and development programs to minimize outages due to turbine/generator rotor/bearing/lube system-related failures.

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PROJECT RESULTS

Based on information gathered from published literature and interviews with technical personnel from utilities and manufacturers, a tentative ranking of proximate root causes of bearing failures was made. Various methodologies for data collection and analysis were reviewed and analyzed. Final selection of methodologies most appropriate to these processes was made with respect to criteria such as degree of accuracy, data availability, and cost. Finally, a data collection plan was developed, which consisted of an EEI-sponsored mail survey of all relevant utilities, on-site visits to selected utilities, and interviews with technical personnel from manufacturers and consultants. The implementation of this data collection plan will take place in Phase II of this project.

The work performed in Phase I has produced an efficient methodology to determine the proximate root cause of bearing-related turbine-generator failures. Coupled with an effective corrective action program, the results of this project will significantly improve the reliability of fossil power plants.

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project, RP1265-3, is one of several failure-cause analyses being conducted by the Fossil Plant Performance and Reliability Program to identify and define the root causes of major generic design, operation, and maintenance problems responsible for utility power plant outages. Based on the analysis of available EEI data in previous EPRI investigations, failures attributable to turbine bearing systems are one of the leading causes of forced outages in turbine-generators. Although these data have been useful in identification and ranking general categories of plant and bearing problems, the information is not specific enough to define the underlying or root causes of these failures, which is the main purpose of this project. Phase I of this project produced a detailed basis for gathering data on failures of turbine-generator bearing systems through the development of a data collection plan, and the results of this work are the subject of this summary report. Phase II will implement this plan by gathering and organizing information for specific examples of problem categories defined in Phase I. The data compiled in Phase II, which is scheduled for late 1981 completion, will be analyzed in Phase III to identify the generic nature of the major failure categories and the root causes attributable to these failures. Phase III will be completed in early 1982 and will be followed immediately by the final project report.

PROJECT OBJECTIVES

The objective of Phase I of this project was to perform an evaluation of available data sources and fault logic formulations and to prepare a complete data collection plan for turbine bearing system failures.

The overall objectives of this project are:

- To identify and define the root causes of generic problems that produce failures of bearing and lubrication systems
- To define the relative importance of each of these generic problems
- To develop plans for a research and development program to address the significant problems identified

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Section 1

INTRODUCTION

This report provides a summary of the first phase of an overall three-phase program entitled: "FAILURE-CAUSE ANALYSIS: TURBINE BEARING SYSTEMS", sponsored by the Electric Power Research Institute (EPRI) under EPRI Contract No. RP1265-3 and being performed by the Franklin Research Center (FRC). A complete report* on Phase I has been prepared and is available from EPRI upon request (see Appendix for details of its contents).

*Interim Report, Phase I, Development of Data Collection Plan, Failure-Cause Analysis: Turbine Bearing Systems, Palo Alto, CA, Electric Power Research Institute Report No. CS-1691, 1981, prepared by the Franklin Research Center under EPRI Contract No. RP1265-3.

Section 2

BACKGROUND AND PURPOSE OF THE OVERALL PROGRAM

The increasing demand for more electrical power at competitive cost during the past several decades has resulted in a marked increase in the generating capacity of new power plant units to the point where unit capacity on the order of 1000 MW is not uncommon. As has been the case with other classes of modern-day machinery, the increase in size and capacity of power plant units has resulted in relatively high levels of unit failures (outages) compared to their smaller-sized predecessors. Moreover, the penalties, in terms of outage cost and lost power generation, are correspondingly much more severe for the larger units.

The average equivalent availability of large fossil-fired power plants, with unit sizes of 600 MW or more, is significantly lower than for smaller plants. Statistics compiled by the Edison Electric Institute (EEI)* show that during the 10-year period, 1967-1976, the average equivalent availability of such large plants was less than 68 percent, compared with 75 percent to 85 percent for fossil-fired plants in various smaller size categories. In addition, the equivalent forced-outage rates for power plant units greater than 600 MW average 21.4 percent, compared with an average of less than 8 percent for smaller units.

Of the 21.4 percent equivalent forced-outage rate reported for these large units, "bearing systems" accounted for 1.44 percent (i.e., approximately 7 percent of the 21.4 percent equivalent forced-outage rate due to any and all causes). Furthermore, while comprehensive statistics are not currently available, it is believed that failures associated with the bearing systems are also responsible for a significant proportion of the more than 32 percent loss of equivalent availability experienced by these units. In terms of fiscal penalties, failures

*Report on Equipment Availability for the Ten-Year Period, 1967-1976. New York, N.Y.: Edison Electric Institute, December 1977, EEI Publication No. 77-64 and a companion report, namely, Equipment Availability Component Cause Code Summary Report for the Ten-Year Period, 1967-1976. New York, N.Y.: Edison Electric Institute, January 1978, EEI Publication No. 77-64A.

of bearing systems impose an annual financial loss upon the utility industry estimated to be in excess of 150-million dollars. Here, the "bearing systems" of interest are those which are used to support, guide and locate the rotor of the steam turbine and generator, both of which are major equipment groups. Outages of power plant units due to failures of the turbine/generator bearing systems are reported under EEI Outage Cause Code Numbers 630, 631, and 701.

The premise of this study* is that industry organizations, manufacturers, utility companies, engineering firms, and insurers have available a significant amount of data on bearing/lubrication system failures. If these data are systematically organized and analyzed it should be possible to identify important generic failure patterns. The primary objectives of the overall program, therefore, are to

- Identify the root causes of generic problems which result in failures of turbine/generator bearings and lubrication systems used in large-size power plant units,
- Establish the relative importance of these generic problems, and
- Develop plans for a recommended research and development program to alleviate the root causes of turbine/generator "bearing system" failures.

Through such a program, it is anticipated that significant increases in power plant availability (with attendant reduction of monetary losses) can be achieved.

In order to accomplish the objectives of this study, the program has been divided into the following three chronological phases:

- Phase I - Development of the Data Collection Plan
- Phase II - Information Collection and Organization
- Phase III - Information Analysis and R&D Recommendations

This summary report describes the approaches used and the results obtained in the Phase I effort. A complete outline of the topics covered in detail in the Phase I Interim Report is shown in the Appendix to this summary report.

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*EPRI Contract No. RP1265-3. "Failure-Cause Analysis: Turbine Bearing Systems."

Section 3

OBJECTIVES OF PHASE I

The goal of Phase I was to identify, structure and delineate the plan for the subsequent collection of data during Phase II. To accomplish this, the work was broken down into three tasks. These were:

- Task 1: Problem Identification and Ranking

  The objective of this task was to identify and tentatively rank the root causes of generic problems that resulted in failures of bearings and lubrication systems in large-size turbine/generators. A secondary goal of this task was to establish the priorities of the pertinent data to be collected and to compile the necessary technical background information relevant to rotor/bearing/lube system problems.

- Task 2: Methodology Selection and Data Requirements

  The objective of this task was to determine the nature of the data available in terms of quality, accuracy, cost, etc., and to select those methodologies most appropriate for both data collection and subsequent analysis.

- Task 3: Development of Data Collection Plan

  The objective of this last task of Phase I was to develop the actual data collection plan to be implemented during Phase II. This included specifying the kinds of information to be collected as well as the methods to be used to obtain the data.

Section 4

APPROACHES AND RESULTS OF PHASE I

TASK 1: PROBLEM IDENTIFICATION AND RANKING

Preliminary Identification of Proximate/Root Causes of Turbine Bearing System Failures

It was recognized that the successful and meaningful accomplishment of the objectives of this task could not be achieved by applying the knowledge, expertise and experience of the personnel of any one organization. Accordingly, Task 1 began with the exploring and exploitation of numerous information sources, each having their own special interests, roles, insights, and pertinent technical information concerning the loss of steam turbine/generator availability due to problems associated with their "rotor/bearing/lube systems". The principal information sources utilized to gather the pertinent technical information required for identifying and ranking the root causes of "Rotor/Bearing/Lube System"-related problems included the following:

- Relevant published literature
- Technical personnel of domestic and foreign manufacturers of large steam-driven turbine-generators
- Technical personnel of an electric utility. Note: During Phase II (data collection) of the overall program, a more extensive survey of and site visits to electric utilities will be conducted.
- Personnel of the National Electric Research Council (NERC) who are responsible for the maintenance of the Edison Electric Institute (EEI) data base.
- Unaffiliated technical consultants having long-term backgrounds of experience in the various life-cycle phases of large-size steam turbines.

To identify potential "causes" of steam turbine loss of availability (due to rotor/bearing/lube system-related problems) a "fault tree" methodology was used. Implementing the fault tree methodology begins with the single top event (effect) and works progressively downward (backward in time), identifying an expanding number and network of intermediate events (modes) and of lower level events (proximate causes), ending up with the lowest level events (root causes). For purposes of this study, the top event of interest was loss of availability of the unit due to rotor/bearing/lube system failure, and the principal intermediate events of interest were those that are recognizable symptoms of operational distress, each of which, in turn, reflect the effect of lower-level proximate/root causes. Table 1 provides a synopsis of the results of Task 1. Included in the table are the principal distressful operational symptoms along with their possible causes thus far identified.

Tentative Ranking of the Proximate/Root Causes of Turbine Bearing System Failures

Ideally, the preferable method of ranking the impact of failure causes is to compress all relevant factors related to each root cause into a single measure, such as dollars, in order that a ranking can be made along a single dimension. Any deviation from a one dimensional scheme would be significantly more complicated since it would involve a determination of the weighting factors, or measures of relative importance, of each dimension.

The single measure chosen must encompass both the frequency and the severity of the various failure modes. A comprehensive measure of severity would not only have to take into account lost megawatt hours of generating capacity, but also the various classes of outages. Additionally, complex factors such as the quantification of safety hazards and the risk of utility rate increase disapproval would also have to be reduced to the single measure. Because of the difficulty of including these external system types of factors directly within the ranking scheme, they must be considered indirectly as ranking modifiers.

Although final ranking of failure causes is not possible until the data collection process (Phase II) has been completed, preliminary ranking has been determined based primarily upon frequency of failure and average forced outage hours experienced by U. S. manufacturers on their units of 500 MW or more (see Table 2). This preliminary ranking may be markedly modified during Phases II and III when equivalent availability is taken into account as well as the information provided by the utilities, insurance companies, and the National Electric Reliability Council (NERC).

From Table 2, the major cause of failure (comprising about 40 percent of the total forced outage incidents related to bearing system problems and over 50

Table 1

SYNOPSIS OF PRINCIPAL SYMPTOMS OF BEARING SYSTEM OPERATIONAL DISTRESS AND THEIR POSSIBLE CAUSES THUS FAR IDENTIFIED

Symptoms of Bearing System Operational Distress	Possible Causes of Bearing System Operational Symptoms Thus Far Identified
Excessively Low Bearing Supply-Oil Pressure	• Failure of automatic control aspects of the main, standby and emergency pumps of the lubrication supply system • Excessive contamination of the oil in the lubrication system
Excessively High Bearing Temperatures	• Excessively contaminated oil in the bearing oil-film(s), (most common cause) • Bearing misalignment (rotor-to-bearing surfaces) • Bearing overload (due to loss of load-sharing alignment or abnormal admission of steam)
Excessively High Rotor Vibration	• Bearing rotor-whirl (due to loss of load-sharing alignment), (most common) • Rotor unbalance (due to loss of rotating hardware, e.g., loss of turbine blades) • Rotor whipping (due to rubbing or steam whirl) has also been reported
Excessively Contaminated Oil*	Inadequate or improper lubricant purification system with regard to: • design, • installation, • flushing, • oil-sampling, • utilization, • maintenance, • repair
Excessively High Axial Displacement of Rotor	• Excessive wear of thrust bearing (due to excessively contaminated oil) • Excessively high water induction in the turbine steam paths • Malfunctions of axial displacement measuring devices
Failures of Bearing Babbitt Liners and/or Journals	• Excessive wear of babbitt and scoring of journals (due to dirty oil) • Pitting erosion of babbitt by electrical discharges (due to faulty grounding brushes) • Babbitt fatigue (due to poor bonding or excessively high vibrations)

*Excessively contaminated oil can result in an extended and/or scheduled outage.

Table 2

PRELIMINARY RANKING OF ROTOR/BEARING/LUBE SYSTEM-RELATED FAILURE CATEGORIES BASED UPON THE OPERATING EXPERIENCE OF TURBINE UNITS OF 500 MW AND GREATER

	Number of Incidents				Four Year Summary				
	Year				Total Incidents		Forced Outage Hours		
Failure Category	1976	1977	1978	1979	No.	(Pct.)	Hours/ Incident	Total Hours	(% F.O.H.)
Contamination in Oil Systems	17	19	14	9	59	(39%)	350	20650	(54%)
Failure of Backup Oil Pumping System	4	6	1	2	13	(9%)	1000	13000	(34%)
Inadequate Repair or Installation	7	2	5	1	15	(10%)	130	1950	(5%)
Bearing Wipes Due to Oil Whip Instability	5	8	5	2	20	(13%)	40	800	(2%)
Other Bearing Failures	4	7	3	0	14	(9%)	100	1400	(3.5%)
Other (Mainly, Misc. Component Failures)	6	8	9	7	30	(20%)	20	600	(1.5%)
Total	43	50	37	21	151	(100%)	254 (avg)	38400	(100%)

Note: This table represents a synthesis of information obtained in widely varying format from U.S. manufacturers only. The numbers and categories should be regarded as rough approximations.

percent of the forced outage hours) was attributed to oil contamination. This compilation indicates that dirty oil has the highest impact of any broad category of bearing-system-reliability problems. This was also the subjective consensus of personnel interviewed at the electric utility and at the U.S. manufacturers of large-size steam turbines.

The failure of backup-oil-pumping systems apparently caused about a third of the forced outage hours, although these types of failures accounted for only 9 percent of the total number of incidents. The causes associated with these failures were due to operational problems or equipment failure. As a consequence of the catastrophic nature of these incidents, we would tentatively rank backup system failures as second in impact.

Failures associated with inadequate repair or installation of the rotor/bearing/lube system were ranked third due to the severity of these incidents, as measured by average downtime. Although this category ranked third in impact, it was well below the first two failure categories since it accounted for only 5 percent of the total forced outage hours and 10 percent of the total incidents.

All remaining failure categories accounted for about forty-two percent of the total incidents of forced outages, although only seven percent of the total outage hours. Included in these groups are the following: (1) bearing wipes due to oil whip instability; (2) other bearing failures (thrust bearing failures, tilt pad spragging, wipes caused by stick-slip, other journal bearing failures); and (3) others (thrust bearing wear detector failures, rotor instabilities, and miscellaneous component failures).

Problems due to oil whip were less severe (in terms of the average forced outage hours per incident) than all categories except the last one. Oil-whip problems accounted for thirteen percent of the incidents, but only two percent of the forced outage hours. Most of these incidents were associated with startup following installation or overhaul.

The "Other Bearing Failure" category, comprising nine percent of the incidents reported, ranked fourth out of the six categories in severity and accounted for less than four percent of the downtime period. The root causes in this category were often associated with wearout or installation considerations.

Finally, the "other" category, although comprising 20 percent of the incidents, resulted in the least severe failures and, as a consequence, accounted for less than two percent of the forced outage time attributed to rotor/bearing/lube systems.

TASK 2: METHODOLOGY SELECTION AND DATA REQUIREMENTS

Selection of Methodologies for Data Collection and Analysis

The original objective of the methodology selection task was to review various existing formulations of fault logic and to select the technique that would most efficiently and effectively lead to the identification of the root causes associated with turbine rotor/bearing/lube system failure. However, information gathered during Task 1 indicated the need for establishing appropriate methodologies for both data collection and analysis since the selected techniques had to not only address the problem of identification but also the problems of establishing reliability parameters, ranking root causes and prioritizing R&D alternatives.

Whereas the selection of a data collection methodology was relatively straightforward, the selection of the data analysis methodology was more involved and complex. Consequently, comprehensive evaluation criteria were established to aid in the evaluation and selection of the available techniques. Since no single selection criterion, such as cost of implementation, provided sufficient information to facilitate adequate selection, a multidimensional selection process was implemented to evaluate each candidate methodology in relationship to the specific program objectives under consideration. Ten criteria were chosen to provide the evaluation framework. They included:

1. Implementability
2. Ability to Integrate Objective and Subjective Data
3. Comprehensiveness
4. Data Availability
5. Computational Feasibility
6. Ease of Communication
7. Accuracy of System Representation
8. Ability to Perform Sensitivity Analysis

9. Timeliness

10. Cost

Each candidate analysis technique appropriate to a given program objective was rated and ranked along each selection criteria by the project team. The Phase I report discusses, in detail, the twenty-three methodologies which were judged to be potentially useful for data collection and analysis.

The net result of the evaluation process by the project team indicated that multiple techniques would be appropriate for each of the program study objectives. Utilization of any specific methodology, especially those dealing with qualitative information, is primarily a function of the nature, scope and depth of quantitative data available during Phase II. Thus, a number of methods selected are contingent in that they would be employed only to the degree necessary to supplement available quantitative data. The overall framework of the recommended methodologies selected is shown in Figure 1 and is termed the "Integrated Analysis Approach"; integrated in the sense that there is at least one methodology directed towards each of the program objectives, and that these techniques, along with study data sources, interact to yield the desired information. It is seen in Figure 1 that an appropriate mixture of quantitative (e.g., Analysis of Categorized Data, Failure Rate Analysis, Fault Trees, Cost/Benefit Analysis, etc.) and qualitative (e.g., DELPHI Technique, Scenario Evaluation, Elite Interviewing, etc.) methodologies have been selected for implementation in subsequent phases of the program.

Data Requirements

From Task 1, it was determined that base operating data is available from essentially three sources, namely, existent data bases, field studies, and specific system studies of turbine bearing failures conducted by manufacturers and/or utilities. Additionally, information related to research and development activities, including appropriate technological projections and associated cost/benefit trade-offs, is also available from R&D groups within EPRI, turbine bearing system and related equipment (i.e., filtration systems, pumps, etc.) manufacturers, selected utilities, insurance companies and the academic community.

A review of these data sources indicated that the required depth and breadth of information necessary to adequately perform the subsequent program phases was not

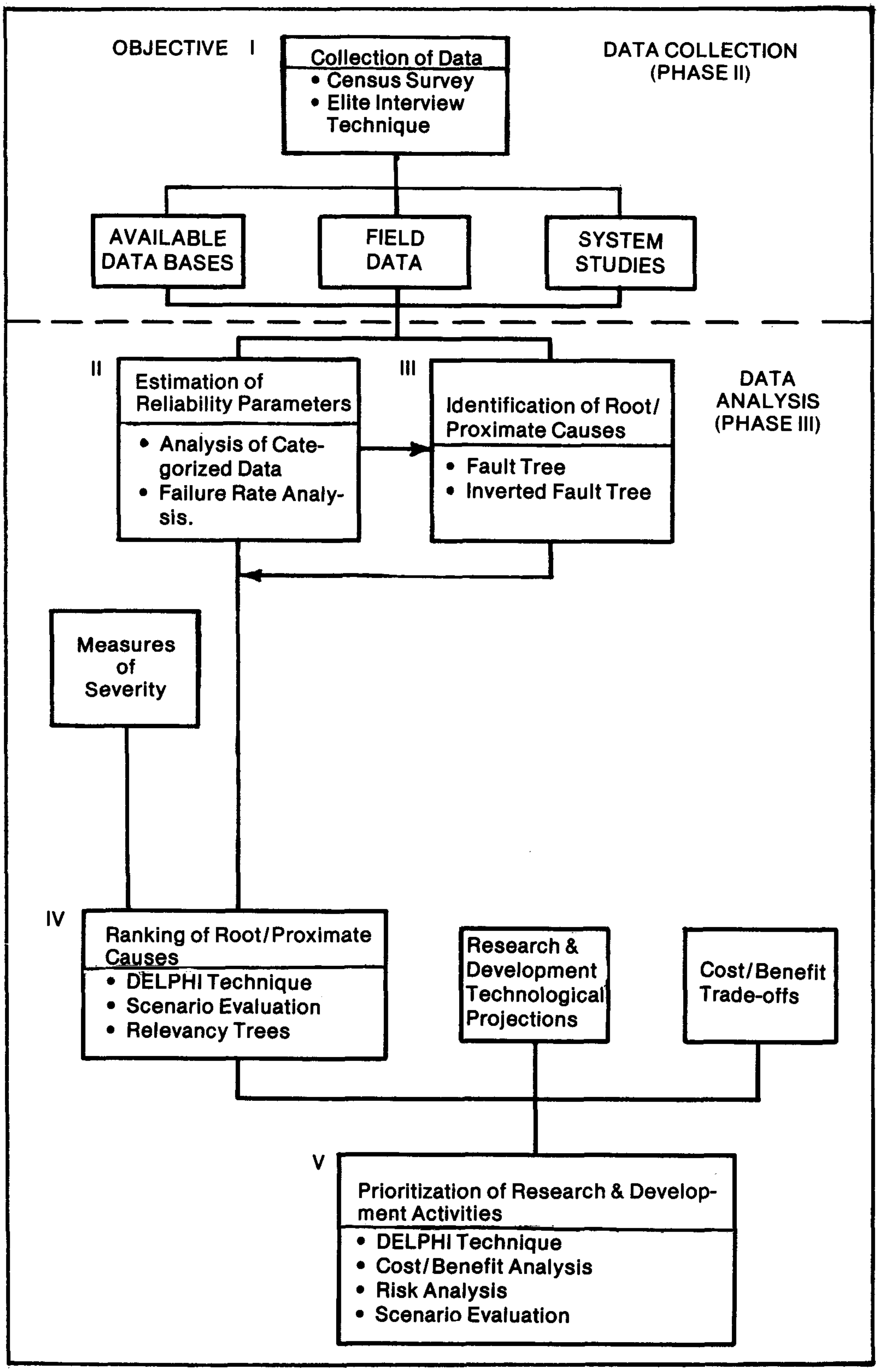

Figure 1. Integrated Analysis Approach Methodology/Informational Relationship

readily available. Generally, these data bases were found to be either too specialized or too broad to be appropriate. In addition, preliminary field interviews with both manufacturers and utilities indicated the relative scarcity of objective, quantitative data related to turbine bearing failures. A major information gap was thus apparent. Additional information sources and/or collection mechanisms therefore had to be identified to supplement existing data. The recommended solution was to supplement the available quantitative data with qualitative information primarily based upon the experiences and insights of turbine systems users, manufacturers and experts. As a result, the Integrated Analysis Approach was created in order to maximize the value of information that could be extracted from these combined data sources.

TASK 3: DEVELOPMEMT OF DATA COLLECTION PLAN

In order to successfully execute the analysis of the loss of availability in large-size units due to turbine-bearing-system problems, data from several sources must be collected and analyzed: published papers, reports and monographs; data bases maintained by EEI, the Nuclear Regulatory Commission (NRC) and others; consultants and insurers; utilities and manufacturers. A literature survey has already been conducted and the various data bases reviewed as part of Phase I. These sources will be studied in the second phase of this project. A summary of the data collection plan follows.

The basic structure of the plan (see Figure 2) consists of three principal data gathering activities:

- a mail survey of all utilities, primarily to obtain basic data on losses-of-availability (due to rotor/bearing/lube system failures) of units having capacities greater than 300 MW;
- visits to ten selected utilities to obtain more detailed information;
- interviews with industry experts to arrive at a conclusion of the most important failure causes and the most potentially beneficial research programs.

The mail survey will be followed up with the mailing of a report of the results of the survey to the utilities. As data is collected, a data base will be constructed and both qualitative and quantitative information will be systematically stored for subsequent analysis in Phase III.

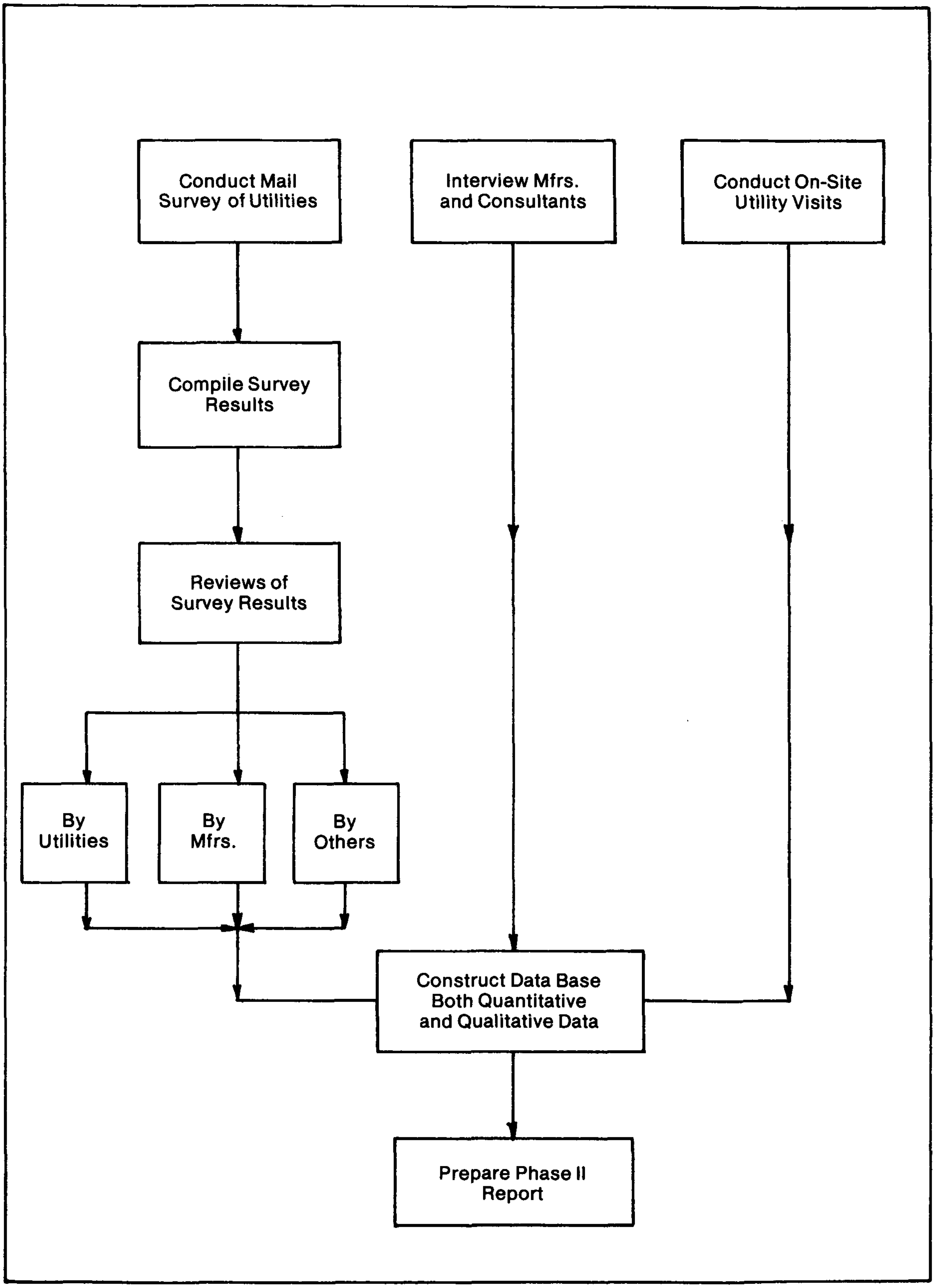

Figure 2. Basic Structure of the Data Collection Plan Recommended for Phase II

The utility mail survey will consist of several activities. First, the survey logistics will be specified; this includes obtaining the names of the utilities and their associated EPRI liaison party to be contacted to obtain the necessary information. Second, the survey instrument will be designed and pilot tested. Third, the questionnaires will be mailed. Lastly, follow-up will be required for nonrespondents and the returned questionnaires will be edited and processed.

Utility site visits represents another major effort associated with data collection. One initial visit will be conducted prior to the completion of the mail survey, primarily as a pilot test of the site visit agenda and procedures. However, most of the visits will be scheduled after the mail survey in order to use the survey data as an aid in the utility selection process. The utility visit logistics will include compiling an agenda, making appropriate contacts and scheduling activities. While at the utility, project team members will conduct meetings and interviews, review records, and inspect hardware.

The data base established by the end of Phase II will contain all the objective and subjective information and failure frequency data obtained in the course of the data collection phase. The data will be organized so that all useful cross-tabulations and statistical analyses can be easily executed. Phase II will conclude with a report summarizing the data collection and fully documenting the turbine bearing system data base.

Section 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The primary objective of Phase I of the study was to establish the appropriate foundation and framework for subsequent phases of the overall program. Project effort during Phase I was concentrated in three areas:

- Rotor/bearing/lube-system-failure problem identification and ranking
- Data collection and data analysis methodology selection and data requirements
- Data collection plan specification and development.

Preliminary causes of failures were identified and ranked (see Tables 1 and 2); an Integrated Analysis Approach, consisting of preferable analysis methodologies was developed (see Figure 1); and a data collection plan was constructed considering anticipated information requirements and the recommended analysis methodologies to be employed (see Figure 2).

Specifically, Phase I objectives were achieved by reviewing the state of the art (both with respect to general reliability methodology and turbine-bearing system technology), assembling the available failure frequency data (from existing data bases and turbine manufacturers), obtaining expert opinions (from a utility, several major turbine-generator manufacturers and independent industry consultants) and applying the knowledge, experience and expertise of the project team concerning data analysis and survey methodology. All of these activities were directly reflected in the development of the recommended data collection plan for Phase II. Also, all these activities were used in the compilation of preliminary event trees to identify failure modes and causes of bearing-system failures. The preliminary ranking of the major categories of failure causes presented (Table 2) is based upon forced outage failure frequency data provided by the major U.S. manufacturers of turbine-generators for their units of 500 MW or greater.

The foundation and framework thus being in place, the subsequent steps are to collect and disseminate the information in Phase II in accordance with the data collection plan developed during Phase I. In addition, the methodologies established in Phase I and data collected during Phase II will be utilized to perform the Phase III final ranking of root/proximate causes. Lastly, research and development programs will be recommended to improve availability of generating units with emphasis on cost/benefit tradeoffs.

Appendix A

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INTERIM REPORT, PHASE I, DEVELOPMENT OF DATA COLLECTION PLAN
FAILURE CAUSE ANALYSIS: TURBINE BEARING SYSTEMS
[Electric Power Research Institute Report No. CS-1691, 1981, prepared by the Franklin Research Center under EPRI Contract No. RP1265-3]

Section

1 INTRODUCTION

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Methodology Selection

Data Requirements

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The "Oil-Film Bearings/Mountings" Sub-System

The "Housings/Pedestals/Foundations" Sub-System

The "Lubrication Supply/Return/Reservoir" Sub-System

The "Lubricant/Purification" Sub-System

The "Instrument/Alarm" Sub-System(s)

Section

The "Controls" Sub-System(s)

The "Human Interfaces" Sub-System

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Theory of Hydrodynamic Lubrication and Analytical Predictions of Bearing Performance Characteristics Based on Laminar Flow

The Effects of Turbulent Flow Conditions in the Hydrodynamic Bearing Oil Film

The Effects of "Misalignment"

Oil-Flow Heat Balances

Fixed vs. Movable Bearings

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Durations of Unplanned Outage Classes

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Lower-Level Proximate Causes of Event No. (T.2) ("Manual Trip Initiated")

Lower-Level Proximate Causes of Class 5 Unplanned Outages [Event No. (E), "Scheduled End-Time of Planned Outage Exceeded"]

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Root Causes of Excessively High Vibration

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Root Causes of Excessively Contaminated Oil
Root Causes of Failure of Bearing (Babbitt) Liner
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Criteria for Ranking of Failure Causes
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Recommended Data Collection Methodology
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In-Depth Utilility, Vendor and Expert Interviews
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Qualitative Methods of Data Analysis
Criteria for Data Analysis
Analysis Methodology Survey
Analysis of Categorized Data
Cost/Benefit Analysis
Decision Theory
Decision Tree Analysis
DELPHI Technique
Exponential Models
Factor Profile Analysis
Failure Analysis Data System (FADS)
Failure Modes, Effects and Criticality Analysis
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Fault Tree Analysis
Inverted Fault Tree
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Markovian Analysis
Matrix Method
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4 TASK 3. DATA COLLECTION

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APPENDIX A LITERATURE SEARCH AND REVIEW OF TURBINE BEARING SYSTEMS

APPENDIX B METHODOLOGY REFERENCES

APPENDIX C REFERENCES FOR SOFTWARE APPLICATION OF VARIOUS METHODOLOGIES