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# System and Equipment Troubleshooting Guide (Update to 1003093)

2020 TECHNICAL REPORT

# System and Equipment Troubleshooting Guide (Update to 1003093)

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# ABSTRACT

Troubleshooting and knowledge transfer were focus areas in the power industry at the time this guide was developed. This guide is intended to aid in both areas.

In regard to troubleshooting, this guide will provide an overview of the troubleshooting process and provide the best practices used by Electric Power Research Institute (EPRI) members in their troubleshooting procedures. Advantages and limitations of the tools used by EPRI members will also be provided. This guide also provides the basis for the Generic Troubleshooting Procedure (attached to this document) that can be applied to a failure or degradation in performance of any process or program, or any system, structure, or component (SSC).

The Generic Troubleshooting Procedure (referenced above) and a troubleshooting knowledgebase have been created to facilitate knowledge transfer. The procedure provides a generic approach to both simple and complex troubleshooting and options for applying failure analysis tools that best fit the problem. It is based on a systematic approach to troubleshooting that is built from the best practices compiled from EPRI members and the contents of this guide. The Preventive Maintenance Basis Database Troubleshooting Knowledgebase (PMBDTK) will aid in rapid development of fault tables during the failure analysis phase by presenting a large library of failure modes, degradation mechanisms, degradation influences, and corrective actions developed through EPRI research and collaboration with members.

The information provided in this report will aid personnel in:

- Understanding the differences between normal operation and maintenance and troubleshooting.
- Understanding and applying tools used in the troubleshooting process.
- Developing troubleshooting plans.
- Using the PMBDTK to rapidly develop fault tables.

### Keywords

Failure analysis
Performance
Root cause
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## Product Title: System and Equipment Troubleshooting Guide (Update to 1003093)

**PRIMARY AUDIENCE:** Personnel involved with troubleshooting systems, structures, or components (SSCs) and processes in power plants

**SECONDARY AUDIENCE:** Power plant station management

### KEY RESEARCH QUESTION

Will consolidating the failure modes inside the EPRI Preventive Maintenance Basis Database (PMBD) and the Nuclear Maintenance Applications Center (NMAC) Troubleshooting Knowledgebase into a single database aid in troubleshooting activities?

### RESEARCH OVERVIEW

Using best practices from 13 nuclear industry troubleshooting procedures, reviewing root cause analysis books, and collaborating with vendors in the problem analysis field, EPRI has developed a guide and accompanying procedure that are intended to provide members the information and instruction necessary to successfully troubleshoot SSCs and processes in power plants.

The information available in the following sources has been merged into the EPRI Preventive Maintenance Basis Database Troubleshooting Knowledgebase (PMBDTK):

- EPRI Preventive Maintenance Basis Database (PMBD) (https://pmbd.epri.com/)
- EPRI Nuclear Maintenance Applications Center Troubleshooting Knowledgebase
- Information inside the many EPRI guides with data applicable to troubleshooting
- Troubleshooting results from members

### KEY FINDINGS

- Troubleshooting is an iterative process.
- Engaging with industry subject matter experts (EPRI and industry working groups), vendors, and organizations that collect operating experience (such as the Institute of Nuclear Power Operations [INPO], the U.S. Nuclear Regulatory Commission [NRC], and the World Association of Nuclear Operations [WANO]) early in the troubleshooting process can expedite the process.
- Many tools used in the root cause analysis process are very applicable to troubleshooting process with slight modification.
- When troubleshooting components in the EPRI PMBD by utilizing the information available in the EPRI PMBDTK, credible failure modes can be quickly populated during failure analysis.

### WHY THIS MATTERS

Troubleshooting and knowledge transfer are focus areas in the power industry. A generic troubleshooting procedure can guide personnel on how to apply the tools at the station to facilitate construction of fault tables during the failure analysis phase of troubleshooting and improve efficiency as well as reducing error.

## HOW TO APPLY RESULTS

Members will have access to the best practices used in the power industry in regard to troubleshooting and the combined knowledgebase from the operational experience accumulated by EPRI and EPRI members by:

- Using this guide to understand the fundamentals of the troubleshooting process.
- Applying the Generic Troubleshooting Procedure.
- Using and providing input to the EPRI PMBDTK.

## LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI members are encouraged to provide feedback on the contents of this guide and procedure for future revisions.
- To ensure that the Preventive Maintenance Basis Database Troubleshooting Knowledgebase (PMBDTK) is updated with the latest information from our members' collective experience, EPRI NMAC encourages members to submit their troubleshooting plans to NMAC for review and inclusion into this database. Troubleshooting plans and/or failure analyses can be delivered to nmachotline@epri.com.

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# 1 TROUBLESHOOTING

## 1.1 Report Purpose

The purpose of this document is to provide guidance to power plant personnel involved in the maintenance and troubleshooting of plant systems, structures, components, and processes. The Nuclear Maintenance Applications Center (NMAC) has developed this document to offer a structured approach to troubleshooting problems. The report aids plant personnel by identifying systematic considerations; offering techniques, suggestions, and cautions; and describing practices applicable to all equipment and systems. A primary goal of the report is to help decrease the time needed to identify necessary actions and restore the system, structure, component, or process to its function as designed. Another goal is to increase the probability that the complete cause of the failure is found so that maintenance or repair activities can be limited to what is required.

Reduction of the error rate in the performance of troubleshooting is also addressed by the use of a controlled process with minimal but necessary reviews and approvals to reduce the potential for error and impact to the station.

Troubleshooting is used to solve many kinds of problems, not just those that occur in station components or systems. The guidance in this report is intended to be applicable both to processes (procedures, programs, personnel performance) and to systems, structures, or components (SSCs).

## 1.2 Report Scope

The scope of this report is limited to the activities typically performed to troubleshoot degraded SSC or process performance and restore it to design conditions. Follow-up activities are discussed in order to put the troubleshooting process in the proper perspective, but those activities are not the focus of the report. The reader is encouraged to reference plant-specific procedures to address these follow-up activities, which might include root cause analysis, design modification, system/equipment performance monitoring, post-maintenance testing, and performance trending.

## 1.3 Intended Users

The generic processes presented in this report are intended for use by utility personnel. The processes were developed for use by either individual troubleshooters or a troubleshooting team. In the context of this report, the term “team” may encompass a single individual or two or more individuals assigned to troubleshoot an SSC or process performance issue.

## 1.4 Basic Concepts and Key Definitions

The generic process for troubleshooting that is presented in this guide has been divided into two main phases – preliminary evaluation and detailed troubleshooting. Section 2 of this report provides a generic process for each of these two phases. For the purposes of this report, the formal process termed *troubleshooting* will be defined as follows:

> **Troubleshooting** – A process that is performed when normal operating and maintenance processes do not exist for a given problem. It is a systematic approach to collecting data, isolating faults, and analyzing abnormal conditions that occur in SSCs or processes that results in high confidence that the complete cause of failure or degradation has been corrected and the SSC or process has been restored to its expected condition. Troubleshooting is required when the scope of normal operation and maintenance is exceeded.

During troubleshooting, existing processes must be manipulated or new processes must be created to identify the optimal solution because work instruction or procedural guidance does not exist. It is for these reasons that troubleshooting must be a systematic approach to collecting data, performing failure analysis to identify the cause, and implementing the corrective actions necessary to resolve events. Proper troubleshooting will result in high confidence that the cause of the failure or degradation has been corrected, and the SSC or process has been restored and can perform its function as designed.

The reader should note that, as defined, the troubleshooting process is not synonymous with root cause analysis, although there are many similarities in the approach to both. *Root cause analysis* is defined as follows:

> **Root cause analysis** – Any method(s) used to identify 1) main and contributing causes of performance problems or adverse trends, and 2) associated corrective action(s) [19]. Root cause investigations are typically performed for significant conditions adverse to quality, and the resulting actions are intended to preclude repetition of the problem or mitigate consequences to an acceptable level. Not all troubleshooting will result in a root cause analysis. For this guide, the term *root cause* will be synonymous with apparent cause.

In some cases, the cause of the degraded performance may be pinpointed to a discrete component or part that is not conforming to design requirements and the reason why has been discovered. For example, the item is out of calibration, has catastrophically failed, or is worn out or damaged. In these cases, the root cause of the degraded system performance was discovered during the implementation of the troubleshooting plan; typically, the only follow-up actions necessary are to document results of the troubleshooting effort and to trend the performance of the restored system/equipment.

In other cases, however, the problem may not get pinpointed to a particular component or part, but there is high confidence that the cause is attributable to a larger assembly that can be removed and replaced with a conforming item. In these cases, the root cause of the problem has not yet been discovered; however, the troubleshooting process has been successful in finding or "bracketing" the general problem, taking the appropriate corrective actions, and restoring the system to design operating conditions. Although the root cause may not have been discovered during the implementation of the troubleshooting plan, there is still a very high level of confidence that the problem will not recur. An example of this in practice would be replacing a skid-mounted pump and motor assembly instead of a damaged impeller. The problem created by the impeller is corrected with the replacement of the pump/motor skid, but the cause of the impeller damage is not known.

*Corrective action* taken to restore system performance is defined as follows:

> **Corrective action** – Action taken to prevent recurrence of identified SSC/process degradation [19]. (Note: This definition is modified from a definition published by INPO, which reads, "action taken to prevent recurrence of an identified adverse condition or trend.")

There are a number of activities that a utility may choose to perform after corrective actions are taken to provide a high level of assurance that the problem will not recur. If the root cause was not discovered during the implementation of the troubleshooting plan, then root cause analysis might be one of these *follow-up activities*. For the purposes of this report, the following definition is provided:

> **Follow-up activities** (as associated with troubleshooting) – Actions that take place after troubleshooting has been completed and the system/equipment is restored to normal operation—for example, root cause analysis or 10CFR Part 21 submittal.

There are several references and organizations focused on root cause analysis; however, there are far fewer references that focus on troubleshooting. Troubleshooting is, in essence, a condensed version of the root cause analysis process, as both are focused on finding the cause(s) of a problem and taking the corrective actions necessary to resolve it. Therefore, the large volume of reference material available on the root cause analysis process will be modified to be applicable in the troubleshooting process.

### *1.4.1 Other Important Definitions*

**assembly.** A combination of subassemblies, components, or both that form a workable unit (for example, control room panels, motor control centers, instrument and piping racks, and skid-mounted equipment) [23].

**credible failure mechanism.** The manner by which an item may fail, degrading the item's ability to perform the component/system function under evaluation [24].

**critical or asset-critical SSC.** A system, structure, or component that has at least one of the following qualities or functions: important to plant operation, safety-related, important-to-safety, security functions, or emergency preparedness.

**event**. A generic term used in this guidance document to describe any failure in a process or SSC when troubleshooting is needed.

**extent of condition**. A review of similar processes or SSCs to determine if the failure that caused the initial event could cause a related event. If so, the vulnerability of the similar processes or SSCs are addressed by creating corrective actions that will apply the learnings from the troubleshooting process to prevent future related events.

**failure**. A mechanism that prevents an item from accomplishing its function [27].

**failure mode**. The effects or conditions that result from an item's credible failure mechanisms or the ways, or modes, in which something might fail.

**failure modes and effects analysis (FMEA)**. An evaluation of an item's credible failure mechanisms and their effect on system/component function. "Failure modes" means the ways, or modes, in which something might fail. "Effects analysis" refers to studying the consequences of those failures. Also known as failure modes analysis (FMA).

**intrusive data collection**. Collection of information that requires physical alteration that may destroy or alter evidence. Data in this category requires physical connection to an open circuit or direct contact with the system process fluid. This may endanger recording and/or preservation of evidence. Examples:

- Lifting leads for use of a volt/ohm meter or installation of a chart recorder, or pressure or temperature gauges subject to process fluid.
- Disassembly and inspection of components by other than installed access/inspection ports that may endanger recording and/or preservation of evidence.
- Operation of components per an approved procedure to obtain data without endangering the recording and/or preservation of evidence [13].

**item**. Any level of unit assembly, including structures, systems, subsystems, subassembly, component, part, or material [28].

**maintenance**. It is acknowledged there are a variety of different types of maintenance, but when performing maintenance is discussed in the troubleshooting process, maintenance is to be considered the activities related to inspecting for and correcting (or resetting) the failure modes that occur in SSCs.

**non-intrusive data collection**. Investigation or troubleshooting that does not normally require physical alteration, interruption, or disconnection of an electrical circuit or direct contact with the system process fluid. Examples:

- Vibration/acoustical diagnostic equipment, thermographic equipment, clamp-on ammeter, contact pyrometer, inspection of components using an installed access/inspection port that does not endanger recording and/or preservation of evidence
- Volt/ohm meter or electrical measurement measuring and test equipment (M&TE) use (for example, recorders) without requiring configuration changes (for example, lifting leads)
- Entering properly authorized passwords into a distributed control system workstation to access alarm, system monitoring, and status information from an installed human/machine interface [13]

**normal operation and maintenance**. A generic term used to define processes that are already defined in operating and maintenance procedures and work orders. Troubleshooting is needed when the scope of normal operation and maintenance is exceeded. This includes abnormal and emergency operating procedures.

**part**. Items from which a component is assembled (for example, resistors, capacitors, wires, connectors, transistors, lubricants, O-rings, springs, gaskets, bolting, and seals) [23].

**preliminary assessment**. Commonly referred to as condition assessment, this is an intrusive initial investigation performed in a timely manner following an event designed to collect as much information as needed in a timely manner to properly develop the problem statement.

**process/processes**. A generic term used in this guidance document to describe any procedure, program, or activity performed by station personnel.

**risk**. The assessment made of the probability of a consequence occurring and the potential impact that could be caused if the consequence does occur.

**root cause**. The fundamental cause(s) and associated corrective action that, if corrected, will prevent recurrence of an event or adverse condition [19]. For the sake of this guide, root cause will be synonymous with "apparent cause."

**system, structure, or component** (SSC). A generic term used in this procedure for the following:

1. System – A group of subsystems united by some interaction or interdependence, performing many duties but functioning as a single unit [18].
2. Structure – An item used to house, enclose, mount, or support components [18].
3. Component – A piece of equipment, such as a vessel, pump, valve, core support structure, relay, or circuit breaker, that is combined with other components to form an assembly. Components are typically designated with an identification number [23].

**troubleshooting team**. Multi-discipline group consisting of station or corporate personnel assembled to solve a higher risk or complex troubleshooting problem. Can also involve vendors and/or manufacturers. Due to advances in technology and connectivity, team members can be local to the station or remote creating "virtual team members."

**troubleshooting lead**. The individual responsible for resolving the event.

### *1.4.2 Acronyms Used in This Report*

| | |
|---|---|
| ANSI | American Nuclear Standards Institute |
| ARC | arc reflection |
| CR | criticality rating |
| EPR | electron paramagnetic resonance |
| EPRI | Electric Power Research Institute |
| FR | frequency rating |
| HV | high voltage |
| ICE | impulse current equipment |
| INPO | Institute of Nuclear Power Operations |

| | |
|---|---|
| LCO | limiting condition for operation |
| LV | low voltage |
| M&TE | measuring and testing equipment |
| MTBF | mean time between failures |
| MTTR | mean time to repair |
| NMAC | Nuclear Maintenance Applications Center |
| NRC | Nuclear Regulatory Commission |
| O&M | operations and maintenance |
| OEM | original equipment manufacturer |
| PMBD | Preventive Maintenance Basis Database |
| RPN | risk priority number |
| SIM | secondary impulse method |
| SME | subject matter expert |
| SR | severity rating |
| SSC | system, structure, or component |
| SUT | start-up transformer |
| TDR | time domain reflectometry |
| TE | task effectiveness |
| WANO | World Association of Nuclear Operators |
| XLPE | cross-linked polyethylene |

## 1.5 Key Points

Throughout this report, key information is summarized in “Key Points.” Key Points are bold lettered boxes that succinctly restate information covered in detail in the surrounding text, making the Key Point easier to locate.

The primary intent of a Key Point is to emphasize information that will allow individuals to take action for the benefit of their plant. The information included in these Key Points was selected by NMAC personnel and the consultants and utility personnel who prepared and reviewed this report.

The Key Points are organized according to four categories: Costs, Technical, Human Performance, and Information. Each category has an identifying icon, as shown below, to draw attention to it when quickly reviewing the guide.

| **Key Cost Point** |
| --- |
| Emphasizes information that will result in reduced purchase, operating, or maintenance costs. |

| **Key Technical Point** |
| --- |
| Targets information that will lead to improved equipment reliability. |

| **Key Human Performance Point** |
| --- |
| Denotes information that requires personnel action or consideration in order to prevent injury or damage or to ease completion of the task. |

| **Key Information Point** |
| --- |
| Denotes information of special importance. |

Appendix A contains a listing of all Key Points in each category. The listing restates each Key Point and provides reference to its location in the body of the report. By reviewing this listing, users of this guide can determine if they have taken advantage of key information that the writers of the guide believe would benefit their plants.

# 2
# TROUBLESHOOTING PROCESS

## 2.1 Overview

This section provides a process and detailed implementation guidance to assist plant personnel when troubleshooting a system, structure, or component (SSC) or process whose performance has degraded from its normal design requirements. The troubleshooting process defined herein has been designed with great consideration to be versatile enough to be applied to any station SSC or process. It consists of a logical sequence of steps but is tailored to use the information typically available with SSCs and processes in power generating facilities.

As noted in Section 1, the root cause and troubleshooting processes are similar in the steps taken to determine the cause of the problem. There are several tools/methods that exist in root cause focused literature that will be applied to the process of troubleshooting. These will aid the users in defining the problem to best guide the other actions that follow. They offer various approaches, but most of them are focused on the 10 steps shown in Table 2-1.

**Table 2-1**
**Troubleshooting process steps [23]**

| 10 Step Troubleshooting Process | |
|---|---|
| **Phase 1: Diagnostic Phase** | **Phase 2: Solution Phase** |
| 1. Define the problem | 6. Identify possible solutions |
| 2. Understand the problem/process | 7. Select solution(s) to be implemented |
| 3. Identify possible causes | 8. Implement the solution |
| 4. Collect the data | 9. Evaluate the effect(s) |
| 5. Analyze the data | 10. Institutionalize the change |

These steps will be divided and/or modified and new steps added to fit the troubleshooting process though the intent will be the same.

The application of the troubleshooting process provided in this guide exists in procedural form in the EPRI Generic Troubleshooting Procedure attached to this report.

Appendix B provides a flow path of the troubleshooting process from start to finish that is detailed within the text of this section, with examples to clarify points.

## 2.2 The "Event"

As defined in Section 1.4.1, *Event* is a generic term used in this guide to describe any failure or identified degradation in an SSC or process. When any event occurs, existing station processes should be considered first. Troubleshooting is typically not needed if the event is addressed in an existing process. If the event is not addressed in the processes of the station, or a process is identified to be incorrect or insufficient, this is a departure from normal operation and maintenance (O&M) and, therefore, the troubleshooting process should be applied.

As previously described, troubleshooting is a systematic approach to collecting data, isolating faults, and analyzing abnormal conditions that occur in SSCs that results in high confidence that the complete cause of system/equipment degradation has been identified and corrected, and that the system/equipment has been restored to normal operation. In effect, the troubleshooting process will result in a new means or method for the station to correct the cause of an event by utilizing existing station processes (for example, work management and engineering design changes).

### *2.2.1 Departure from Normal O&M – Transitioning into Troubleshooting*

Troubleshooting, as defined in Section 1.4, is applied when the scope of existing procedures and processes are exceeded, and no formal guidance exists for discerning the cause of, or solution to, the current problem. The personnel at the station are responsible for identifying this point and notifying supervision. Simply put, if guidance does not exist, personnel should stop and consider if it is time to enter the troubleshooting process.

Once it is identified that the scope of normal O&M processes has been exceeded and troubleshooting is needed, it is important to notify station personnel of the need to formally troubleshoot in a timely manner. The passage of time can allow the situation to change, and important evidence needed for the troubleshooting process may be lost.

Case studies are provided in Appendix C that describe events where troubleshooting was required, with identifiers at the transition from normal O&M to troubleshooting.

**Key Human Performance Point**

Simply put, if guidance does not exist, personnel should stop and consider if it is time to enter the troubleshooting process.

### *2.2.2 Notification of Event Requiring Troubleshooting*

There are many methods in which the event can be communicated (refer to Table 2-2 for examples), and some fleet/station processes may exist to drive this communication. Face-to-face or verbal communication should take place prior to initiating a formal notification so preparation for the troubleshooting process can begin. The event could be an anomaly observed by maintenance personnel, a symptom of a more serious problem identified by an operator, or a management decision to take corrective action.

**Table 2-2**
**Methods to communicate SSC performance issues**

| Methods the SSC Performance Issues May Be Communicated | |
|---|---|
| **Internal** | **External** |
| Maintenance Work Order or Request | Vendor technical bulletins |
| Corrective Action Report | Nuclear Regulatory Commission (NRC) reported industry events |
| Failed In-Service Test | Institute of Nuclear Power Operations (INPO) Operating Experience or Event Report |
| Performance or Condition Monitoring Reports | World Association of Nuclear Operators (WANO) Operating Experience or Event Report |
| Operations Rounds or Turnover Sheets | Other industry operating experience sources |
| Communications (telephone call, mobile work device video call, station page, or email) | 10 CFR Part 21 Notification (or equivalent) Reporting of Part Defect or Noncompliance |
| Plant Walkdowns | |
| Meeting Actions | |

It is important that station management empowers all personnel to identify problems at a station. The resolutions of the problems are typically performed by operations, maintenance, engineering, and/or the responsible organization of the SSC or the process.

### *2.2.3 Preliminary Assessment*

When an event occurs and troubleshooting is determined to be needed, it is important to properly define the problem and bound the focus of the troubleshooting investigation. To be effective, the preliminary assessment of the situation requiring troubleshooting needs to be prompt and flexible but regimented enough to get the information needed for all scenarios. The preliminary assessment serves as a non-intrusive initial investigation performed in a timely manner following an event designed to collect as much information as needed to properly develop the problem statement.

The individual(s) performing the preliminary assessment must gain a clear understanding of the issue before the problem can be properly defined and a solution can be created. This is a matter of eliminating the non-issues and understanding and acting on the remaining issues in a systematic manner. A clear understanding of the issues enables this process to be successful and require the least amount of iterations. Because of this, it is an important role of station management to assign the correct personnel to the preliminary assessment.

See Appendix D for an example of a form that can be used to guide a preliminary assessment.

**Key Technical Point**

To be effective, the preliminary assessment of the situation requiring troubleshooting needs to be prompt and flexible but regimented enough to get the information needed for all scenarios.

### *2.2.4 Define the Problem – Problem Statement*

Following the preliminary assessment, enough information should have been collected to define the problem and bound the extent of the troubleshooting to be performed.

The involved personnel will need to clearly define the problem before proceeding with troubleshooting. The troubleshooter should try to understand the scope and nature of the issue in order to identify the severity of the problem and to establish to what extent the problem has been observed in the plant or operating system. To accomplish this, the troubleshooter should understand how the problem could apply to other systems/components of similar design and application.

Utility experience suggests that defining the problem is the most important step for implementing the troubleshooting process in an efficient manner following the structured approach presented in this report and determining the right solution to the problem the first time. Defining the wrong problem or incorrectly defining the issue increases the risk that the same problem will occur again, which will require the troubleshooting process to be performed again.

Methods that can assist individuals and teams when defining the problem are:

- Ensure that individuals involved take a broad and objective view of the issue presented and apply appropriate human performance and technical rigor tools.
- Involve various technical disciplines.
- Brainstorm various scenarios and considering past system performance.
- Employ a “devil’s advocate” position or maintaining a questioning environment.

For the sake of consistency, the problem caused by the event should be described in a formal problem statement. The problem statement should be technically correct and as detailed as possible, referencing the details collected in the preliminary assessment. Best practices involve attaching this to the source corrective action or work order for record retention.

During the development of the problem statement, it is not appropriate to speculate about the source of the problem, nor is it yet practical to offer corrective actions.

**Key Human Performance Point**

During the development of the problem statement, it is not appropriate to speculate about the source of the problem, nor is it yet practical to offer corrective actions.

### *2.2.5 Determining the Level of Complexity of Troubleshooting Required*

By incorporating industry best practices and simplifying the troubleshooting process, troubleshooting has been divided into two levels in this guide: simple troubleshooting and complex troubleshooting. These will be briefly introduced below but described in greater detail in Sections 2.3 and 2.4.

#### 2.2.5.1 Simple Troubleshooting

This category of troubleshooting is the most common and should constitute a large fraction of all troubleshooting activities. Simple troubleshooting will normally be led by operations (simple system troubleshooting) or by a maintenance first-line supervisor and maintenance workers (simple component troubleshooting). These simple troubleshooting plans are typically applied to SSCs that are out of service or will not cause a plant transient or system or component perturbation.

Simple troubleshooting plan activities are generally limited to visual inspection, verification of plant conditions using installed instrumentation, and obtaining data relative to equipment status, input/output values, and readings. Repair or replacement activities are often performed as well but are typically of consumable or “weak link” parts (gaskets, fuses, etc.). Depending on the complexity of the event being addressed with simple troubleshooting, the failure analysis tools described in this guide can be used in simple troubleshooting at the discretion of direct supervision or management while still remaining “simple.”

Data may be obtained utilizing intrusive or non-intrusive approaches. A benefit to utilizing existing station/fleet work order processes for implementing simple troubleshooting tasks is that operations personnel will review and approve work orders. Shift managers can be engaged as necessary.

Transition from simple to complex troubleshooting occurs when simple troubleshooting attempts have been exhausted or at the discretion of either the shift manager or the station management [13].

#### 2.2.5.2 Complex Troubleshooting

This category of troubleshooting can be the most impactful to the station and often requires response at an organizational level where many personnel are assigned to the troubleshooting team. Complex troubleshooting may require large amounts of data from diverse resources, for example:

- Extensive engineering analysis
- Significant effect on production/safety risk margins
- Industry Benchmarking
- Meet any of the criteria in Table 2-3

In general, criteria that would result in a recommendation to perform complex troubleshooting are applicable any time the troubleshooting activities would have a higher potential to affect plant operation. Table 2-3 provides examples of troubleshooting level determination screening criteria for events related to SSCs.

**Table 2-3**
**Troubleshooting level determination screening criteria**

| Troubleshooting Level Determination Screening Criteria for SSC-Related Events |
|---|
| 1. Could troubleshooting or failure to correct the cause of the event result in one or more of the following consequences?<br>a. Unit downpower > 5%<br>b. Reactor or turbine trip<br>c. Emergency safety function actuation<br>d. Trip of in-service nuclear safety-related equipment, start of standby safety-related equipment, or cause for other functional safety-related equipment to become inoperable<br>e. Prevention of startup of unit following outage or shutdown |
| 2. Does the activity involve potential operational risks that cannot be mitigated, such as daisy-chained wiring, multiple wires on one terminal strip lug, a common manifold, or a common sensing line? |
| 3. Has failure resulted in a short-term LCO<72 hours and is the solution not readily apparent? |
| 4. Is the affected SSC a new installation and/or do personnel have minimum experience with the SSC? |
| 5. Will test equipment be required to be connected to in-service equipment by lifting wiring leads or performing alternate system alignments? |
| 6. Is engineering analysis required that needs data gathered through troubleshooting activities? |
| 7. Is troubleshooting on a complex software-driven control system or other digital asset where there is limited knowledge and skill set available required? |
| 8. Is this event suspected to be related to a previously performed troubleshooting effort that may have been ineffective? |
| 9. Has the activity been determined by the plant management to required complex troubleshooting? |
| 10. Does the response action required by maintenance or operations go beyond the scope of content contained in existing procedures or work orders available for use in operations and/or maintenance (O&M)? |

As with simple troubleshooting, data may be obtained utilizing intrusive or non-intrusive approaches.

It is important to note that in certain organizations, complex troubleshooting as described in this guide mirrors the failure investigation process.

A complex troubleshooting plan will typically require multiple work order activities, system alignments, complicated analysis, expedited sample tests, review, and approval by many personnel at the station or corporate office. It is, in effect, a simplified root cause analysis investigation, and the level of effort and required failure analysis methods will vary dependent on the specifics of the event.

When investigating or troubleshooting a process is desirable, it is best to use the complex troubleshooting method. The complex troubleshooting process and methods described in Section 2.3 are better suited to handle the steps and inputs/outputs of processes.

Although the majority of the events, based on industry experience, will screen to the simple troubleshooting level, it is very important to properly screen the event. Improperly identifying an event as simple when there are some complex elements could cause rework in the troubleshooting process or lead to undesired consequences (such as availability, lost time, or damaged equipment). It is also very important to consistently screen the event and potential impact on the station when determining the level.

## 2.3 Complex Troubleshooting Process

Complex troubleshooting will be described first, because occasionally elements of the complex troubleshooting process can be used during simple troubleshooting.

As stated above, events screened as complex troubleshooting can have a large scheduling and financial impact to the station; therefore, this process is more regimented and requires more personnel to support the data collection and evaluations necessary to make the correct decisions that limit the impact on the station.

Because the risk associated with complex troubleshooting events is often higher—and can affect the schedule, the health of the station's SSCs, and ultimately the business plan—significantly more information is needed to be collected and analyzed to ensure that the process is efficient and moves forward with high confidence that no time or effort is being wasted.

It is important to note that complex troubleshooting is an iterative process. The practices defined below are not executed in a sequential manner. There are many cases where they are all done in parallel or repeated, depending on the event. Applying the knowledge gained from one process to the others to fine tune the troubleshooting effort is expected.

### *2.3.1 Assign the Troubleshooting Lead*

The troubleshooting team in a complex troubleshooting scenario is led by the troubleshooting lead, whose title may vary depending on the organization (for example, complex troubleshooting team lead). Typically, this individual is a direct supervisor/manager or an individual contributor (for example, engineer, operator, maintenance technician, procedure writer, or process owner). The troubleshooting lead can be a subject matter expert (SME) or new to the SSC or process. The role of this person during complex troubleshooting is to:

- Effectively utilize the skill sets on the troubleshooting team
- Effectively communicate with all team members, whether they are present or working remotely; full-time or part-time; employees or vendors
- Efficiently move through the process with the proper technical rigor to ensure the success of the troubleshooting process
- Function as the single point of contact for the management team throughout the troubleshooting process, to allow the team to focus on resolving the problem
- Conduct formal shift turnover meetings between shifts of complex troubleshooting teams
- Conduct pre-job briefings
- Review and approve products of the complex troubleshooting team

### 2.3.2 Assemble the Troubleshooting Team

The troubleshooting team for a complex troubleshooting effort should consist of cross-functional personnel with diverse knowledge about the SSC or process. Examples of cross-functional personnel are those from engineering (design, procurement, system, maintenance), maintenance (work planners, technicians, etc.), operations, and other organizations. Team members can be full- or part-time depending on normal job assignment, job schedule, and station/management priorities. Virtual team members should also be considered. Due to the advances in technology and connectivity, team members can support the team from a remote location and interface through video conferencing and file collaboration services that exist, creating "virtual team members." With respect to staffing, troubleshooting can be time- and labor-intensive, so it is not uncommon for troubleshooting team members to be assigned to support the troubleshooting team on a part-time basis while they spend the majority of their time performing their normal job assignments. The troubleshooting lead will coordinate with all team members (present, virtual, full-time and part-time) to ensure an effective troubleshooting process.

A blend of SMEs and those with little to no experience, in combination with a supportive questioning attitude, can create a collaborative environment where discussion and brainstorming can identify the less obvious faults in the SSC or process.

#### 2.3.2.1 Special Consideration for Work Planners

A special note is in order regarding the work planner when troubleshooting SSCs—so much of the development and timely execution of a complex troubleshooting effort relies on the coordination between the troubleshooting team and the work planner. A work planner assigned and stationed in the same area as the troubleshooting team can develop needed work order tasks in parallel with discussions. In addition, work planners are familiar with the processes that exist to perform the needed tasks, whereas other personnel (engineers, operations, etc.) may not be familiar with the maintenance procedures in existence.

**Key Technical Point**

A work planner assigned and stationed in the same area as the troubleshooting team can develop needed work order tasks in parallel with discussions. In addition, work planners are familiar with the processes that exist to perform the needed tasks, whereas other personnel (engineers, operations, etc.) may not be familiar with the maintenance procedures in existence.

#### 2.3.2.2 Special Consideration for Troubleshooting Team Location

Whenever practical, the troubleshooting team should be located in a common area (conference room) to facilitate the collaboration and focus necessary during complex troubleshooting events. Based on the facilities and technology available to the station, the following should be considered for the troubleshooting team's common area:

- Sufficient workspace for team members
- Cameras and video monitors to allow the virtual and local team members to communicate visually

- Power and internet connections for team computers
- Additional monitors to facilitate report generation, data collection, and organization
- Electronic work package devices (if utilized) for review of active documents
- Telephone to allow the troubleshooting lead to communicate with station/fleet management and contact station/fleet/external personnel who can assist the troubleshooting effort
- Projector screens
- White boards, smart boards, and/or large flip charts to facilitate team brainstorming, meetings, and action tracking
- Large tables for drawing and document review
- Storage area (bin, laydown area, etc.) for SSC piece parts (faulty or new condition for comparison), mockups, or other equipment useful in troubleshooting

**Key Human Performance Point**

Whenever practical, the troubleshooting team should be located in a common area (conference room) to facilitate the collaboration and focus necessary during complex troubleshooting events.

### *2.3.3 Brief the Complex Troubleshooting Team on the Defined Problem*

The troubleshooting lead should provide the team with the initial briefing of the event, including the latest information available to date. It is essential to provide the information gained from the notification, preliminary assessment, and problem statement to the team. If the accuracy of any of the data is questionable, it should be identified as such and tracked for validation in the data collection phase that follows.

### *2.3.4 Determine the Data Needed to Diagnose Cause of Event*

After the initial brief, the troubleshooting team should then decide what data needs to be collected for the failure analysis phase. Appendix E provides examples of data collection sources that are valuable to troubleshooting efforts.

### *2.3.5 Perform Failure Analysis*

Using the data that was collected as described above as inputs, the failure analysis is often the most intensive and iterative part of the troubleshooting process. Determining what caused the failure resulting in the event is critical to resolving the problem in a timely manner.

It is very common during the troubleshooting process to identify deficiencies in areas that could have contributed to the event. The desire to fix every problem encountered can distract the troubleshooting effort and prolong the discovery of the cause of the event. This is a distinct difference between troubleshooting and root cause analyses. When other deficiencies are identified during the troubleshooting process that are not aligned with the problem statement (for example, an adjacent SSC or supporting document), it is best practice to generate a new corrective action related to the newly identified problem, and to proceed with troubleshooting the original problem. Capturing the new issue as an open item to be addressed at the completion of the troubleshooting process ensures that focus remains on solving the problem requiring troubleshooting and that attention and resources are not diverted.

The methods selected for use in this guidance document are described below. Advantages and limitations of each method are provided following each topic discussion.

The tools reviewed in the following section are:

- Fault Tree Table (Section 2.3.5.1)
- Ishikawa Diagram (Section 2.3.5.2)
- 5 Whys (Section 2.3.5.3)
- Failure Mode and Effects Analysis (FMEA) (Section 2.3.5.4)
- Support/Refute Matrix (Section 2.3.5.5)
- Change Analysis / Sequence of Events (Section 2.3.5.6)
- Pareto Chart (Section 2.3.5.7)
- Vendor-Supported Failure Analysis Tools (Section 2.3.5.8)

#### 2.3.5.1 Failure Analysis Tool: Fault Tree Table [13, 14]

The fault tree analysis, also known as an "event and causal factor chart," is one of the most widely used methods in system reliability, maintainability, and safety analysis. It is a deductive process used to determine the various combinations of hardware/software failures and human errors that could cause undesired events for the SSC or process.

The value of the fault tree is to aid in identifying potential causes of SSC or process failures that occurred. The information generated from this analysis can be transferred into more advanced failure analysis methods (for example, a support/refute matrix or a failure mode and effects analysis).

Depending on the event being investigated via troubleshooting, fault trees analysis can be performed simply (as shown in Figure 2-1) or can be made more complex by including logic gates (if, or, and, etc.) to provide greater relational detail with how the contributors lead to the cause of the fault tree. The format can be adjusted to match the SSC or process being analyzed.

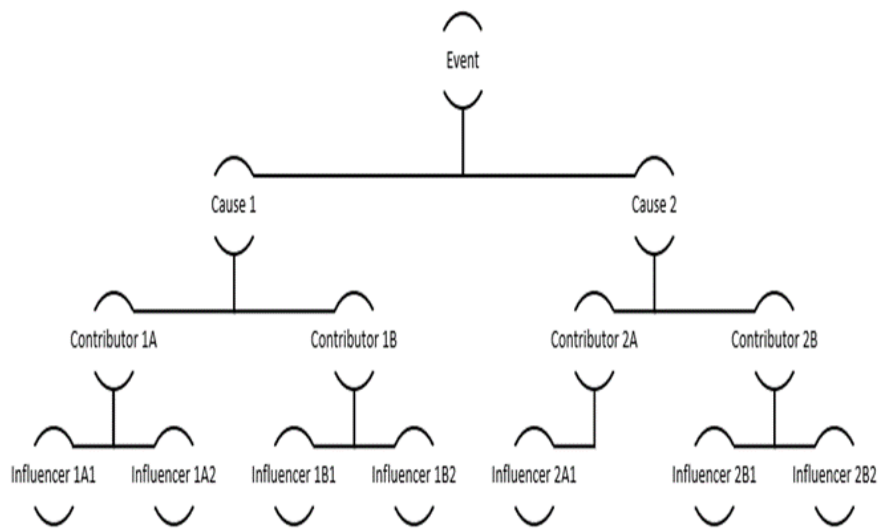


**Figure 2-1**
**Simple fault tree table**

To develop a fault tree table:

1. **Event**: State the problem statement at the top of the tree.
2. **Cause**: Use technical information, professional judgments, and other data collected to determine the possible causes for the event.
3. **Contributor**: Further reduce each cause to what contributor can lead to the applicable cause.
4. **Influencer**: Define what allowed the contributor to exist.
5. Finalize and review the complete diagram. The chain can only be terminated in a root fault: human, hardware, or software.
6. At the completion, post the fault tree table diagram in an area visible to all, revisit it often, and encourage further development. Troubleshooting is an iterative process.

The above levels can be repeated or further divided into sub-causes, sub-contributors, and so on if additional levels are needed.

Many templates exist online and can be developed or modified for the troubleshooting being performed.

**Advantages of the fault tree table:**

- Highly visual brainstorming tool that can spark further causes of failures
- Quickly identifies whether the root cause is found multiple times in the same tree or a different causal tree
- Allows troubleshooting team to see all causes simultaneously
- Provides a structure for recording causes and evidence that is easy to follow
- Can handle multiple scenarios
- Works well as a master analysis technique

- Can incorporate results from other tools

**Limitations of the fault tree table:**

- Complex defects might yield a lot of causes, which might become visually cluttering.
- Interrelationships between causes are not easily identifiable [18].
- Templatizing for use in procedures is difficult.
- Time-dependent events are difficult to handle and display.
- Complexity makes it harder to treat sequence dependencies.
- Knowledge gaps are identified but it does not have a means of filling them in.
- Stopping points may be arbitrary.

> **Key Information Point**
>
> The fault tree analysis is one of the most widely used methods in system reliability, maintainability, and safety analysis. It is a deductive process used to determine the various combinations of hardware/software failures and human errors that could cause undesired events for the SSC or process.

### 2.3.5.2 Failure Analysis Tool: Ishikawa Diagram [18, 31, 26]

The Ishikawa diagram is also known as a cause-and-effect diagram or fishbone diagram; it is an alternative to the fault tree failure analysis tool discussed in Section 2.3.5.1. Figure 2-2 provides an example of an Ishikawa diagram or fishbone diagram.

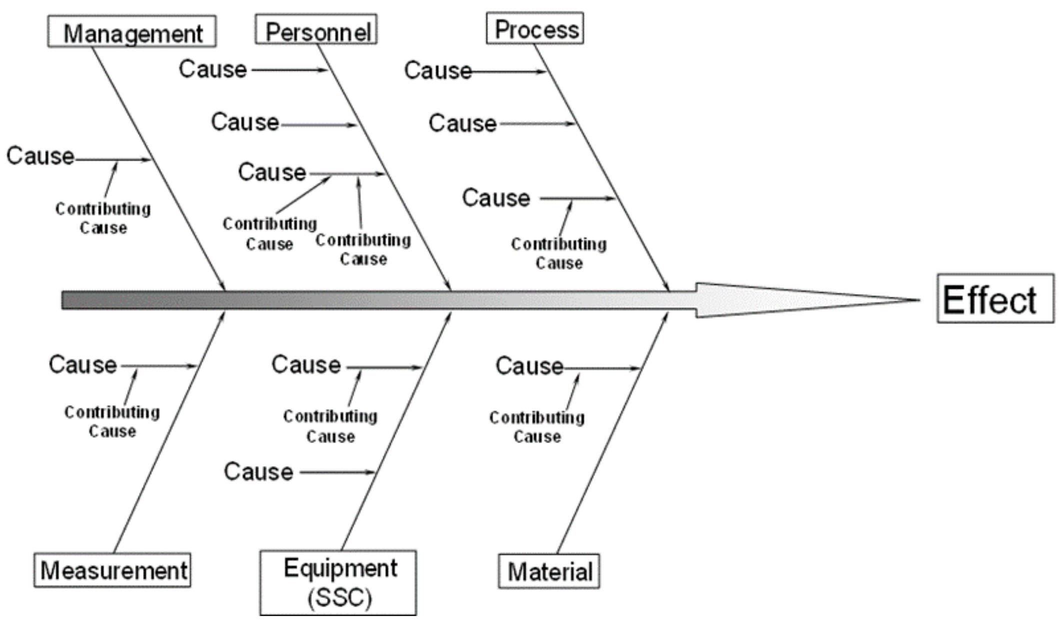


**Figure 2-2**
**Ishikawa (fishbone) diagram example**

This method tends to align more with troubleshooting process-related issues but may have a place in brainstorming SCC issues as well, depending on the situation. Many templates exist online and can be developed or modified for the troubleshooting being performed.

To develop an Ishikawa diagram, perform the following steps:

1. Provide the problem statement/effect as the output of the process.
2. Brainstorm the major categories of causes of the problem. Examples include:
   - Process
   - Personnel
   - Equipment (SSC)
   - Management
   - Material
   - Measurement
   - Environment
3. Place the categories on the “branches” from the main arrow.
4. Brainstorm all possible causes contributing to the problem (as many iterations as necessary).
5. Again ask, “Why does this happen?” about each cause. Write sub-causes branching off the causes. Continue to ask, “Why?” and generate deeper levels of causes and contributing causes. Contributing causes can be shown as branches from causes, as indicated in Figure 2-2.
6. Revisit each branch a final time to ensure no other causes were recognized during the evolution.
7. Post the Ishikawa diagram in an area visible to all, revisit it often, and encourage further development. Troubleshooting is an iterative process.

**Advantages of the Ishikawa diagram:**

- Highly visual brainstorming tool that can spark further examples of root causes
- Quickly identifies whether the root cause is found multiple times in the same tree or a different causal tree
- Good visualization to see all causes simultaneously
- Good visualization for presenting issues to stakeholders [25]
- Shows relationships between potential causes
- Good way to involve people in problem-solving
- Effective when used by a single person [18]

**Limitations of the Ishikawa diagram:**

- Complex defects might yield a lot of causes that may become visually cluttering.
- Interrelationships between causes are not easily identifiable.
- Templatizing for use in procedure is difficult.

- Involving multiple people in a fishbone diagram can limit its effectiveness because it encourages a divergent approach, where the temptation to identify and fix everything that might cause the problem
  - This can be mitigated by placing the problem statement above the diagram and redirecting focus to the intent of the troubleshooting plan. When other areas are identified that can be improved, generating a new corrective action during the troubleshooting process can add value beyond resolving the defined problem statement [18].

#### 2.3.5.3 Failure Analysis Tool: 5 Whys [19]

Figure 2-3 depicts the 5 Whys process. The 5 Whys process is based on the simple question of “Why?” With the problem defined, the troubleshooting team asks, “Why did this problem occur?” The possible causes of the problem are then recorded as “Because…” statements. Each “Because” is then subjected to further “Why” questions. This process repeats until the root cause has been defined.

| | | | | | |
|---|---|---|---|---|---|
| Problem Statement: | | | | | |
| **Why did this event occur?** | | | | | |
| Because… | | | | | |
| **Why?** | Because… | | | | |
| ↳ | **Why?** | Because… | | | |
| | ↳ | **Why?** | Because… | | |
| | | ↳ | **Why?** | Because… | |
| | | | ↳ | **Why?** | Because… |

**Figure 2-3**
**5 Whys example**

Note that the question “Why?” can be asked more than five times; in most cases, after five whys are asked, the team will have clarity on the cause of the problem.

The primary goal of the technique is to determine the root cause of a defect or problem by repeating the question “Why?” Each answer forms the basis of the next question. The “five” in the name is derived from an anecdotal observation on the number of iterations needed to resolve the problem.

It is important to note that not all problems have a single root cause. If multiple root causes are suspected, then the method must be repeated, asking a different sequence of questions each time.

(Note: the process works best in a brainstorming environment.)

To perform the 5 Whys process:

1. Define the problem statement.
2. Ask, “Why did this problem occur?”
3. List the reasons given as “Because” statements.
4. Create a new list for each “Because” statement.

5. Continue asking "Why" for each "Because," creating new "Why" and "Because" statements as required.
6. This process repeats until the root cause has been defined.

**Advantages of the 5 Whys process:**

- Beneficial in initial troubleshooting team brainstorming discussions to later feed into more complex failure analysis
- Very valuable in simple troubleshooting

**Limitations of the 5 Whys process:**

- Basic tool with a lack of facilitation and support to help troubleshooting team to ask the right questions
- Tendency of investigators to stop at symptoms and not to proceed to lower-level root causes
- Low repeat rate of results; different teams using the 5 Whys technique have been known to come up with different causes for the same problem

**Key Information Point**

The 5 Whys process is based on the simple question of "Why?" With the problem defined, the troubleshooting team asks, "Why did this problem occur?" The possible causes of the problem are then recorded as "Because…" statements. Each "Because" is then subjected to further "Why" questions. This process repeats until the root cause has been defined.

#### 2.3.5.4 Failure Analysis Tool: Failure Mode and Effects Analysis (FMEA) [18]

Figure 2-4 provides an example of the failure mode and effects analysis (FMEA) table. Through this method, failures are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate the possible failures, starting with those most likely and significant.

It is important to note that typically an FMEA is performed before the SSC or process (if applicable) is placed into service. However, if an FMEA has not been performed historically, performing one can be advantageous to both the current event investigation and in preventing future events. If an FMEA is available, it can be very valuable in diagnosing causes of failures and should be considered during the data collection phase. Most often, existing FMEAs are referenced and not developed during troubleshooting activities.

Failure modes and effects analyses are often incorporated into the design record of a station and updated as required to incorporate operating experience and improvements in maintenance practices and performance monitoring.

| FAILURE MODES AND EFFECTS ANALYSIS (FMEA) | | | |
|---|---|---|---|
| Corrective Action#:<br>Work Order #: | | Corrective Action or Work Order Title: | |
| Problem Statement: | | | |
| SSC/Process Function: | | | |
| FMEA Boundary: | | | |

| Failure Modes and Effects Analysis (FMEA) Table **[Note 1]** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Priority (RPN) SR*FR*TE **[Note 2]** | SSC/Process Title **[Note 3]** | Function | Critical Function (Y/N) | CR **[Note 4]** | Failure Mode | SR **[Note 5]** | Failure Mode Cause | Failure Mode Monitoring Task | (TE) **[Note 6]** | Failures Mode Effect | FR **[Note 7]** | Result (FM/N/I/P) **[Note 8]** |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |

Notes:

1. Rows may be mostly duplicated if SSC/Process have multiple Function, Failure Modes, Failure Mode Causes, etc.
2. Risk Priority Number (RPN) = SR × FR × TE. The lowest numbered RPN has the highest priority and provides guidance for ranking potential failures in order they should be addressed.
3. Depending on complexity, it may be valuable to divide and describe the scope and function of SSCs/Processes into systems, subsystems, items, parts, assemblies, or process steps.
4. Criticality Rating (CR) = SR × OR. Prioritize the lowest CR number as it identifies the failure modes effect with highest effect on the critical characteristics of an SSC or process.
5. Severity Rating (SR) = Scale based on 1 to 10, where 1 is catastrophic and 10 is insignificant.
6. Task Effectiveness (TE) = Scale based from 1 to 10, where 1 means task is NOT effective and 10 means task is 100% effective.
7. Frequency Rating (FR) = Scale base on 1 to 10, where 1 is common and 10 is never (or similar scale).
8. Determination of specific combination of the Failure Mode & Failure Mode Cause. Values are FM = Failure Mode, R = Refuted, I = Indeterminate, P = Pending.

| FMEA Summary: | |
|---|---|

**Figure 2-4**
**Example failure modes and effects analysis (FMEA) table**

To perform an FMEA:

1. **FMEA Team**: Assemble the FMEA team to perform the FMEA analysis. This team should consist of cross-functional personnel with diverse knowledge about the SSC or process. Examples of cross-functional personnel are subject matter experts, vendors, engineering (design, procurement, system, maintenance), maintenance (work planner, technicians, etc.), operations, and other organizations.
   – Typically, the troubleshooting team is very involved with the FMEA, but occasionally, personnel not assigned to the troubleshooting team are involved, hence the difference between the FMEA team and the troubleshooting team.
2. **Problem Statement**: State the problem caused by the event in a problem statement. The problem statement should be technically correct and as detailed as possible—reference the details collected in the preliminary assessment. Best practices involve attaching this statement to the source corrective action or work order for record retention.
3. **SSC/Process Function**: Identify the functions of the SSC or process. For example, ask, "What is the purpose of this SSC or process?" and "How is the SSC or process expected to perform/function?"
   – Depending on complexity, it may be valuable to divide and describe the function of SSCs/processes into systems, subsystems, items, parts, assemblies, or process steps.
4. **FMEA Boundary**: Identify the boundary of the FMEA for the SSC or process.
5. **Priority**: After all of the data is populated into the FMEA table, calculate the priority/risk priority number (RPN) using the formula SR × FR × TE. The lowest number for the RPN has the highest priority. This can be used as guidance for ranking potential failures in the order in which they should be addressed.

6. **SSC/Process Title:** List the SSC or process name (in its entirety or by subcomponent/part, depending on complexity) to be evaluated. Each process or SSC may have multiple rows depending on complexity.
7. **Function:** Define the role the SSC or process (entire or part) performs. Note that depending on the complexity of the process or SSC, it may have multiple functions.
8. **Critical Function**: Determine if the failure mode for the SSC or process has a failure mode associated with a critical characteristic (critical characteristics are measurements or indicators that reflect safety or compliance with government regulations and need special controls). Depending on the determination, the Critical Function column is marked Y or N to show whether special controls are in place.
9. **Criticality Rating (CR)**: Calculate the criticality rating (CR) by multiplying severity by occurrence, SR × OR. The lowest number for the CR has the highest priority and provides guidance for ranking the failure modes effect of critical characteristics of an SSC or process.
10. **Failure Mode**: For every function defined above, identify the failure modes or ways failures could happen for that function.
11. **Severity Rating (SR)**: The severity rating is a scale of how significantly the effect of a failure mode would challenge the performance of the SSC or process. Determine the severity rating (SR) of each effect of failure and scale for comparison. Severity can be scaled from 1 to 10, where 1 is catastrophic and 10 is insignificant (or a similar scale). This can be a subjective scale, so setting a standard scale for the specific SSC or process to be referenced by the team is effective. Also, if a failure mode has more than one effect, select the most conservative/lower severity rating.
    - An alternative to the above is to use the severity rating that the EPRI PMBD provides in the failure modes for the given SSC. These ratings were developed during industry expert elicitation sessions before inclusion in the PMBD. A possible scale based on the EPRI PMBD templates for a given SSC is None = 4; Low (L) = 3; Medium (M) = 2; and High (H) = 1.
12. **Failure Mode Cause**: For each failure mode, determine all of the potential root causes. Use tools classified in this failure analysis section, as well as the best knowledge and experience of the team. List all possible causes for each failure mode on the FMEA form.
13. **Failure Mode Monitoring Task**: For each cause, identify the failure mode monitoring task that exists to test, maintain, or monitor the failure modes to prevent failures. These can range from actual maintenance tasks on SSCs to operator rounds or program assessments.
14. **Task Effectiveness (TE)**: For each control, the task effectiveness (TE) rating estimates how well the controls can detect either the cause or its failure mode after they have happened but before a failure occurs. Task effectiveness can be rated on a scale from 1 to 10, where 1 means the control is certain not to detect the problem (or no control exists) and 10 means the control is absolutely certain to detect the problem. This can be a subjective scale, so setting a standard scale for reference by the team in the beginning of this effort is effective.
15. **Failure Mode Effects**: For each failure mode, identify the symptoms or consequences of the failure on the SSCs/processes, considering systems, subsystems, items, parts, assemblies, or process steps.

16. **Frequency Rating (FR)**: For each cause, determine the frequency rating (FR). This rating estimates the probability of failure occurring for that reason during the lifetime of the scope. Frequency rating can be a scale from 1 to 10, where 1 is common and 10 is never (or a similar scale). This is a subjective scale, so setting a standard scale for the specific SSC or process to be referenced by the team is effective.
    – The frequency rating can be based on station, vendor, or working group feedback. The EPRI PMBD can be referenced as well.
17. **Result**: An identifier noting the result of the FMEA item can be useful for tracking and sorting as actions are completed, recording results and the date on the FMEA form. Examples provided in this guide and procedure are FM = Failure mode, R = Refuted, I = Indeterminate, P = Pending.

**Advantages of FMEA process application:**

- Catalyst for teamwork and idea exchange between functions.
- Identifies potential failure modes.
- Reduces the possibility of same kind of failure in future.
- Very detailed approach to problem analysis.
- Useful in contingency planning, where it is used to evaluate the impact of various possible failures (contingencies); can be used in place of a “what if” analysis should greater detail be needed.
- When combined with criticality analysis, the analysis will systematically establish relationships between failure causes and effects, as well as the probability of occurrence, and will point out individual failure modes for corrective action.
- When used to complement fault tree analysis, more failure modes and causes may be identified [18].

**Limitations of FMEA process application:**

- By itself it may only identify major failure modes in a system.
    – To counter this potential disadvantage, it is best performed in parallel with a fault tree, 5 Whys, and other methods of failure mode identification.
- Time and effort required to complete the analysis.
- Inability to easily deal with combined failure events.
- Does not typically include human interactions (operator error) [18].

**Key Technical Point**

It is important to note that typically an FMEA is performed before the SSC or process (if applicable) is placed into service. However, if an FMEA has not been performed historically, performing one can be advantageous both to the current event investigation and in preventing future events.

#### 2.3.5.5 Failure Analysis Tool: Support/Refute Matrix [19]

A support/refute matrix (Figure 2-5) is essentially a simplified failure mode and effects analysis and, when used effectively, can lead to properly confirming the failure mode in a timely manner. Support/refute matrices are the most widely used failure analysis tool used in troubleshooting procedures by the EPRI member population. When developing a support/refute matrix, suspected credible failure modes are identified, along with supporting or refuting evidence for whether or not the failure mode exists. Then, often through intrusive maintenance activities, the troubleshooting task plan is developed and executed to determine if each failure mode is the cause of the event (supported) or is not (refuted). When the failure mode is identified, it is labeled as such and any contributing factors are identified.

**Work Order/Condition Report #:**

**Problem Statement:**

**Provide resources of Credible Failure Modes:**

*1.*

*NOTES:*

1. *Consider, Vendor Manuals, Preventive Maintenance (PM) Basis documents, Electric Power Research Institute resources(Preventive Maintenance Basis Database Troubleshooting Knowledgebase (PMBDTK) (https://pmbd.epri.com/) and Nuclear Maintenance Applications Center Support Hotline (nmachotline@epri.com).*
2. Situations where source documentation or verifications cannot be obtained are addressed with supporting basis / evidence.
3. The use of engineering judgment is allowable and is identified with justification for the judgment and communicated to the Management Sponsor of the Failure Investigation Process (FIP) team.
4. Option to reference resource in Failure Mode Column.

| Sequence # [Note 1] | Failure Mode [Note 2] | Supporting Evidence [Note 3] | Refuting Evidence [Note 4] | Troubleshooting Task OR Work Order Number [Note 5] | Notes/Results [Note 6] | FM / CF / I / R [Note 7] |
|---|---|---|---|---|---|---|
| 1 | | | | | | |
| 2 | | | | | | |
| 3 | | | | | | |
| 4 | | | | | | |
| 5 | | | | | | |

**Notes:**

1. Sequence does not represent priority but represents sequence of execution and may change based on results.
2. Insert the possible credible failure that could cause the problem identified in the problem statement.
3. Provide supporting evidence for the condition if the failure mode IS present.
4. Provide refuting evidence for the condition if the failure mode IS NOT present.
5. Troubleshooting Tasks are basic instructions to aid in planning of task. Option to use Attachment 17, Troubleshooting Task Sheet as attachment in Work Oder if additional detail is needed. Not required for every task.
6. Quantitative evidence is used to support or refute a failure mode. Qualitative or soft wording is avoided. Can also contain notes collected during tasks.
7. Determined to be Failure Mode (FM), Contributing Factor (CF), Indeterminate (I), or Refuted (R).

**Figure 2-5**
**Support/refute matrix**

The value of a support/refute process is that each failure mode is proven or disproven to be the cause of the event. This identification of the actual failure mode through investigation and elimination of other credible failure modes can provide a high level of confidence that the failure mode identified as the cause is the actual cause of the event.

Support/refute matrixes are best suited for troubleshooting SSC-related events.

To perform a support/refute matrix:

1. **Problem Statement**: Input the problem statement and important evidence collected during the data collection phase.
2. **Sequence #**: In the Sequence # column, define the order in which the troubleshooting task plan will be performed. It is important to define the sequence correctly, because the evidence needed to determine if some failure modes exist may be destroyed if certain tasks are performed. For example, performing a reverse flush of a heat exchanger could dislodge and remove material covering a tube sheet, obstructing flow. All non-intrusive maintenance tasks should be performed before intrusive tasks, to prevent affecting evidence.

3. **Failure Mode**: In the Failure Mode column, list all credible failure modes identified during the troubleshooting investigation.
4. **Supporting/Refuting Evidence**: In the Supporting/Refuting Evidence columns, provide the evidence for (supporting) and against (refuting) each failure mode.
5. **Troubleshooting Task Plan and Implementing Work Order Number**: Develop a troubleshooting task plan that will perform the actions to collect the data necessary to support or refute the credible failure mode(s). The sequence and scope of the tasks are developed throughout the evolution of the troubleshooting process. In other words, it is often not possible to know all tasks that are needed at the very beginning of the troubleshooting process. Section 2.3.6, "Develop Troubleshooting Tasks," of this guide provides additional discussion regarding developing troubleshooting tasks.
   - Simple tasks can be entered into this column (for example, "acquire thermography image of identical component operating" or "sample oil and test per procedure").
   - Consider both intrusive and non-intrusive actions.
   - Complex tasks should use a separate attachment that provides the necessary detail to perform the actions and collect the data necessary to support or refute the failure mode.
     - See Attachment 17," Troubleshooting Task Sheet" in the Generic Troubleshooting Procedure attached to this guide for an example of a troubleshooting task sheet and the considerations that should go into a troubleshooting task.
   - It is very beneficial to temporarily assign a planner to the troubleshooting team to develop the troubleshooting task plan directly in the work management program, to reduce redundant paperwork created by the troubleshooting team.
6. **Notes/Results**: Provide additional information in the Notes/Results column for the supporting/refuting evidence.
7. **FM/CF/I/R (Failure Mode/Contributing Factor, Indeterminate or Refuted)**: This column identifies whether the Failure Mode in the row is the Failure Mode (FM), Contributing Factor (CF), Indeterminate (I), or Refuted (R).
   - FM – Identifies the subject failure mode of the row was the failure that caused the event.
   - CF – Identifies the subject failure mode of the row was a contributing factor to the failure that caused the event.
   - I – Identifies there was not sufficient evidence to support or refute the subject failure mode. It is best practice to limit the number of Indeterminate items in a Support/Refute Matrix and provide basis for why a "I" label is acceptable.
   - R – Identifies that sufficient evidence existed for the subject failure mode of the row.

The process above should be repeated and refined (adding new failure modes and additional evidence, as needed) until enough evidence has been acquired to identify the failure mode that caused the event. Because the focus is on troubleshooting, and quickly restoring an SSC to operation is the primary goal, not all contributing factors may be defined. The troubleshooting lead should consult with management to determine if additional time and effort can be used to support/refute possible contributing factors.

**Advantages of the support/refute process:**

- Uses actual evidence from inspections, tests, or other tasks from the actual SSC involved with the event
- Simpler, yet equally effective, approach to failure analysis that finds the evidence needed to identify the failure mode(s) that caused the event

**Limitations of the support/refute process:**

- If the results from the troubleshooting task plan are inconclusive or misinterpreted, it could lead to identification of an incorrect failure mode as the cause.
- Alternate explanations for the evidence collected need to be considered, as these may lead to new failure mode identification.
- Incorrect sequencing of troubleshooting task plans can destroy evidence that could have supported or refuted a failure mode.

**Key Information Point**

Support/refute matrices are the most widely used failure analysis tool in troubleshooting procedures by the EPRI member population.

**Key Technical Point**

The value of a support/refute process is that each failure mode is proven or disproven to be the cause of the event. This identification of the actual failure mode through investigation and elimination of other credible failure modes can provide a high level of confidence that the failure mode identified as the cause is the actual cause of the event.

#### 2.3.5.6 Failure Analysis Tool: Change Analysis/Sequence of Events [23]

The change analysis/sequence of events approach is applicable to situations where performance of an SSC or process has deviated over time. Through development of a timeline, or other time-based comparison, change analysis can aid in identifying turning points and/or slow decay in performance over time. Changes made in operation practices, engineering processes, personnel, equipment, and other SSC or process performance contributors can be identified. This process will correlate changes made in process, equipment, personnel, material, or design changes, and other intentional or unintentional, planned or unplanned changes made over the history of the SSC or process.

Common approaches to change analysis (shown in Figure 2-6) use time series data comparisons, sequence of events tables, Gantt charts, or similar method.

| SEQUENCE OF EVENTS [Note1] | | | | | | |
|---|---|---|---|---|---|---|
| Condition Report# | | | | | | |
| Problem Statement | | | | | | |
| Evaluated Time Frame | | | | | | |
| SEQUENCE | EVENT RESULT | EFFECT +/-/0 | DATE | TIME | REFERENCE [Note 2] | EVENT DESCRIPTION |
| | | | | | | |
| | | | | | | |
| | | | | | | |
| NOTE 1: Some complicated events benefit from defining the sequence of events. This can help identify the failure as inflection points are identified. | | | | | | |
| NOTE 2: This can also be plant computer outputs (alarms, points, etc...). | | | | | | |

**Figure 2-6**
**Example of change analysis: sequence of events table**

To develop a change analysis:

1. **Problem Statement**: Input the problem statement and important evidence collected during the data collection phase.
2. **Evaluated Time Range**: Define the time range that is being investigated. This can be expanded or reduced depending on the event being evaluated.
3. **Event Result**: Provide a brief description of what happened.
   – For example, "Failed Weld 12SW345" or "Modification A12345 rejected at final review."
4. **Effect**: Indicate if the event result was positive (+), negative (-), or neutral (0).
5. **Date**: While reviewing the historical data collected during the data collection phase, enter all relevant events that are inputs or outputs of the SSC or process function.
6. **Time**: By recording the date and time, the events can be sorted into chronological order.
7. **Reference**: Record a reference of the event for later review if identified to be an inflection point.
8. **Event Description**: Providing a description of the event can aid in understanding the changes in performance.
   – From the examples above, "Weld 12SW345 was rejected because the wrong filler material was used by Welder JAD98765" or "Modification A12345 was rejected at final review because of an incorrect assumption critical to an analysis justifying the modification."

**Advantages of change analysis process:**

- Simple to use.
- Results can be used in other fault analysis tools.
- Can be used to identify causes that are not obvious.

**Limitations of change analysis process:**

- The effectiveness of a change analysis is completely dependent on the quantity and quality of data available; to clarify, unintentional or unplanned changes made over history of the SSC or process may not be captured.
- Not all inflection points or changes are guaranteed to be failures, but must be investigated to confirm whether or not they are the failure or a contributing factor that caused the event.

**Key Technical Point**

The change analysis/sequence of events approach is applicable to situations where performance of an SSC or process has deviated over time. Through development of a timeline, or other time-based comparison, change analysis can aid in identifying turning points and/or slow decay in performance over time.

### 2.3.5.7 Failure Analysis Tool: Pareto Chart [23]

Statistical methods, like the Pareto chart (Figures 2-7 and 2-8), are useful in representing variations in processes and SSC performance. A Pareto chart can aid in identifying trends or clusters of issues in process steps or SSC performance. For example, a Pareto chart can provide value in determining mean time between failures (MTBF), mean time to repair (MTTR), schedule compliance, work order backlog, work order age, etc. Statistical tools are typically not thought of as being useful in troubleshooting in the area of failure analysis; however, their application in identifying trends and deviations from a desired outcome can be extremely beneficial.

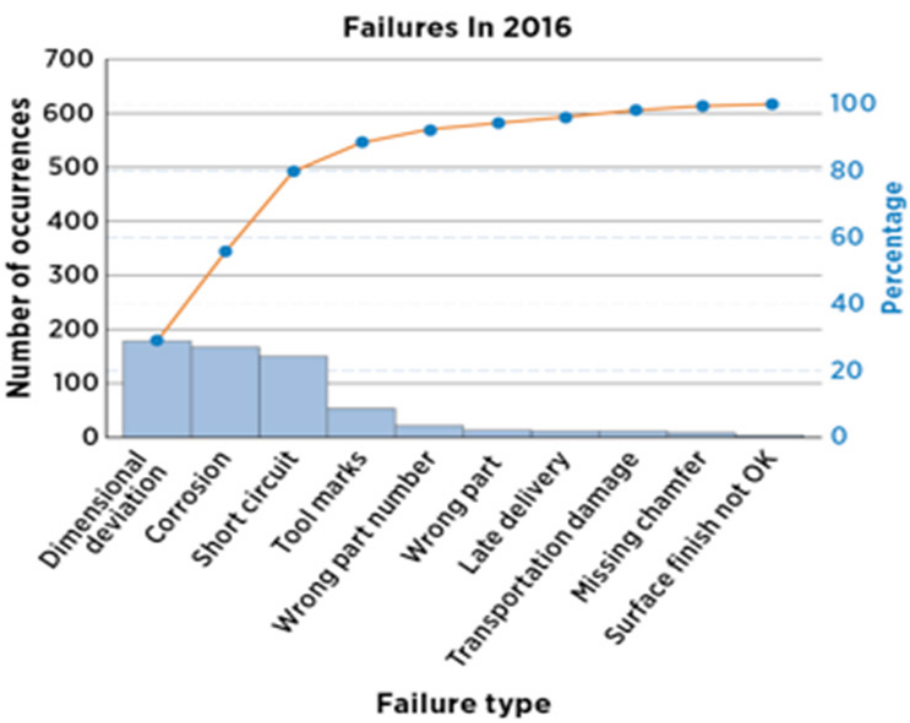


**Figure 2-7**
**Pareto chart example [29]**

A Pareto chart is often referred to as the 80-20 rule, based on the principle that 20% of the issues cause 80% of the problems, or a relatively small number of issues account for an overwhelming share of the problems.

A Pareto chart shows the relative frequency of defects in rank order, allowing one to organize reliability efforts to ensure the return on investment considering the effort, or to address lesser or inconsequential defects compared to larger challenges.

A Pareto chart can be developed using any spreadsheet or charting software. The chart in Figure 2-8 is an example of a Pareto analysis used to identify areas in a maintenance program where the most time and money was spent. For this example, addressing the first item in the chart decreased maintenance expenditures by more than $1 million per year and, most importantly, allowed maintenance resources to be used for other reliability work. The first five items in the chart resulted in $18 million in increased revenue per year.

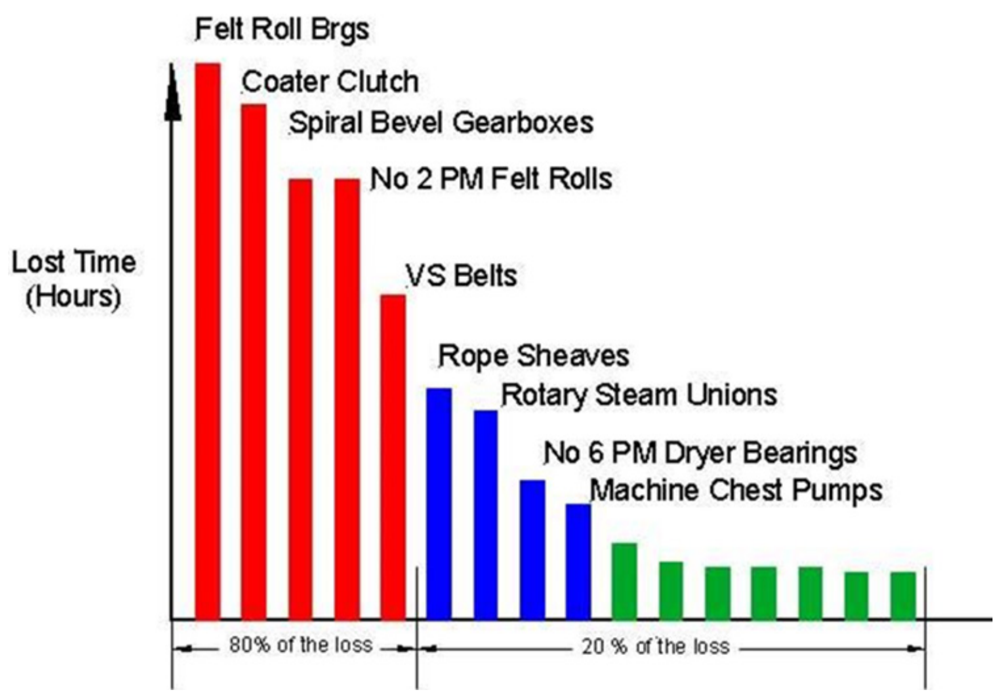


**Figure 2-8**
**Pareto analysis example [18]**

To perform a Pareto analysis for a bar chart comparison:

1. Using the problem statement and information collected in the preliminary assessment and data collection phases, decide what categories you will use to group items.
2. Determine what method of measurement will be used. Effective and common measurements are frequency, quantity, cost, and time.
3. Bound your analysis to a time range (work cycle, day, week, fuel cycle, etc.).
4. From the collected data, populate the categories with sum of the measurements decided upon above.

5. The spreadsheet will allow maintaining the source of each value to refer back to once the areas of interest have been identified so the population is already defined.
6. Decide upon the best units and scale for the measurements collected and categories compared, in order to properly represent the relative magnitudes.
7. Graph the data in a bar chart, designating the left Y-axis for the sum of the measured categories and the bottom X-axis for the categories.
8. Sort and label the total of the measurements for each category.
9. Many groups with smaller or insignificant values independently can be combined and categorized as “other” to reduce numbers of categories to those most significant.

Including a Percentage Comparison (Optional):

1. Designate the right Y-axis for the percentage for each category.
2. Calculate the cumulative sums for each point
3. Divide each cumulative sum by the total sum to determine the cumulative percentage
4. Plot the cumulative percentage in a Scatter Plot style assigning the same X axis values used for the bar chart above.

In summary, the Pareto chart is a simple-to-use and powerful graphic to identify where most problems in a plant originated. It is considered to be more effective in finding opportunities for improvement in processes, as it excels in representing event reoccurrence over a period of time, as demonstrated in the example mentioned above. The Pareto chart is, on average, less effective in troubleshooting events investigating SSC-related failures; however, that depends on the SSC issues being investigated.

**Advantages of the Pareto chart:**

- Chart generation is simple and quickly performed once the data is collected.
- Segregates problems and their causes.
- Applies focus on solving the few causes generating the most problems.
- Identifies problems to focus on in order to get a significant improvement.
- Aids in visualizing problems quickly; excellent visual communication tool [30].
- Templates are available from internet resources and in popular spreadsheet programs.

**Limitations of the Pareto chart:**

- The Pareto principle is a rule of thumb that cannot be applied in all cases.
- If there are many problems, more sub-Pareto charts to segregate are needed, which sometimes may be cumbersome.
- Shows the frequency of a problem; not the severity.
- Focuses on past data, which might not be significant to current or future scenarios [18].

**Key Technical Point**

Statistical methods, like the Pareto chart, are useful in representing variations in processes and SSC performance. A Pareto chart can aid in identifying trends or clusters of issues in process steps or SSC performance.

#### 2.3.5.8 Vendor-Supported Failure Analysis Tools

Appendix F-1 is provided to make members aware of vendor-supported troubleshooting tools. (Note that EPRI does not endorse or recommend specific vendors or products.)

### *2.3.6 Develop Troubleshooting Tasks*

The support/refute failure analysis tool requires the development and execution of tasks to facilitate the supporting or refuting of credible failure modes. Other tools discussed earlier do not explicitly execute tasks in their process flow.

During the failure analysis phase, because the troubleshooting process is iterative, a troubleshooting task plan will be developed to perform the actions and collect the data necessary to identify and confirm the failure mode that caused the event. Troubleshooting should consider both intrusive and non-intrusive actions. At the beginning of the troubleshooting process, the steps/tasks that need to be taken are often unknown; however, by performing the steps/tasks that are required in order to provide solutions to the questions generated from the failure analysis in the proper sequence (non-intrusive to intrusive), the failure mode(s) will be determined.

An example of a troubleshooting task is provided in Attachment 17, “Troubleshooting Task Sheet,” in the Generic Troubleshooting Procedure attached to this guide. Considerations for troubleshooting tasks are listed below for reference:

- Reference documents needed by the station personnel for performing the task.
- Any necessary prerequisites, unit, system, or component status for the task to be performed.
- Sections or steps in proper sequence if portions of approved procedures used for troubleshooting.
- Special tools or Vendor support required for this task.
- Expected results of the troubleshooting activity for normal and faulted condition.
- The degree to which technical measurements and test results are quantified and documented.
- Acceptance criteria for each test/inspection/measurement.
- Contingency actions based on the actual readings/measured results
- Provide “Notification steps” to communication with operations, or other organizations, before performing any steps that will affect/initiate an actuation, alarm, plant computer point, etc.
- Any retests required for operability, if necessary.
- Any plan termination requirement, if necessary.

- Notification for Nuclear ALARA to assist with dose estimates during preparation of task if dose is expected to be accumulated.
- The awareness of possible consequences of initial intrusion into equipment (attaching test equipment, lifting leads, applying power, etc.).
- Specify if any defective/replaced parts or debris/foreign material found during troubleshooting efforts need to be retained for inspection by troubleshooting team. Provisions for preservation of evidence.
- Define hold points and contact information if troubleshooting team members are required to be present during certain activities.
- Provide specific details that are needed to be included in Completion Comments or Documentation from results or data gathered.
- Communication and work hold-points (for example, if inspection by troubleshooting team during the task is needed).
- Attach custom developed sketches, tables, etc. needed for execution of this task.

Prior to performing any troubleshooting tasks, it is essential to consider and plan the sequence in which all of the known the tasks will be executed. The correct sequence is important because the evidence needed to determine if some failure modes exist may be destroyed when certain tasks are performed. For example, performing a reverse flush of a heat exchanger could dislodge and remove material covering a tube sheet, obstructing flow. All non-intrusive maintenance tasks should be performed before intrusive tasks to prevent affecting evidence.

**Key Technical Point**

Troubleshooting should consider both intrusive and non-intrusive actions. At the beginning of the troubleshooting process, the steps/tasks that need to be taken are often unknown; however, by performing the steps/tasks that are required in order to provide solutions to the questions generated from the failure analysis in the proper sequence (non-intrusive to intrusive), the failure mode(s) will be determined.

### 2.3.7 Define Risk, Potential Station Impact, and Expected Results

During work order development, at a minimum, the following information should be taken into consideration to ensure personnel are aware of potential consequences. However, if additional or specific information is needed, the troubleshooting team should provide it.

1. **Risk**: The value of using the established work order process at the station is that risk is assessed through established processes. Risk can be risk to personnel or nuclear safety, possibly affecting a piece of equipment that is in a “protected” status. Another reason to have a work planner assigned to the troubleshooting team is that if special conditions are identified, they can be specifically addressed in the risk analysis and work order task.

2. **Potential station impact**: If the task will result in an impact to the operating station (delays in schedule, unexpected costs, expanded scope, engineering modification required, etc.) this should be captured in the troubleshooting plan. In addition, the troubleshooting lead will need to notify station management. Examples of scenarios where station impacts should be considered are:
   - Operating a piece of equipment for an extended time to acquire data with a temporary monitoring system or data collection unit to support troubleshooting
   - The need for a specialty part that is not available on site
   - The discovery of a design flaw that needs to be evaluated by engineering for acceptability or repair/replacement
   - A situation in which a specialty vendor, needed for additional troubleshooting, cannot arrive immediately
3. **Expected results**: The results expected for a normal and faulted condition that could cause the event, if known, should be defined in the troubleshooting task/work order to educate the maintenance technicians, operators, or other personnel performing the tasks.

### *2.3.8 Execute Troubleshooting Tasks*

When using the normal work management system to implement the troubleshooting task plans developed by the troubleshooting team, the normal process of work order review is applied. This ensures that the shift manager and all supporting organizations are aware of their role in the troubleshooting effort and take the steps necessary to support the work required (for example, clearances, dose estimates, security support, etc.).

To prevent delays in the troubleshooting process, it is good practice for the troubleshooting team lead to brief station management at major milestones and provide updates as agreed upon by management. Often, this is dependent on the severity of the event being investigated through the troubleshooting process. This ensures alignment with the station and prevents delays from re-designing troubleshooting tasks that cannot be performed (system alignments, protected equipment, other work, procedural restrictions, etc.).

It is a best practice to have a member of the troubleshooting team present in the field during execution of tasks for the purpose of observing troubleshooting activities and/or collecting important data that could support or refute credible failure modes, possibly altering the direction of the troubleshooting plan.

As tasks are executed and information is gained, some member fleets will establish a troubleshooting team field lead. The field lead is assigned to be engaged with the organizations implementing the troubleshooting tasks and supporting the troubleshooting team by collecting and communicating relevant data as it becomes available during execution.

**Key Cost Point**

To prevent delays in the troubleshooting process, it is good practice for the troubleshooting team lead to brief station management at major milestones and provide updates as agreed upon by management.

### 2.3.9 Review Data from Troubleshooting Tasks

The consistent review of data collected during all phases of the troubleshooting effort is essential to success. It is an iterative process that persists during data collection and execution of the troubleshooting plans to improve the understanding of the cause of the fault, and to challenge or adjust the current plan. As new information is acquired, the troubleshooting team should consider if the plan requires additional tasks, or can other tasks can be cancelled if they serve a redundant function.

**Note:** At this point, complex troubleshooting merges with the final stages of troubleshooting as shown in the flow chart in Appendix B and as described beginning with Section 2.5 Hold Point – Has the Cause of the Event Been Defined.

## 2.4 Simple Troubleshooting Process

As previously mentioned, simple troubleshooting is the most common troubleshooting approach and should constitute a large percentage of all plant troubleshooting activities. It will normally be led by operations (simple system troubleshooting), a maintenance first-line supervisor, or a maintenance technician (simple component troubleshooting). These plans are typically for SSCs that are out of service and/or will not cause a plant transient or system or component perturbation. Based on best practices from EPRI members and consistent and repeatable implementation, a simple troubleshooting plan should be developed for simple troubleshooting activities to ensure a consistent and thought-out approach. The simple troubleshooting plan can exist as a "templated form" in a procedure or in a work order that contains all of the necessary criteria of the simple troubleshooting plan.

Simple troubleshooting plan activities are generally limited to visual inspection; verification of plant conditions using installed instrumentation; and obtaining data relative to equipment status, input/output values, and readings. As long as the criteria for simple troubleshooting are met per the troubleshooting level determination screening criteria (see Table 2-3 in Section 2.2.5.2), additional failure analysis tools can be used to provide additional detail to ensure that the correct cause(s) are identified for the problem.

Simple troubleshooting is not ideal for troubleshooting process performance due to the limited analysis and data collection that need to be performed. As stated previously, use the complex troubleshooting approach when troubleshooting processes.

Once it has been determined that the simple troubleshooting method will be used, a troubleshooting lead and team will be assigned.

1. Assigning the troubleshooting lead

   The direct supervisor/manager will assign the troubleshooting lead. The troubleshooting lead should be a person who is familiar with the SSC or has experience troubleshooting.

2. Assigning the troubleshooting team

   The direct supervisor/manager will determine the team size and skill set needed for the troubleshooting team in simple troubleshooting evolutions. Because simple troubleshooting is most often performed by maintenance or operations personnel, the troubleshooting team members are typically members of the maintenance team or operations shift that was originally responsible for the activity that led to the event requiring troubleshooting. If personnel familiar with similar events are assigned to other teams or shifts, it can be very valuable to assign them to the troubleshooting team with concurrence from their direct supervisor/manager.

The remainder of this section explains what tasks are performed for a simple troubleshooting plan based on member best practices.

**Key Information Point**

Simple troubleshooting is the most common troubleshooting approach and should constitute a large percentage of all plant troubleshooting activities. It will normally be led by operations (simple system troubleshooting), a maintenance first-line supervisor, or a maintenance technician (simple component troubleshooting).

### *2.4.1 Define Current Facts and Assumptions*

Using the information gained from preliminary assessment and the problem statement as the driver for what facts and assumptions need to be defined, the troubleshooting team could coordinate with knowledgeable maintenance or operations personnel to further define the facts and assumptions that need to be validated via work order tasks or other station processes. It can also be beneficial to review previously executed process documents or work orders to determine what has already been performed, what was effective or ineffective, or what is different from past issues that may rule potential failure modes in or out.

### *2.4.2 Additional Data/Resources/Tools: Find Causes, Validate Assumptions*

In a simple troubleshooting plan, typically the data needed, beyond additional design drawings or vendor manual information, if not contained in procedures, is obtained utilizing non-intrusive measuring and test equipment (M&TE) at isolated test points provided by the equipment design. Station processes may allow collection of data from system or component test connections, as well. Any data collected should be captured in a troubleshooting task, and be mutually agreed upon by the shift manager (or designee) and direct supervisor/manager.

**Note:** Refer to Appendix E for common data sources used in troubleshooting tasks. Resources that should be considered when performing troubleshooting have been compiled in this appendix to prevent redundancy in this guide.

For the sake of efficiency and to utilize the strengths of team members, if the troubleshooting team is large enough, a best practice is to divide the team up to collect the data needed in parallel paths. Suggested divisions of data collection are:

- Assemble data from station databases and record systems
- Assemble data from station personnel
- Assemble data from the scene of the event
- Assemble data from external sources

Using the data that was collected above as inputs, the failure analysis performed in a simple troubleshooting plan should be simpler, less intrusive, and less impactful to the station than a complex troubleshooting plan. As with complex troubleshooting, determining what caused the SSC or process failure resulting in the event is critical to resolving the problem in a timely manner. To ensure proper identification of the cause, the troubleshooting lead should consider using one or two of the failure analysis tools described in the complex troubleshooting section.

The troubleshooting tools best suited for the activities in simple troubleshooting are the fault tree table, 5 Whys, change analysis/sequence of events, and the support/refute table. The Kepner-Tregoe method may be useful, depending on the ability to compare the affected SSC to a correctly functioning SSC. If the Ishikawa diagram, FMEA, or Pareto chart are believed to be the best tools for the problem, then consideration should be given to elevating to a complex troubleshooting plan.

If other deficiencies are identified during the simple troubleshooting activities that are not essential to the correction of the problem, it is a best practice to generate a new corrective action to identify the problem and proceed with simple troubleshooting so focus is not taken away from solving the problem requiring troubleshooting.

**Key Information Point**

In a simple troubleshooting plan, typically the data needed, beyond additional design drawings or vendor manual information, if not contained in procedures, is obtained utilizing non-intrusive measuring and test equipment (M&TE) at isolated test points provided by the equipment design.

### *2.4.3 Develop Troubleshooting Task Plan, Basis, and Expected Results*

1. Troubleshooting task plan

   The simple troubleshooting plan is typically less intrusive than the complex troubleshooting plan and should rely on utilizing existing station/fleet work order processes for implementing simple troubleshooting tasks.

   These activities can be initiated and executed using existing processes that can provide valuable information to the team. Examples include:

   – Vibration/motion amplification video
   – Thermography
   – Clamp-on ammeter
   – Contact pyrometer
   – Acoustical measurements
   – Volt/ohm meter on test/terminal points or panel meters
   – Inspection of components using installed access/inspection ports, etc.

These are typically issued via work orders. Each request should be evaluated by the direct supervisor/manager of the troubleshooting lead to ensure that it will not affect any evidence possibly needed.

2. Basis

   The basis provided with each troubleshooting task is intended to be the supporting data for why the particular troubleshooting task must be performed. The basis is provided to allow reviewing technicians, operators, and the direct supervisor/manager to review the data and understand why a specific task is needed.

3. Expected results

   The results expected for a normal and faulted condition are provided here. Adding this into the troubleshooting task/work order educates the maintenance technicians, operators, or other personnel involved with the tasks.

### *2.4.4 Define Risk and Potential Station Impact*

Because of the nature of simple troubleshooting, it should pose minimal risk or potential station impact, if any; however, every troubleshooting task initiated by a work order should take these considerations into account.

- **Risk**: The value of using the established work order process at the station is that risk is assessed through established processes. Risk can be the risk to personnel or nuclear safety, possibly affecting a piece of equipment that is in a “protected” status. It should be noted that simple troubleshooting plans should have no impact on equipment that could lead to a transient affecting protected or nuclear safety-related equipment. Risk should be addressed during the work order planning phase. If special conditions are identified, they can be specifically addressed in the risk analysis and work order task.
- **Potential station impact**: If the task will result in an impact to the operating station (delays in schedule, unexpected costs, expanded scope, engineering modification required, etc.) this should be captured in the troubleshooting plan. In addition, the troubleshooting lead will need to notify station management. Examples of scenarios where station impacts should be considered are:
  – Operating a piece of equipment for an extended time to acquire data with a temporary monitoring system or data collection unit
  – The need for a specialty part that is not available on site
  – The discovery of a design flaw that needs to be evaluated by engineering for acceptability or repair/replacement
  – A situation in which a specialty vendor, needed for additional troubleshooting, cannot arrive immediately

**Key Technical Point**

Because of the nature of simple troubleshooting, it should pose minimal risk or potential station impact, if any; however, every troubleshooting task initiated by a work order should take these considerations into account.

### *2.4.5 Execute Troubleshooting*

Prior to execution, a simple troubleshooting task will have been processed through the work order development process, obtaining the required reviews for accuracy and station impacts (safety clearance, dose estimate, etc.). A final review and approval from direct supervision should be acquired before performing the pre-job brief conducted before the work is executed.

### *2.4.6 Review Data from Troubleshooting Tasks*

The consistent review of data collected during all phases of the troubleshooting effort is essential to success. This is an iterative process that is ongoing during data collection and execution of the troubleshooting plans. This will improve understanding of the cause of the fault and to challenge or adjust the current plan. As new information is acquired, consider whether the plan requires additional tasks, and whether some tasks can be cancelled if they serve a redundant function.

**Note:** At this point, simple troubleshooting merges with the final stages of troubleshooting as show in the flow chart in Appendix B and as described beginning with Section 2.5 Hold Point – Has Cause of Event Been Defined.

## 2.5 Hold Point – Has the Cause of the Event Been Defined

Following the identification of the failure mode that caused the event, there should be a review of the data collected, work performed, and logic path. This review should be performed by troubleshooting lead, troubleshooting team (if needed), and direct supervisor/manager. This is also a prime opportunity to perform a third-party review.

This hold point exists because the next step is to stop the data collection and investigation process and perform the corrective maintenance activities. This hold point is to validate the failure mode and corrective action. If a corrective action were to be taken based on the wrong failure mode, then the actual failure mode goes unaddressed and the same failure of the SSC could occur when returned to service. Rework like this will add time to restoration of the SSC that can affect the budget, personnel, schedule, or other aspects of the organization.

If the results of implementing the troubleshooting plan provide a high level of confidence that the cause of the problem (and resulting system performance degradation) has been correctly identified, then corrective actions can be planned and scheduled. Confidence is achieved by systematically addressing each failure mode and determining if the cause explains the observed conditions/symptoms.

If the results of implementing the troubleshooting plan do not provide a high confidence level that the cause of the problem has been identified, then the troubleshooting team should consider collecting additional system/component data and/or postulating additional failure modes.

In some cases, the troubleshooting will identify equipment problems that explain only some of the symptoms. When this is the case, it is likely that there will be multiple equipment issues to resolve.

An important caution is that in the absence of a high level of confidence regarding the cause of the failure, replacing a damaged component may result in similar damage to the replacement component. Such failures may occur when the cause of failure is external to the damaged component. For example, a defective input (such as power supply) may damage a circuit board. Before replacement of the board, an evaluation of its inputs should be considered. Following implementation of these corrective actions to resolve known problems, it may be appropriate to reevaluate the remaining symptoms.

**Key Technical Point**

Following the identification of the failure mode that caused the event, there should be a review of the data collected, work performed, and logic path. This review should be performed by troubleshooting lead, troubleshooting team (if needed), and direct supervisor/manager. This is also a prime opportunity to perform a third-party review.

## 2.6 Correcting the Failure Mode That Caused the Event

Following validation that the cause of the event has been correctly identified as per Section 2.5, the corrective actions can be performed to correct the process or repair the SSCs.

The resulting corrective actions may encompass adjustments to the system components. Options include:

- Removing, repairing, and/or replacing the nonconforming item or component containing the faulty item.
  - For example, if a motor has a faulty bearing, replacing the entire motor instead of the faulted bearing.
- Performing SSC maintenance and/or repair.
- Reconfiguring the system via design modification.
- Adjusting system operating parameters.

Once the corrective actions are taken and the system/equipment performance has been restored to operating conditions, follow-up activities are often performed to provide confidence that the problem will not recur.

At this point, follow-up activities, such as return-to-service requirements, inspections, audits, or post-maintenance tests, should be reviewed, to ensure that they will be ready to execute when the SSC or process is returned to service or active status as discussed in the following section. This review should be performed in parallel with the execution of the corrective actions. In addition, any actions for personnel to perform more rigorous trending of the performance of the restored SSC should be developed and issued.

## 2.7 Perform Test to Determine If Troubleshooting Has Been Effective

Following the corrective action and with the high confidence of the troubleshooting team and direct supervisor/manager that the cause of the failure has been corrected, the SSC or process can be returned to service. Following return to service, perform any performance test of the SSC, or audit or dry run of the process.

## 2.8 Review Results – Determine If Troubleshooting Is Effective

If the results are positive and sufficient evidence exists that the failure mode that caused the event in the SSC or process has been corrected, then approval from the shift manager and direct supervisor/manager should be obtained in order to procced to the activities discussed in Section 2.8.2 Completing the Troubleshooting Process.

If the results are not positive and the failure is still present or another failure is identified, then consider notifying the shift manager, station management, and direct supervisor/manager at the earliest opportunity. It is common to assume that if an SSC or process does fail during the re-test following troubleshooting that the previous troubleshooting effort was not effective, and the original failure mode still exists. To mitigate this assumption, the immediate response should be to perform a new preliminary assessment to ensure a new failure mode did not cause the latest failure, and then consider revisiting the failure analysis and data collection phases.

### *2.8.1 Third-Party Troubleshooting Plan Challenges*

Third-party challenges are often performed by fleet or vendor personnel who are not involved with the ongoing troubleshooting team. These provide an outsider's assessment of the problem and are often used to validate the troubleshooting team's actions and conclusions to date. They can be performed at any time during the troubleshooting process; however, there is typically greater value gained near the midpoint (identification of the failure that caused the event) or the end of the troubleshooting effort (prior to performing the performance tests) to review the thought progression of the team and the actions taken and planned. Challenges at these points offer greater value because the majority of the information has been collected, failure analysis has been developed, and the troubleshooting plan is underway or nearly complete. If certain influences of failure modes were not considered, they can be included in the failure analysis and the troubleshooting plan for further investigation or disposition.

When performing third-party troubleshooting plan challenges, it is a best practice to share as much of the troubleshooting plan as possible so the third party can perform their own independent assessment. Examples of third-party challenge questions are provided in Table 2-4.

**Table 2-4**
**Examples of third-party challenge questions**

| Third-Party Challenge Questions | |
|---|---|
| **NOTE:** Human performance, technical conscience, and staffing topics can also be found in some examples; however, those questions are outside the scope of this guide. | |
| 1 | Was the problem properly defined? |
| 2 | What are the design functions, key parameters, and margins? |
| 3 | Was the level of troubleshooting properly screened as simple or complex? |
| 4 | Were the troubleshooting termination/acceptance criteria properly defined and discussed? |
| 5 | Were the troubleshooting activities appropriate to problem/issue (simple versus complex troubleshooting)? |
| 6 | Was this a repeat issue and/or a long-standing issue? |
| 7 | Were other departments (operations, maintenance, etc.) appropriately consulted and involved with the problem/issue? |
| 8 | Was additional equipment monitoring considered? |
| 9 | How have subtle differences, contradictory information, or anomalies in the data been reconciled? |
| 10 | Was industry operating experience considered and appropriately applied? |
| 11 | Were all potential failure modes identified, discussed, challenged, and fully vetted? |
| 12 | Was the troubleshooting team considering “what is the worst that could happen?” as the troubleshooting plan was being developed? |
| 13 | Were proper rigor and justification provided to eliminate and/or confirm failure modes? |
| 14 | Were the troubleshooting activities appropriate to the problem/issue? |
| 15 | Was operational and equipment risk (as well as aggregate risk) discussed and properly assessed? |
| 16 | Was the operational impact of degraded equipment discussed? |
| 17 | What unintended consequences could this have on other components or systems? Consider all operational modes and system lineups? |
| 18 | Were the proper fleet/site subject matter experts (SMEs) on the call or part of the troubleshooting team? |
| 19 | Were the proper industry experts on the call or part of the troubleshooting team? (For example, EPRI, etc.)? |
| 20 | Was the EPRI contacted to provide assistance and collaboration with other EPRI members? |

**Table 2-4 (continued)**
**Examples of third-party challenge questions**

| **Third-Party Challenge Questions (continued)** | |
|---|---|
| 21 | Were the proper vendors or original equipment manufacturers (OEMs) on the call or part of the troubleshooting team? |
| 22 | Was the vendor or OEM inspection, assessment, and conclusion properly challenged? |
| 23 | Was engineering judgement appropriately applied? |
| 24 | Were the individuals who were involved with reviews or who provided advice qualified to provide support in the roles they performed? |
| 25 | Were all steps taken clearly understood, with the basis properly provided? |
| 26 | Were assumptions that were made properly vetted, or tracked with conditional tasks? |
| 27 | Were any steps or actions taken that would be regarded as being outside industry operating experience? |
| 28 | Have all actions been recorded and assigned to appropriate personnel with appropriate due dates? |
| 29 | Review all actions and assign owners prior to ending challenge. |
| 30 | Were the challenge call questions sufficiently intrusive? |
| 31 | Is a follow-up third-party challenge needed at a later time? |

**Key Human Performance Point**

There is typically greater value gained from third-party challenges near the midpoint (identification of the failure that caused the event) or the end of the troubleshooting effort (prior to performing the performance tests) to review the thought progression of the team and the actions taken and planned. Challenges at these points offer greater value because the majority of the information has been collected, failure analysis has been developed, and the troubleshooting plan is underway or nearly complete. If certain influences of failure modes were not considered, they can be included in the failure analysis and the troubleshooting plan for further investigation or disposition.

### *2.8.2 Completing the Troubleshooting Process*

#### 2.8.2.1 Root Cause Analysis

In some cases, the cause of the degraded performance may be pinpointed to a discrete component or part that is not conforming to design requirements, and the reason why has been discovered (for example, the item is out of calibration, has catastrophically failed, or is worn out or damaged). In these cases, the root cause of the degraded system performance was discovered during the implementation of the troubleshooting plan, and typically the only follow-up actions necessary are to document results of the troubleshooting effort and to trend the performance of the restored system/equipment.

In other cases, however, the problem may not get pinpointed to a particular component or part, but there is high confidence that the cause is attributable to a larger assembly that can be removed and replaced with a conforming item. In these cases, the root cause of the problem has not yet been discovered, but the troubleshooting process has been successful in finding or "bracketing" the general problem, taking the appropriate corrective actions, and restoring the system to design operating conditions. Although the root cause may not have been discovered during the implementation of the troubleshooting plan, there is still a very high level of confidence that the problem will not recur. Thus, the need for performing follow-up root cause analysis on the nonconforming equipment that was removed and replaced becomes a business decision and is not necessarily considered part of the troubleshooting plan or process.

#### 2.8.2.2 Documentation and System/Equipment Performance Monitoring

Successful troubleshooting efforts should be documented for future reference. The performance of the restored system/equipment should also be monitored and documented. Both of these documentation activities should be described in the troubleshooting plan. If they are implemented properly, they will contribute greatly to the building of a useful and historical troubleshooting reference database.

At minimum, industry best practice is to include a copy of the completed troubleshooting plan in the originating corrective action and the corrective work order.

It is recommended to consider sharing the completed troubleshooting plan and corrective action with the industry to enable shared learnings from the operating experience via the Institute of Nuclear Power Operations (INPO) or the World Association of Nuclear Operators (WANO).

EPRI NMAC requests that completed troubleshooting and corrective action plans be submitted for review and inclusion in the PMBD and/or PMBDTK, as applicable. This will further improve the information in the two databases, to assist other members when they are evaluating maintenance strategies and performing troubleshooting. The information can be shared by emailing the completed troubleshooting plan and corrective action to EPRI NMAC at nmachotline@epri.com.

## 2.9 Related Follow-Up Activities

In addition to formal root cause analysis, related follow-up activities might include:

1. Debriefing of the troubleshooting team by the troubleshooting lead, and capture of lessons learned
2. Additional training on the troubleshooting process
3. Training on failure modes and effects analysis
4. Communicating lessons learned and best practices with the station, fleet, industry, and EPRI
5. Procedural revision and enhancement
6. Equipment operational enhancements

7. System design modification
8. Modification of predictive or preventive maintenance practices
9. Enhanced monitoring of system/equipment performance
10. 10CFR Part 21 reporting of defects or notification to the vendor if not under the requirements of 10CFR Part 21 (or other similar directives)
11. Equipment surveillance activities related to compliance with the Maintenance Rule
12. Post-maintenance activities

Like formal root cause analysis, the need for performing these follow-up activities becomes a business decision and is not necessarily considered part of the troubleshooting plan or process.

## 2.10 EPRI Specialty Troubleshooting Guidance

This section is developed with information available at the time of the release of this guide. It is not intended to encompass all of the guidance that EPRI has to offer in regard to troubleshooting; however, it will provide two tools specifically designed to facilitate troubleshooting and performance monitoring and improvement of SSCs, as presented in the appendices listed below. These are products of EPRI's Plant Engineering Programs. It is common practice for technical guidance developed by EPRI NMAC and Plant Engineering Programs to contain sections specific to troubleshooting. Those resources are not listed.

- Appendix G Troubleshooting Thermal Performance Issues
- Appendix H Troubleshooting Medium Voltage Cable Fault Location for Nuclear Power

# 3
# ADVANCES IN TROUBLESHOOTING

## 3.1 Member Advances in Troubleshooting

During the development of this guide, while interacting with the Technical Advisory Group, it was discovered that many EPRI members are advancing the area of troubleshooting in ways that are worth describing for the consideration of other members.

Examples of advances in troubleshooting and other areas applicable to the troubleshooting process are provided below.

### *3.1.1 Member Offering: Preliminary Assessment Questionnaire*

In a form similar to one presented in Appendix D of this guide, a member is providing a preliminary assessment questionnaire as an optional approach to obtaining additional and valuable information during the following three phases of new work order requests or corrective action generation:

1. When personnel are creating a new corrective action or work order request
2. When plant operators review a new corrective action or work order request
3. Following routing:
   - When the new work order request is routed to maintenance for correction
   - When the new corrective action is routed to the appropriate personnel for resolution

### *3.1.2 Member Offering: Previous Failure Analysis*

A member is offering previous failure analysis for the components identified during new work order request or corrective action creation. When personnel are creating a new corrective action or work order request, a member is presenting past failure analysis performed on the component(s) identified in the new work order request or corrective action creation. This allows the personnel to review the past problems that have occurred with related/similar components and determine if a previously completed analysis is applicable to the witnessed event.

### *3.1.3 Member Offering: Advanced Software and Data Analytics*

An EPRI member that operates several nuclear plants has recognized that the current process in place for troubleshooting is not systematic or consistently implemented across their fleet. This inefficiency leads to wasted time and effort along with requiring increased staffing to meet administrative requirements, during a time when staffing across the nuclear fleets is being reduced in response to economic challenges. To improve efficiency and consistency, the member has decided to leverage an existing platform to facilitate their troubleshooting process as listed below:

- Leverage the existing fleetwide platform to facilitate a consistent and systematic approach to troubleshooting through software-driven processes.
- Focus on a common support/refute matrix template that can import information from past troubleshooting, including recommended actions and potential causes.
- Leverage the software platform to create a common failure modes/mechanisms library for components in the fleet.
- Import past troubleshooting documents into the platform for convenient access for referencing during troubleshooting activities.
- Leverage the new software tool to aid in developing the risk ranking that is needed for the operational decision-making process if plant conditions at the time of issue identification prevent completion of a troubleshooting plan or if troubleshooting fails to determine the failure mode of the SSC.

## 3.2 Consolidation of EPRI Data to Create the PMBDTK

EPRI, through the creation of the Preventive Maintenance Basis Database Troubleshooting Knowledgebase (PMBDTK), has consolidated over 50,000 failure modes for over 500 unique components into a single database. This database is available to members in raw form via a Microsoft Excel file download for use in their own application or via the PMBD following the version 5.0 release. This database will be further developed by EPRI through collaboration with its members to continue advancements in the area of troubleshooting. More information is available in Appendix J.

# 4
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## 4.2 EPRI Member Procedures


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# A KEY POINTS

## A.1 Key Cost Point

| Page | Key Point |
|---|---|
| 2-28 | To prevent delays in the troubleshooting process, it is good practice for the troubleshooting team lead to brief station management at major milestones and provide updates as agreed upon by management. |

## A.2 Key Technical Points

| Page | Key Point |
|---|---|
| 2-4 | To be effective, the preliminary assessment of the situation requiring troubleshooting needs to be prompt and flexible but regimented enough to get the information needed for all scenarios. |
| 2-8 | A work planner assigned and stationed in the same area as the troubleshooting team can develop needed work order tasks in parallel with discussions. In addition, work planners are familiar with the processes that exist to perform the needed tasks, whereas other personnel (engineers, operations, etc.) may not be familiar with the maintenance procedures in existence. |
| 2-18 | It is important to note that typically an FMEA is performed before the SSC or process (if applicable) is placed into service. However, if an FMEA has not been performed historically, performing one can be advantageous both to the current event investigation and in preventing future events. |
| 2-21 | The value of a support/refute process is that each failure mode is proven or disproven to be the cause of the event. This identification of the actual failure mode through investigation and elimination of other credible failure modes can provide a high level of confidence that the failure mode identified as the cause is the actual cause of the event. |
| 2-23 | The change analysis/sequence of events approach is applicable to situations where performance of an SSC or process has deviated over time. Through development of a timeline, or other time-based comparison, change analysis can aid in identifying turning points and/or slow decay in performance over time. |
| 2-26 | Statistical methods, like the Pareto chart, are useful in representing variations in processes and SSC performance. A Pareto chart can aid in identifying trends or clusters of issues in process steps or SSC performance. |
| 2-27 | Troubleshooting should consider both intrusive and non-intrusive actions. At the beginning of the troubleshooting process, the steps/tasks that need to be taken are often unknown; however, by performing the steps/tasks that are required in order to provide solutions to the questions generated from the failure analysis in the proper sequence (non-intrusive to intrusive), the failure mode(s) will be determined. |
| 2-33 | Because of the nature of simple troubleshooting, it should pose minimal risk or potential station impact, if any; however, every troubleshooting task initiated by a work order should take these considerations into account. |
| 2-34 | Following the identification of the failure mode that caused the event, there should be a review of the data collected, work performed, and logic path. This review should be performed by troubleshooting lead, troubleshooting team (if needed), and direct supervisor/manager. This is also a prime opportunity to perform a third-party review. |

## A.3 Key Human Performance Points

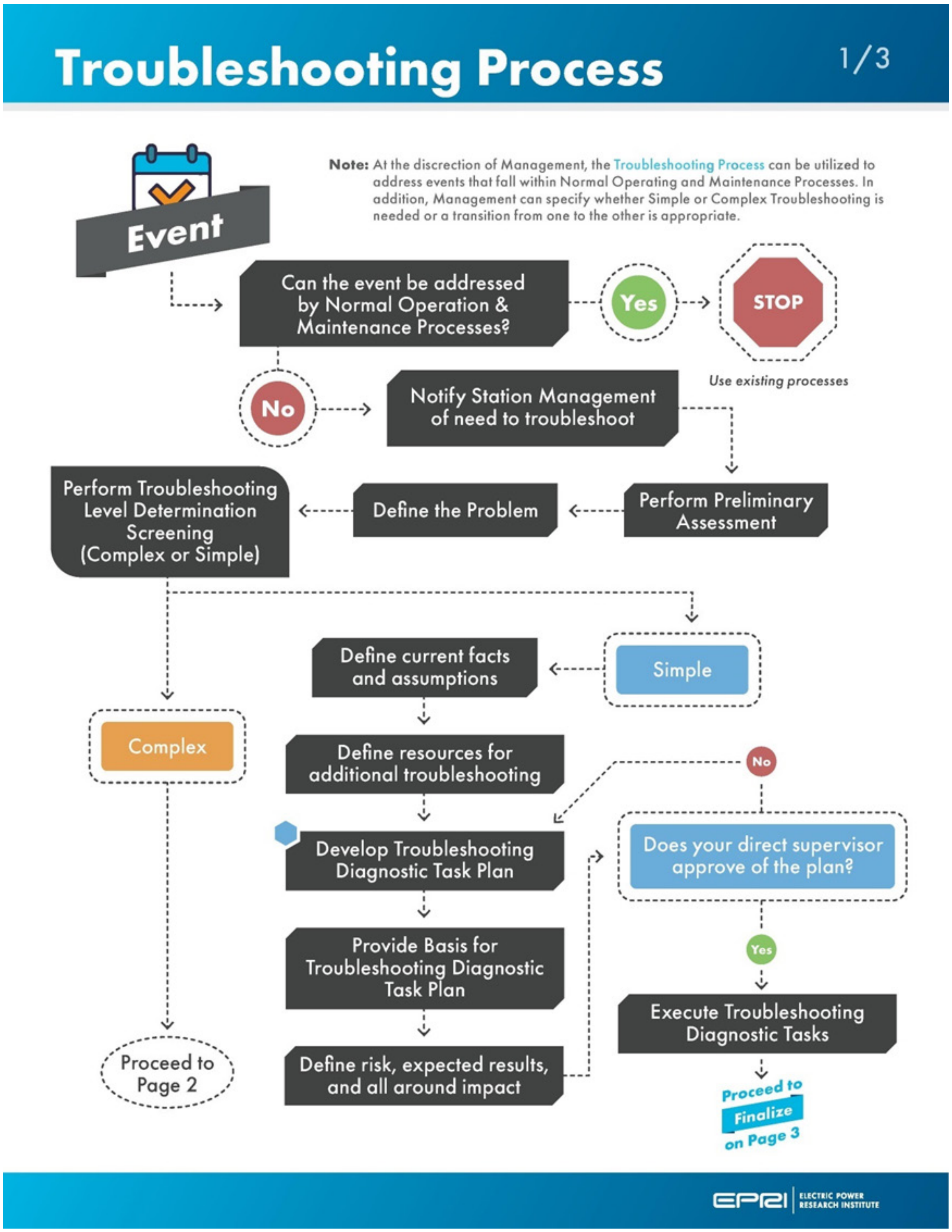
| Page | Key Point |
|---|---|
| 2-2 | Simply put, if guidance does not exist, personnel should stop and consider if it is time to enter the troubleshooting process. |
| 2-4 | During the development of the problem statement, it is not appropriate to speculate about the source of the problem, nor is it yet practical to offer corrective actions. |
| 2-9 | Whenever practical, the troubleshooting team should be located in a common area (conference room) to facilitate the collaboration and focus necessary during complex troubleshooting events. |
| 2-37 | There is typically greater value gained from third-party challenges near the midpoint (identification of the failure that caused the event) or the end of the troubleshooting effort (prior to performing the performance tests) to review the thought progression of the team and the actions taken and planned. Challenges at these points offer greater value because the majority of the information has been collected, failure analysis has been developed, and the troubleshooting plan is underway or nearly complete. If certain influences of failure modes were not considered, they can be included in the failure analysis and the troubleshooting plan for further investigation or disposition. |

## A.4 Key Information Points

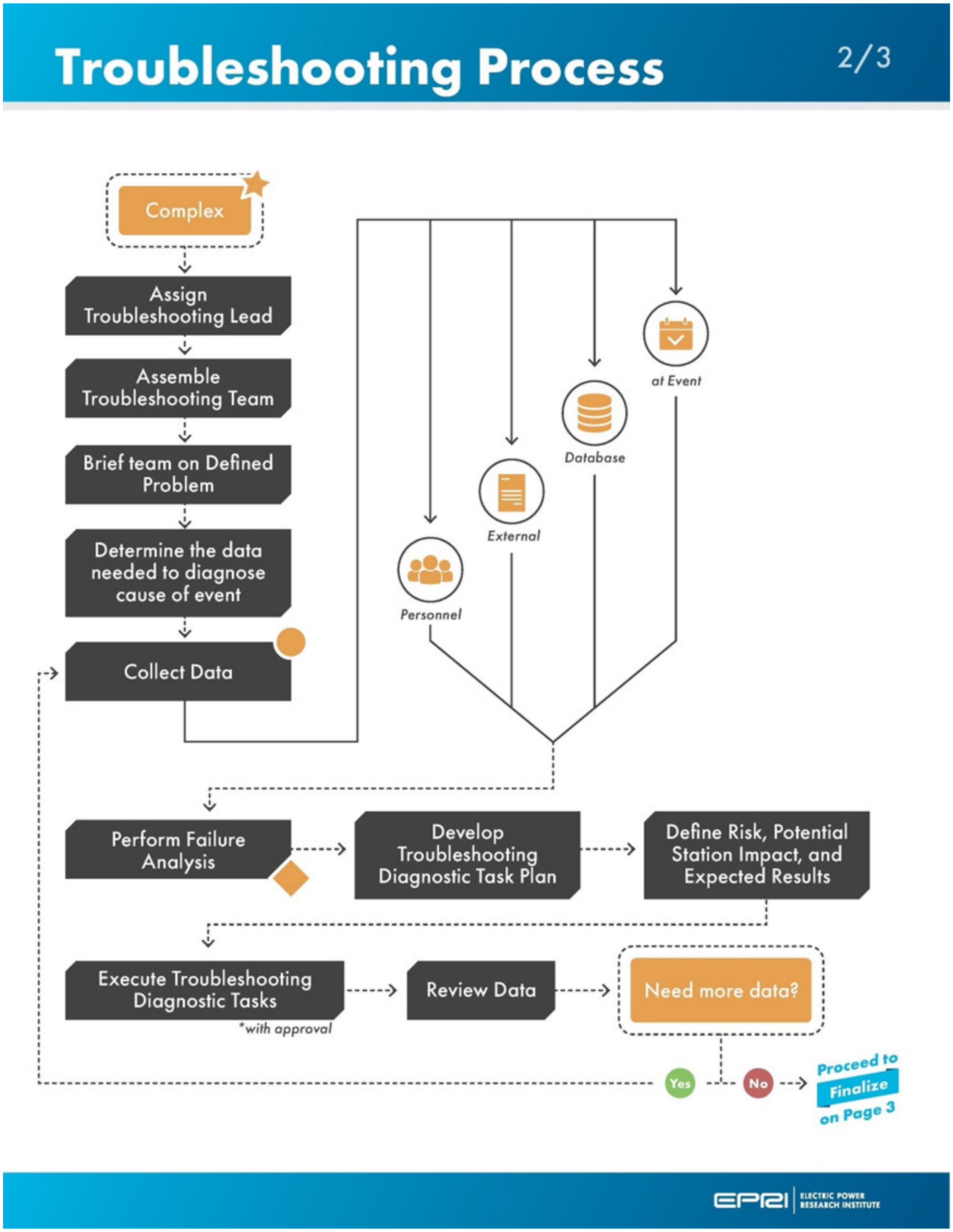
| Page | Key Point |
|---|---|
| 2-12 | The fault tree analysis is one of the most widely used methods in system reliability, maintainability, and safety analysis. It is a deductive process used to determine the various combinations of hardware/software failures and human errors that could cause undesired events for the SSC or process. |
| 2-15 | The 5 Whys process is based on the simple question of “Why?” With the problem defined, the troubleshooting team asks, “Why did this problem occur?” The possible causes of the problem are then recorded as “Because…” statements. Each “Because” is then subjected to further “Why” questions. This process repeats until the root cause has been defined. |
| 2-21 | Support/refute matrices are the most widely used failure analysis tool in troubleshooting procedures by the EPRI member population. |
| 2-30 | Simple troubleshooting is the most common troubleshooting approach and should constitute a large percentage of all plant troubleshooting activities. It will normally be led by operations (simple system troubleshooting), a maintenance first-line supervisor, or a maintenance technician (simple component troubleshooting). |
| 2-31 | In a simple troubleshooting plan, typically the data needed, beyond additional design drawings or vendor manual information, if not contained in procedures, is obtained utilizing non-intrusive measuring and test equipment (M&TE) at isolated test points provided by the equipment design. |

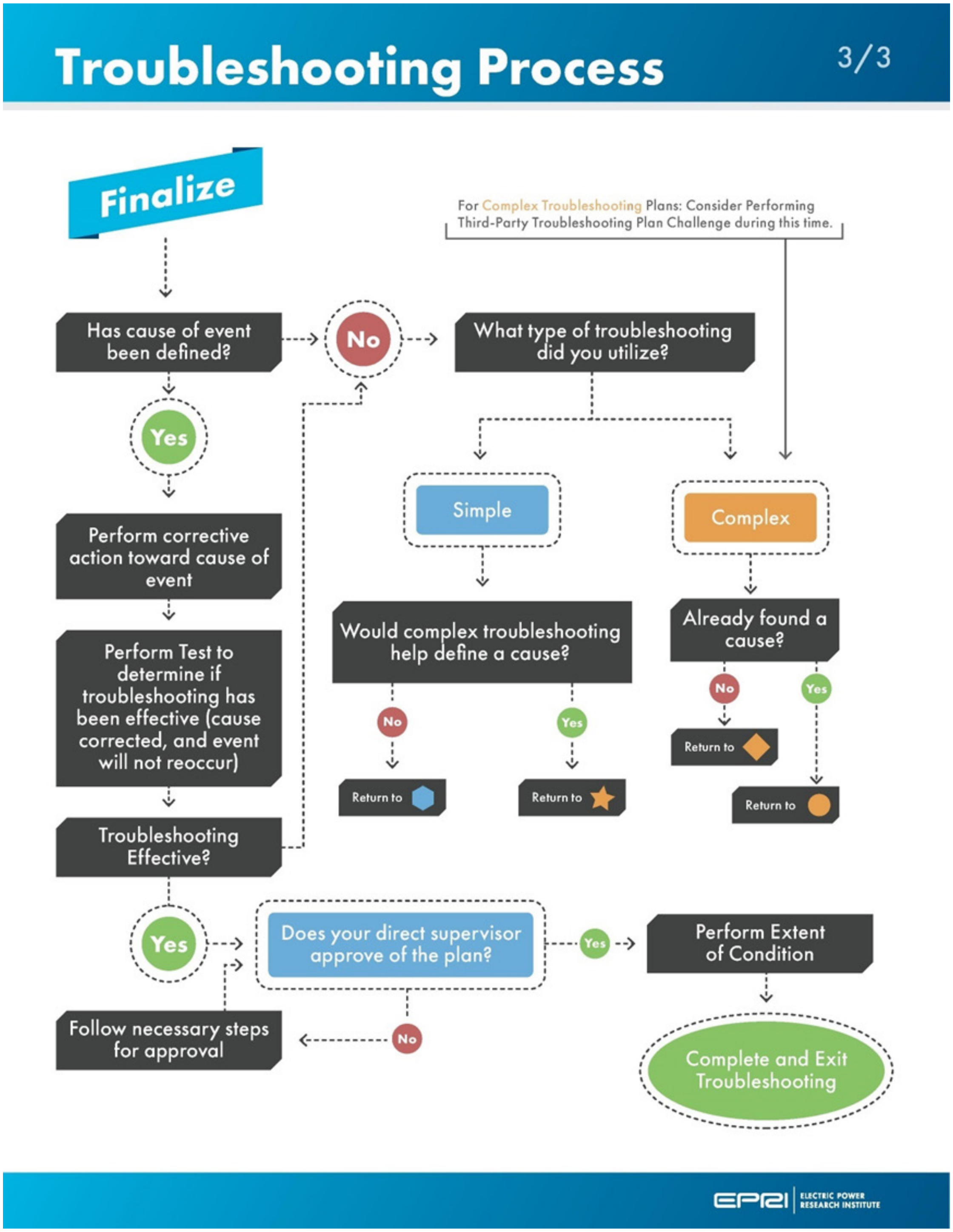
# B

# TROUBLESHOOTING PROCESS FLOW PATH



*Troubleshooting Process Flow Path*





Troubleshooting Process
3/3
Finalize
For Complex Troubleshooting Plans: Consider Performing Third-Party Troubleshooting Plan Challenge during this time.
Has cause of event been defined?
No
What type of troubleshooting did you utilize?
Yes
Simple
Complex
Perform corrective action toward cause of event
Would complex troubleshooting help define a cause?
Already found a cause?
Perform Test to determine if troubleshooting has been effective (cause corrected, and event will not reoccur)
No
Yes
No
Yes
Return to
Return to
Return to
Return to
Troubleshooting Effective?
Yes
Does your direct supervisor approve of the plan?
Yes
Perform Extent of Condition
Follow necessary steps for approval
No
Complete and Exit Troubleshooting
EPRI
ELECTRIC POWER RESEARCH INSTITUTE

# C
# CASE STUDIES

This appendix presents a collection of excerpts from operating experience of EPRI members, or other sources as noted, that have been converted into case studies to demonstrate how different failure analysis tools can be used in the troubleshooting process.

It is not the intent of this section to provide full case studies. Rather, portions relevant to understanding how the respective failure analysis tools were used are presented.

## C.1 Case Study 1: Pareto Chart Case Study – Using the Pareto Chart to Uncover Reliability Problems Obscured by the Volume of Plant Work Requests

*Special thanks are extended to Efficient Plant Magazine (https://www.efficientplantmag.com/) for permission to reprint "Using Pareto Analysis to Focus Reliability Improvements." This article is presented in its entirety with only minor edits to anonymize member and vendor information at the request of Efficient Plant Magazine.*

An EPRI member nuclear power plant in the United States took a proactive approach in 2003 to identify and improve equipment performance. Power plants like this one have more than 100,000 components. Personnel perform thousands of maintenance activities annually.

With large organizations and personnel turnover, many equipment reliability issues can go unnoticed or even become "expected" maintenance. It is not always easy to identify equipment that degrades prematurely when it occurs over many years with different people involved.

All plant components require some level of maintenance over time. Some contribute more than others to the maintenance workload. To minimize operation and maintenance costs, plant equipment needs to operate at a maximum maintenance interval. The component engineering group at the plant employed a simple statistical method known as a Pareto analysis that, when applied to maintenance work requests, can identify the equipment that contributes the most to the plant maintenance workload.

### *C.1.1 Conducting Pareto Analysis*

A Pareto analysis is conducted by adding the number of work requests for each component type over the time frame of interest. When ordered by the count of work requests for each component, the analysis identifies the "vital few" components that contribute the most to plant maintenance and distinguishes them from the "trivial many" that have a small contribution. The objective is to then take action to reduce the vital few into the trivial many.

Work requests from 2001-2003 were reviewed at the plant and sorted by equipment type. The counts for equipment that comprised 40 percent of all maintenance performed at the plant over the 3-year period are shown in Figure C-1.

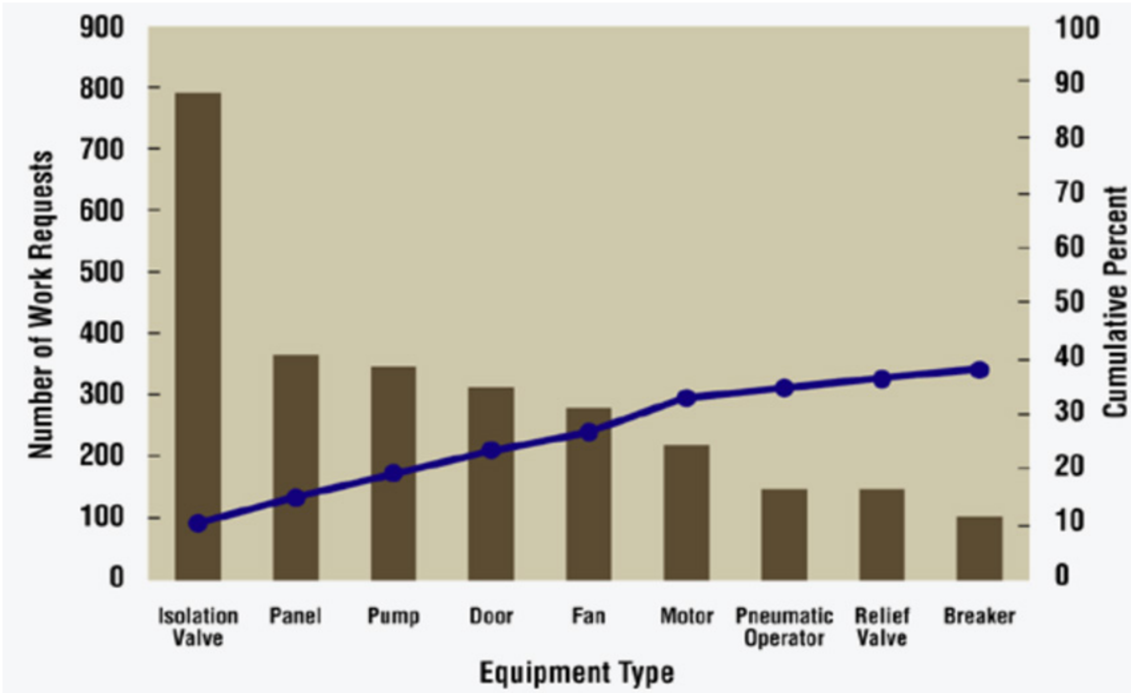



**Figure C-1**
**Breakdown of work request by equipment type (courtesy of *Efficient Plant Magazine*)**

There are several hundred equipment types in use at the plant. The benefit of this systematic breakdown is a focused review of a limited number of components. In this case, nine equipment types were involved: isolation valve, panel, pump, door, fan, motor, pneumatic operator, relief valve, and breaker.

### *C.1.2 Breakdown by Manufacturer, Model*

The work requests for a specific equipment type are reviewed by manufacturer and model. The information for one equipment type, fans, is illustrated in Figure C-2.

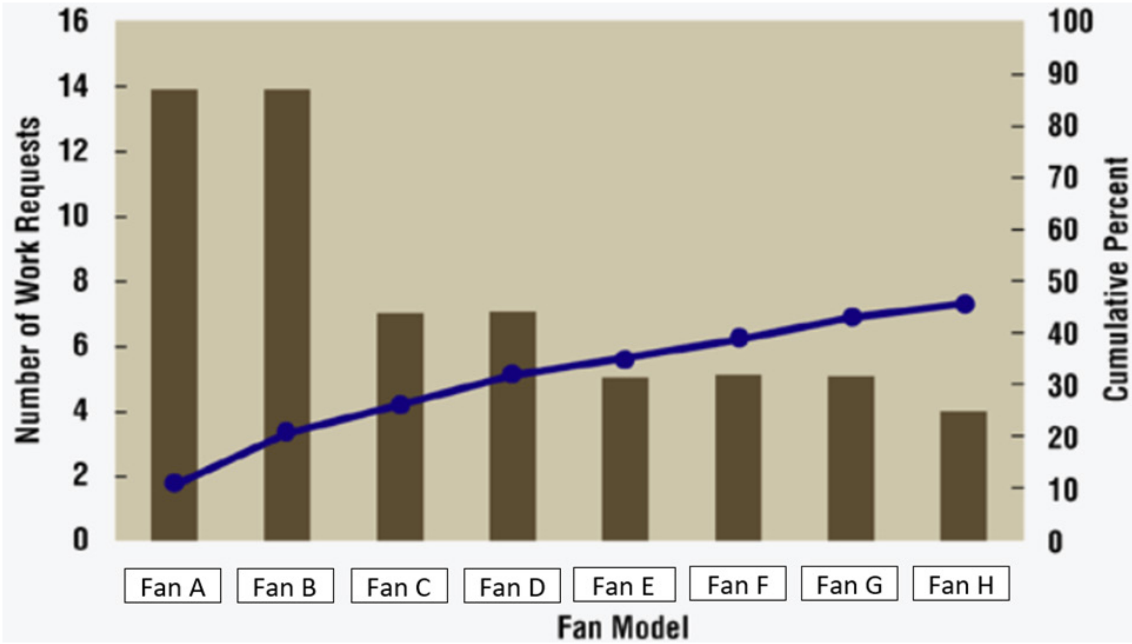



**Figure C-2**
**Breakdown of fan work requests by model number (courtesy of *Efficient Plant Magazine*)**

Of the 58 fan models at the plant, eight models required nearly 50 percent of the fan maintenance work during the 2001–2003 period. Again, this systematic breakdown permits a focused review of a manageable number of fan applications.

Of the 14 work requests on the model FAN B fans (a centrifugal belt driven fan), 36 percent were triggered by vibration and 64 percent by loose belts (Figure C-3). A study of corrective maintenance work orders revealed that bearings had failed.

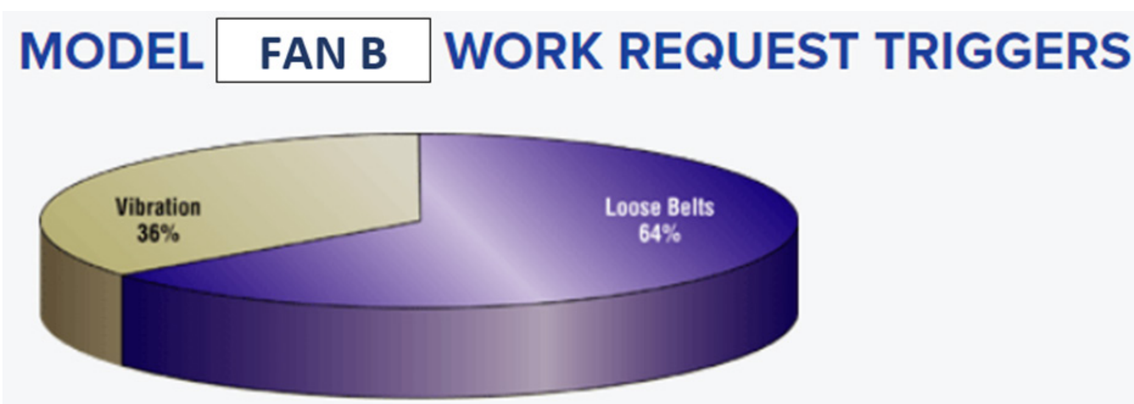



**Figure C-3**
**Breakdown of fan work request triggers for model FAN B (courtesy of *Efficient Plant Magazine*)**

The cam-lock style roller element bearings (MODEL A-123) were failing on an average of every 2-3 years compared to their L10 design life of 12-15 years. A thorough review was conducted of the maintenance practices for belt and bearing replacements, the preventive maintenance strategy employed on the fan, and the design of the fan.

Discussions with the bearing manufacturer identified a problem with the site maintenance practice which did not require relocking the collar of the bearing after the run-in of fan belts. Additionally, a more reliable bearing was identified for the application that is expected to improve the overall reliability of the fan. The result of these improvements will reduce fan maintenance at the plant by $21,900.

### *C.1.3 Same Approach Applied to Isolation Valves*

The same systematic approach was used for isolation valves. Since initial plant operation in the late 1980s, the plant had experienced repeated position indication (for example, dual indication or loss of indication) with a particular manufacturer's solenoid valves. The solenoid valves use a reed switch assembly and a magnet mounted on the valve stem to actuate open or closed lights on the main control room panels.

Over the years various root cause analyses focused on the switch assembly and maintenance practices for adjusting the reed switches. Modifications to the reed switch bracket and enhancements to the maintenance procedures did improve reliability. However, a significant number of these position indication problems were still occurring.

A Pareto analysis (Figure C-4) of position indication failures by valve model number was conducted over a 10-year period from 1994 through 2003. Three models were responsible for 75 percent of the problems. Recognizing this permitted a focused comparison that identified the same three models had a relay in the position indication electrical circuit. The other models did not have the relay.

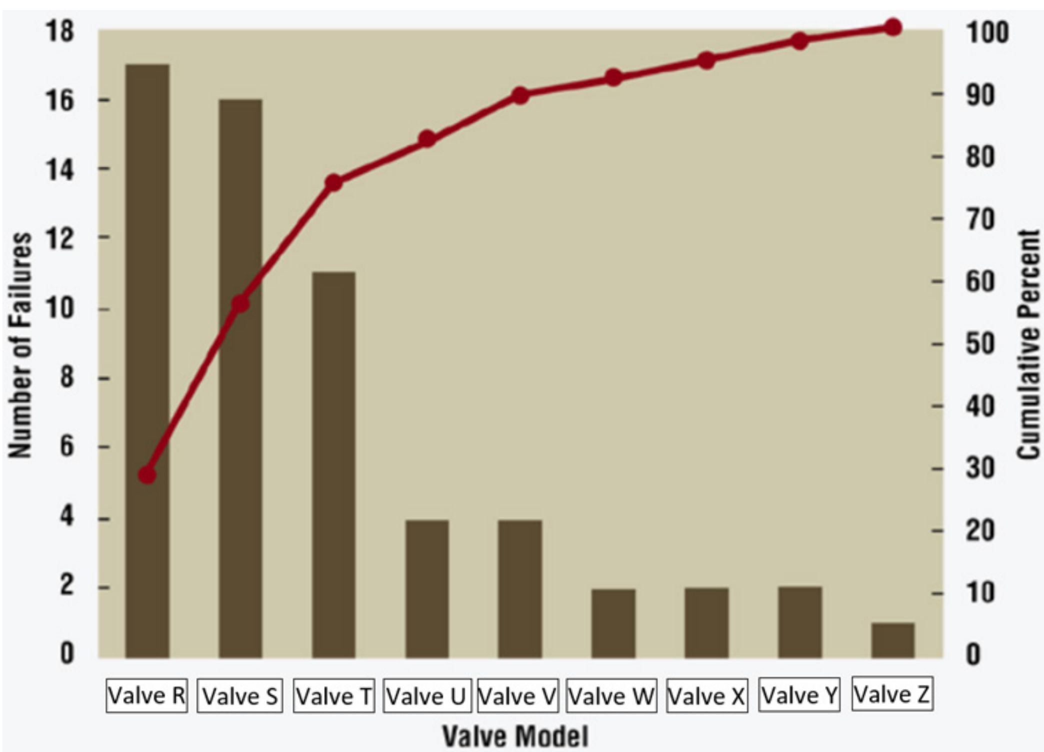



**Figure C-4**
**Breakdown of solenoid valve position indication failures, 1994-2003, by model numbers (courtesy of *Efficient Plant Magazine*)**

Mock-up testing verified the relay was causing excessive voltage spikes across the reed switch contacts that resulted in electrical arcing. Over time, the condition would result in micro-welding the reed-switch contacts together thus producing a malfunction of the position indication. The solution was to install a low cost varistor for voltage suppression that will eliminate the electrical arcing. The expected savings in maintenance is $68,000.

### *C.1.4 Focus the Investigation*

In both of these examples the Pareto analysis provided a systematic breakdown of work requests to focus on the vital few components that have the highest contribution to plant maintenance. The further breakdown of this data by equipment model number and the cause of the equipment degradation focused available resources on a limited number of applications that required investigation. The investigation of the corrective maintenance procedures, preventive maintenance strategies, and equipment design revealed equipment that was not operating at the optimum maintenance interval.

The Pareto analysis was effective at uncovering the equipment reliability problems. Once the problem is recognized, a solution can be formulated. The systematic application of a Pareto analysis resulted in improved equipment reliability and reduced equipment maintenance.

This case study was developed by *Efficient Plant Magazine* (https://www.efficientplantmag.com/). This article is presented in its entirety with only minor edits to anonymize member and vendor information. https://www.efficientplantmag.com/2005/01/using-pareto-analysis-to-focus-reliability-improvements/

## C.2 Case Study 2: Why Staircase – Residual Heat Removal Motor Operated Valve Failed to Open

*Permission provided from originator of the operating experience. Request was made to anonymize the operating experience.*

### *C.2.1 Abstract*

Residual Heat Removal (RHR) Motor Operated Outboard Injection Valve (RHR-MOV-1B) failed to open when the control switch was placed in the open position. This was because the motor pinion gear of the Valve Operator (RHR-MO-M1B) shifted on the motor shaft and broke.

Consequence: This resulted in RHR Low Pressure Coolant Injection (LPCI) Subsystem B being inoperable and a Maintenance Rule Functional Failure. Plant operation and personnel safety were not affected.

Cause: Optimal set screw length had not been provided in the procedure, along with a lack of verification during gear installation that sufficient shaft material existed at the end of the shaft for set screw holding force.

### C.2.2 Description

During routine operability testing of RHR LPCI Subsystem B valves in accordance with surveillance procedures, the LPCI outboard injection MOV, RHR-MOV-M1B, failed to open from its closed position. The control room indication light for the open direction never illuminated. After determining that the indication light was not malfunctioning, an Operator dispatched to the area confirmed that the motor had started but had not resulted in valve movement.

The valve team members used the Why staircase in Table C-1 to begin investigating the condition. By asking “why” and finding out the answer (“because”), they found that when the motor was removed from the Limitorque gearbox housing, there was no motor pinion gear attached to the motor shaft. No key was found in the shaft keyway.

**Table C-1**
**Why staircase example 1**

| | |
|---|---|
| 1st Why: | Why did the RHR-MOV-MO27B motor pinion gear fail? |
| 1st Because: | The motor pinion gear failed due to material overload. |
| 2nd Why: | Why did the motor pinion gear become overloaded? |
| 2nd Because: | The motor pinion gear was overloaded because it had moved on the shaft. |
| 3rd Why: | Why did the motor pinion gear move on the shaft? |
| 3rd Because: | The gear moved on the shaft due to lack of friction fit and inability for the set screw to hold. |
| 4th Why: | Why didn't the set screw hold? |
| 4th Because: | The set screw did not hold due to failure of minimal shaft edge material and shallow dimple. |
| 5th Why: | Why did the shaft material fail at the edge? |
| 5th Because: | The set screw indentation, or dimple, was drilled too close to the edge of the shaft. Past drilling of the set screw dimple for different motor pinion gears had caused loss of critical material near the end of the shaft such that holding force of the set screw for the helical gear axial loads had been diminished. |

A search through the gearbox clutch housing found the motor pinion gear broken into three pieces. The motor pinion key, however, was intact but deformed. The worm shaft drive gear was not damaged. The motor pinion set screw was in position on the broken gear and had torn through the wall of the set screw dimple. Excess lubricant was removed, and valve team members inspected the clutch cavity. No other internal subcomponents were missing or damaged.

The set screw indentation, or dimple, was drilled too close to the edge of the shaft. The set screw dimple had been egg-shaped due to past installations that had not been perfectly aligned between different motor pinion gears. The set screw dimple was confirmed to be of appropriate depth and the set screw had been well-seated into the bottom of the dimple. Past drilling of the set screw dimple for different motor pinion gears had caused loss of critical material near the end of the shaft such that holding force of the set screw for the helical gear axial loads had been diminished.

The MOV is equipped with an SB-4 size 3600-RPM speed Limitorque actuator and a 24-inch (61-cm) globe valve that is used for RHR injection and shutdown cooling throttling purposes. For this size of actuator, plant procedures allow installation of a set screw that could be 1/4 inch

(6.3 mm) in length or 5/16 inch (8 mm) in length, in addition to the Limitorque Maintenance Update 13-01 prescribed optimal length of 3/8 inch (9.5 mm). The use of the shorter set screw is a contributor to this failure. It did not meet current Limitorque guidelines for optimal installation.

### C.2.3 Cause Summary

The following details/steps were provided in the procedure:

- Required set screw length for proper engagement
- Verification step during preventive maintenance that sufficient material existed at the end of the shaft to retain set screw

### C.2.4 Corrective Action Summary

Corrective Action: Installed a 3/8-inch (9.5-mm) set screw in the RHR-MOV-M1B and the dimple depth was drilled deeper to accept this set screw.

### C.2.5 Preventive Action

1. Revise Maintenance Procedures to incorporate Limitorque size-specific optimal set screw length and verify end of shaft material adequacy.
2. Inspect opposite division (RHR-MOV-M1A) motor pinion gear set screw for optimal length and wall material of spot drill indentation.

## C.3 Case Study 3: Why Staircase and Sequence of Events – Service Water Pump Failed to Start on Blackout Sequence

*Permission provided from originator of the operating experience. Request was made to anonymize the operating experience.*

### C.3.1 Problem Statement

On 1/2/20XX at approximately 1800 hours, during the sequencing of the Safeguards loads on Emergency Bus E1 and Emergency Diesel Generator (EDG) A, Service Water Pump (SWP) A failed to start.

The expectation is that such equipment, critical to the safe operation of the plant, should perform as designed when called upon.

The consequence of the 25/20B (Service Water Pump A) breaker's failure to close resulted in:

- Operations personnel having to compensate/intervene to account for the loss of the service water pump A failure to auto start.
- A Maintenance Rule Failure
- A Mitigating Systems Performance Index failure
- Entry into Limiting Condition of Operability (LCO) 3.7.7, per Technical Specifications, for loss of a train of Service Water.

### *C.3.2 Background*

On 1/2/20XX at approximately 1300 hours, Operations personnel attempted to transfer 4KV busses 1 and 2 to the Unit Auxiliary Transformer from the Start-Up Transformer (SUT) by closing Circuit Breaker 25/7. The operator turned the 25/7 control switch on the Reactor Turbine Generator Board (RTGB) to close the breaker. However, breaker 25/7 had a mechanical failure, so only two of the three phases closed in the breaker. When the control switch was returned to the center position, breaker 25/12 opened, removing the SUT from 4kV busses 1 and 2, leaving only two of the three bus phases powered through breaker 25/7.

The event resulted in a single phasing to 4kV Buses 1 and 2, Station Service Transformer 2F, and ultimately Emergency Bus E1. This resulted in a loss of E1 Bus voltage via the degraded grid voltage relays and the automatic start of the A Emergency Diesel Generator and the Train A Safeguards Sequencer. (The single phasing of 4kV busses 1 and 2 and failure of breaker 25/7 are being addressed by AR 123456.)

During the sequencing of the Safeguards loads on Emergency Bus E1 and Emergency Diesel Generator A, Service Water Pump A failed to start.

<u>Sequence of Events</u>:

**Time 0** – Both the A and B Service Water pumps lost power due to the load shed on E-A1, resulting in a loss of all service water. Both header pressures immediately drop to 0 psig (0 barg).

**Time 21 seconds** – Breaker 25/10B does not close and the A SW pump does not start.

**Time 27 seconds** – The B Service Pump is started by the Emergency Diesel Generator A sequencer.

**Time 27 to 42 seconds** – Service Pump system header pressure (both headers) rise steadily from 0 psig (0 barg) to 17 psig (1.17 barg).

**Time 78 seconds** – The turbine building isolation valves have closed, and header pressure increases to 25 psig (1.72 barg).

**Time 4 minutes and 26 seconds** – Operations has diagnosed the situation with Service water system and started the D SW pump which restores pressure to 53 psig (3.65 barg).

<u>Timeline of Service Water Pump “A” starts while declared inoperable</u>:

(The following data came from a mix of OSI/PI, Control Room logs, and Outage Command Center logs)

- 1/2/20XX – 03:00: Started and secured “A” SW pump in accordance with Operations Procedure – 123, section 4.3.2 from the RTGB control switch for maintenance troubleshooting.
- 1/2/20XX – 08:19: Started and stopped “A” SW pump to test safeguards auto start feature, using Work Order 12345678-07 installing a jumper in Auxiliary Panel BC terminals 1 and 2.
- 1/2/20XX – 20:23 – 21:41: Started and stopped “A” SW pump in accordance with Operations Procedure – 123.

- 1/3/20XX – 02:00 – 02:32: Started and stopped "A" SW pump in accordance with Operations Procedure – 123.
- 1/3/20XX – 03:15: Started and stopped "A" SW pump to test safeguards loss of voltage sequencer relay E1LV using Work Order 12345678-08.
- 1/3/20XX – 13:15: Started and stopped "A" SW from the RTGB following the locating and tightening of the loose wire in the pump's breaker control circuit, prior to declaring the "A" SW pump operable.

### C.3.3 Why Staircase Analysis

Using evidence found during troubleshooting and research on past maintenance activities on the affected components, this analysis developed a Why Staircase (see Table C-2) to determine the cause of the failure of the SW-PMP-A to start on a blackout sequencing for EDG-A.

For the case study understanding, Breaker 25/20B is the supply breaker for SW-PMP-A. ESX is the emergency start relay associated with SW-PMP-A, and the reference circuit wiring diagram is B-12345 SH003.

**Table C-2**
**Why staircase example 2**

| | |
|---|---|
| 1st Why: | Why did SWP-A fail to start on blackout sequencing of EDG-A? |
| 1st Because: | Breaker 25/20B did not close |
| 2nd Why: | Why did Breaker 25/20B not close? |
| 2nd Because: | Breaker 25/20B did not receive a close signal |
| 3rd Why: | Why did Breaker 25/20B not receive a close signal? |
| 3rd Because: | ESX contact 1-2 did not close |
| 4th Why: | Why did ESX contact 1-2 not close? |
| 4th Because: | ESX relay did not energize |
| 5th Why: | Why did ESX relay not energize? |
| 5th Because: | ESX relay (-)DC control power had an open contact |
| 6th Why: | Why did ESX relay (-)DC control power have an open contact? |
| 6th Because: | Loose control power wire on local/remote transfer switch contact (Failure Mode) |
| 7th Why: | There was a loose control power wire the on local/remote transfer switch (**Failure Mode**)? |
| 7th Because: | Historical condition of less than adequate termination torque. (**Apparent Cause**)<br>*NOTE: This condition was considered "Historical" based on maintenance records searches going back over 15 years that did not identify any work performed in this control box. Environmental causes were not identified due to the infrequent operation of the component, solid mounting on a concrete wall, and lack of temperature fluctuations.* |

### C.3.4 Cause Analysis Summary

Based on the why staircase in Table C-2, the most likely failure mode for the Service Water Pump "A" start failure on 1/5/20XX was due to a loose wire (B321K, conductor WC) in the Emergency Control Station. All of the active control components including all relays in the Service Water Pump "A" control circuit have been functionally tested and have been verified to be functional by Work Orders 12345678-04 and 12345678-07.

During performance of WO 12345678-17, a loose conductor (B321K, conductor WC) was found in the Emergency Control Station Local/Remote Switch. The conductor could be easily moved under the terminal. It took approximately 3/4 of a turn to tighten the termination.

It is noted that based on the testing performed during WOs 12345678-04 and 12345678-07, the failure for SWP-A was intermittent, which is consistent with a loose wire in the control circuit.

With terminations having been inspected outside of breaker 25/20B as a precaution based on the intermittent nature of the event, the 20B5 circuit breaker (25/20B) in Emergency Bus E1 was replaced to minimize any potential failure mode in the circuit breaker. The replacement breaker was verified to be functional prior to placing in service. All of the active control components including all relays in the Service Water Pump A control circuit have been functionally tested and have been verified to be functional by Work Orders 12345678-04 and 12345678-07. The 25/20B circuit breaker is not considered a contributing cause.

## C.4 Case Study 4: Fault Table and Support/Refute Table – Emergency Diesel Generator Failed to Execute

*Permission provided from originator of the operating experience. Request was made to anonymize the operating experience.*

This is an example of a fault tree developed following an event where an emergency diesel generator failed to excite during a slow start. The fault tree (shown in Figure C-5) was developed with the failure modes of all components in the circuit that would prevent the generator from exciting.

The fault tree was then used to develop the support/refute table (shown in Table C-3) for every possibility provided in the fault tree. The entire support/refute table is not presented here, but an excerpt of the section identifying the failure mode is shown that provides examples of both refuted and supported failure modes.

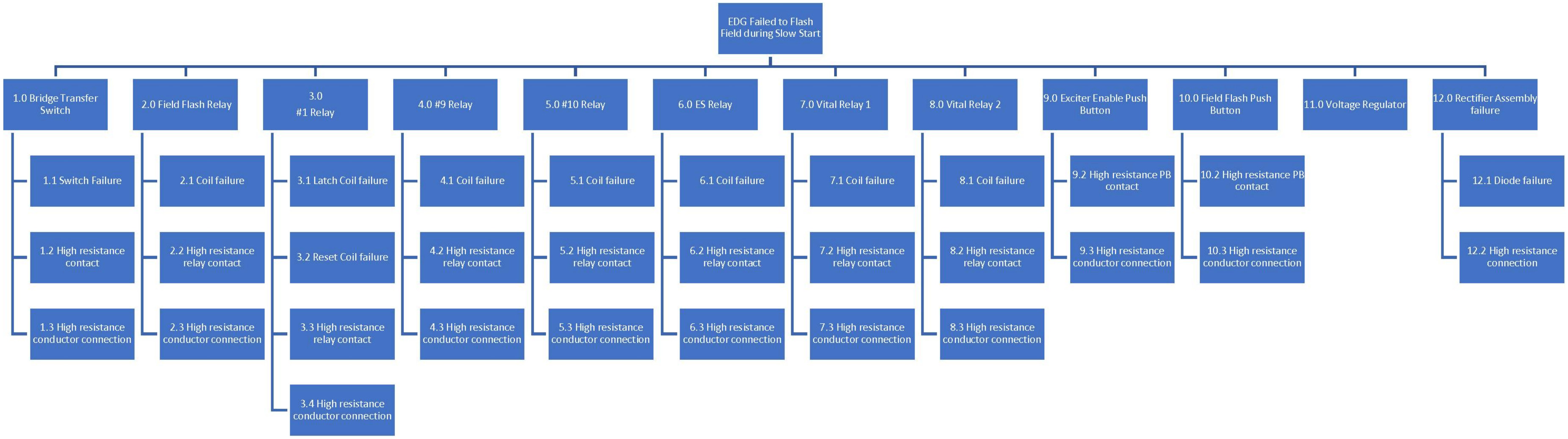



**Figure C-5**
**Fault table for failure of emergency diesel generator to excite during slow start**

**Table C-3**
**Failure mode identification**

| Sequence # [Note 1] | Failure Mode [Note 2] | Supporting Evidence [Note 3] | Refuting Evidence [Note 4] | Troubleshooting Task OR Work Order Number [Note 5] | Notes/Results [Note 6] | FM/CF/I/R [Note 7] |
|---|---|---|---|---|---|---|
| 1.1 | Switch Failure | Switch does not operate smoothly. | Switch operates smoothly. | Test/operate switch to ensure it operates smoothly. WO 1234567-1 | RESULTS: Switch operated smoothly. No issue. | R |
| 1.2 | High-resistance contact | High resistance across the bridge transfer switch when in position 2. | Contacts open when required and when closed <5Ω. | Measure the resistance across the bridge. Transfer switch terminals when in position 1 and 2. WO 1234567-1 | RESULTS: From terminal 13 on the Bridge Transfer Switch there is 31 KΩ between terminal 1 and 2 when in position 1 and 2, respectively. | FM |
| 1.3 | High-resistance conductor connection | Conductor loose. | Conductor appeared to slip for 13 when checked: however, the terminal connection plate may have turned with bolt. | Test tightness of all associated connections on switch. WO 1234567-1 | RESULTS: Conductor is tightly connected to terminal. | R |

**Notes**:

1. Sequence does not represent priority but represents sequence of execution and may change based on results.
2. Insert the possible credible failure that could cause the problem identified in the Problem Statement.
3. Provide Supporting Evidence for the condition if the Failure Mode IS present.
4. Provide Refuting Evidence for the condition if the Failure Mode IS NOT present.
5. Troubleshooting Tasks are basic instructions to aid in planning of task. Option to use Troubleshooting Task Sheet as attachment in Work Order if additional detail is needed. Not required for every task.
6. Quantitative evidence is used to support or refute a failure mode. Qualitative or soft wording is avoided. Can also contain notes collected during tasks.
7. Determined to be Failure Mode (FM), Contributing Factor (CF), Indeterminate (I), or Refuted (R).

### *C.4.1 Cause Summary*

The original bridge transfer switch had contacts that were open when it was in position 2, which prohibited the voltage regulator from applying voltage to the field. The electricians installed a new switch, which allowed the voltage regulator to apply voltage to the field. It was determined that after a recent maintenance task, a failure across the connection at the field contacts prevented the 2B EDG from exciting the field.

## C.5 Case Study 5: Ishikawa Diagram – Unit 1 RX Tripped Suspect Control Bank D Rod H-8 Dropped

*Permission provided from originator of the operating experience. Request was made to anonymize the operating experience.*

### *C.5.1 Abstract*

Reactor automatically tripped due to a dropped rod causing a negative rate trip. The consequence is the loss of power generation. The root cause has been determined to be excessive wear on the Stationary Gripper Latch Mechanism, resulting in the inability to maintain the rod in the fully withdrawn position or nearly fully withdrawn position for an extended period of time.

In order to facilitate brainstorming with the Root Cause Team, a fishbone was used to come up with potential causes of the dropped rod. No ideas were discarded during this first brainstorming session, but during the second phase of brainstorming, more ideas were generated and not included on the fishbone presented in Figure C-6.

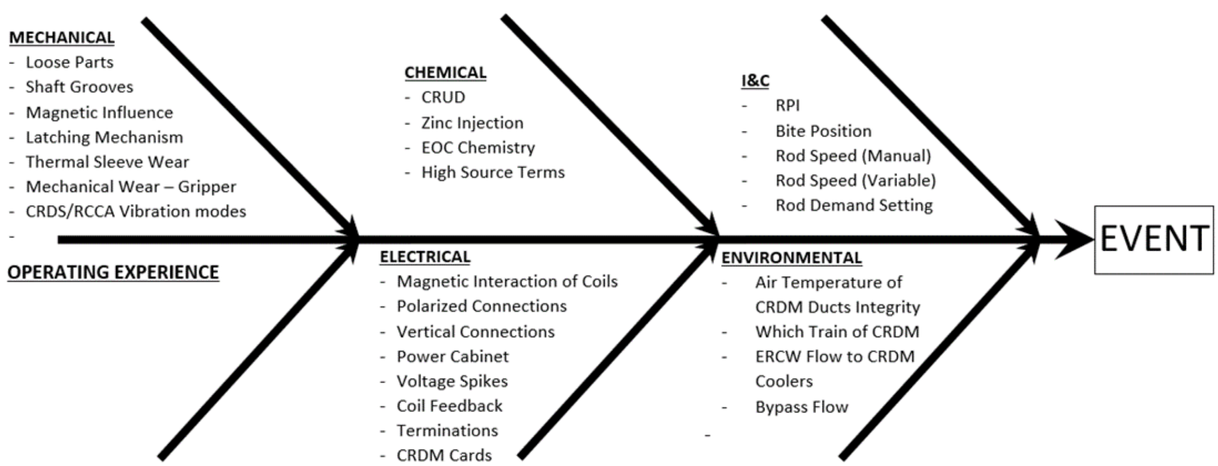



**Figure C-6**
**Fishbone diagram (case study #5)**

The second phase of brainstorming transferred the causes generated from the fishbone diagram to a support/refute matrix, which was then used to resolve the issue.

The support/refute matrix was provided in a previous case study and will not be repeated here.

# D

# EXAMPLE PRELIMINARY ASSESSMENT FORM

The following form can be used to guide the preliminary assessment process.

| | |
|---|---|
| | **Page 1 of 2** |
| **A. PRELIMINARY ASSESSMENT BRIEF - Before Arriving at the Scene** | |
| ☐ 1. | Perform pre-job brief with direct supervisor/manager. |
| ☐ 2. | Acquire the following before reporting to the scene:<br>- Applicable personal protective equipment<br>- Cameras and/or video recorders<br>- Note-taking equipment (paper and pens, portable computer, mobile work device, etc.)<br>- Measuring devices (measuring tape) |
| ☐ 3. | Identify the following:<br>- Scope of the preliminary assessment:<br>- Define priority actions:<br>- Define the preliminary assessment team: |
| **B. PERFORM PRELIMINARY ASSESSMENT - After Arriving at the Scene** | |
| ☐ 1. | Request assistance from Operations, Engineering, Radiological Protection, and Industrial Safety, or other groups, as needed, to facilitate preliminary assessment. |
| ☐ 2. | Evacuate uninvolved personnel who could cause distractions or modify the scene. |
| ☐ 3. | Limit access to the area by setting a perimeter using tape, cones, personnel, etc. |
| ☐ 4. | Leave all debris, tooling, etc. in the as-found location until the scene is preserved. |
| ☐ 5. | Use photographs, video records, or sketches to record the scene.<br>- Record as-found locations of significant failure-related materials. |
| ☐ 6. | Get copies (or temporarily take possession, if needed) of active work orders and procedures. |
| ☐ 7. | Other actions from Pre-Job Brief: |
| **C. PRELIMINARY ASSESSMENT INTERVIEWS - Questions to Ask Involved Individuals at the Scene** | |
| ☐ 1. | What date, time, and location did the event occur? |
| ☐ 2. | Describe sequence of events from your perspective. |
| ☐ 3. | Who was in the area at the time of the event? (For planning interviews) |
| ☐ 4. | What plant evolutions / actions / work were in progress near the time of the event? |
| ☐ 5. | What exact step in the work document or procedure was being performed at the time of the event? |
| ☐ 6. | What was expected to happen, but did not? |
| ☐ 7. | What changed from before the event?<br>- This can be states of devices, inputs to senses (smell, sound), equipment operation nearby. |

| | |
|---|---|
| | **Page 2 of 2** |
| ☐ 8. | What SSCs are potentially involved? |
| ☐ 9. | What tools were being used during the event?<br>- Take possession of tools if a faulted tool could have contributed to event. |
| ☐ 10. | What external energy or environmental factors were the SSC that failed exposed to?<br>- Energy: motive power, control power, instrument air, hydraulic fluid, etc.<br>- Environmental: humidity, temperature, radiation, sunlight, wind, rain, airborne debris, etc. |
| ☐ 11. | How is the SSC designed to be operated? |
| ☐ 12. | How was the SSC actually operated? |
| ☐ 13. | Was a controlled digital asset being used? (assessing for cyber/software related issues) |
| **C. PRELIMINARY ASSESSMENT INTERVIEWS (continued)** | |
| ☐ 14. | Should personnel not present be questioned to provide alternate perspectives?<br>- Control Room Operators, Security Guards, and other station personnel can provide insight regarding sequence of events. |
| ☐ 15. | Other questions from pre-job brief: |
| **D. DEBRIEF DIRECT SUPERVISOR/MANAGER** | |
| ☐ 1. | Promptly debrief the above information with direct supervisor/management. |
| **E. RELEASE THE SCENE FOR TROUBLESHOOTING** | |
| ☐ 1. | With concurrence from direct supervisor/management, release the scene of the vent for clean up and start of corrective actions. |
| **Summary:** | |
| | |
| **DEBRIEFING** | |

| | | | |
|---|---|---|---|
| **Preliminary Assessor(s):** | | **Date/Time/Location of event:** | |
| **Supervisor/Manager Debriefed** | | **Date/Time** | |

# E
# DATA COLLECTION SOURCES

The following is a listing of troubleshooting data sources.

| INTERNAL – DATA FROM STATION DATABASES AND RECORD SYSTEMS |
|---|
| Video Records:<br>- Security, thermography, or other |
| Plant Computer Data:<br>- Time series, waveform, alarms, etc. |
| Monitoring and Diagnostic Center Assessments, if available:<br>- Software used can provide advanced analysis of plant data in support of troubleshooting. |
| Operations Logs:<br>- What activities were being performed around the time of the event?<br>- What operators were on shift and may need to be interviewed? |
| Security Access Records:<br>- What personnel were in the zone for interview planning? |
| Procedures and Instructions:<br>- Include past revisions. |
| Process Records:<br>- Completed procedures, work order packages, nondestructive examination records, calibration records, etc. |
| Design Basis Information:<br>- Existing failure modes and effects analyses reports, plant drawings, specifications, license requirements, modification packages, etc. |
| Corrective Action Database:<br>- Historical condition reports identifying similar issues and corrective actions, trend identification. |
| Procedures and Instructions:<br>- Including past revisions to determine if revision contributed to event. |
| Work History Database:<br>- Historical work order history for similar events, corrective tasks, change in materials, etc. |
| **INTERNAL – DATA FROM STATION PERSONNEL** |
| Interviews |
| Active Process Documents:<br>- Those in use during event collected from organizations involved with the event. |

| |
|---|
| **INTERNAL – DATA FROM SCENE OF EVENT** |
| Faulty parts, tools, and/or in-use process documents (procedures, work orders, etc.) |
| Field walkdown data (pictures, videos, and measurements) |
| Non-Intrusive Data Acquired from Work Order Tasks and Station Processes<br>- These are activities that can be initiated and executed using existing processes that can provide valuable information to the team. Examples include vibration, motion amplification video, thermography, clamp-on ammeter, contact pyrometer, acoustical measurements, volt/ohm meter on test/terminals points or panel meters, inspection of components using installed access/inspection ports, etc. These are typically issued via work orders. Each request should be evaluated by the team to ensure it will not affect any evidence possibly needed.<br>- NOTE: It is important to record these tasks and populate them in the troubleshooting task plan so the results can be retained, tracked, and prevent inadvertently reperforming the activities by new troubleshooting team personnel or alternate shift. |
| **INTERNAL - DATA FROM SCENE OF EVENT (continued)** |
| Intrusive Data Gathering Acquired from Work Order Tasks and Station Processes<br>- **NOTE: This may endanger recording and/or preservation of evidence. Special consideration shall be applied when using intrusive data collection, as it may destroy or alter evidence.**<br>- Data in this category requires physical connection to an open circuit or direct contact with the system process fluid. Examples: Lifting leads for use of a volt/ohm meter or installation of a chart recorder, pressure or temperature gauges subject to process fluid; disassembly and inspection of components by other than installed access / inspection ports that may endanger recording and/or preservation of evidence; operation of components per an approved procedure to obtain data without endangering the recording and/or preservation of evidence. |
| **EXTERNAL - DATA FROM EXTERNAL SOURCES** |
| Original Equipment Manufacturer (OEM) Documentation<br>- Design information, parts lists, troubleshooting information, maintenance and operation procedures. |
| Vendor Support<br>- Technical support, manuals, service bulletins, etc. |
| EPRI Guides (https://membercenter.epri.com/)<br>- It is recognized that many guides exist in the EPRI database. The Equipment Reliability (ER) Matrix, located at https://ermatrix.epri.com/Matrix.aspx, can aid in finding what guides exist for specific components.<br>- See nmachotline@epri.com entry below for further support. |

| **Page 2 of 3** |
|---|
| EPRI Preventive Maintenance Basis Database (PMBD) (https://pmbd.epri.com/)<br>- See the following references for an overview of PMBD:<br>- 3002007555 - 6-minute PMBD Familiarization Video; 3002007394 - PMBD Quick Reference Guide<br>- Additional resources can be found on the PMBD Help Page. |
| PMBD Troubleshooting Knowledgebase (PMBDTK)<br>- PMBD Version 5.0 will incorporate a new tool to support troubleshooting. It is known as the “PMBD Troubleshooting Knowledgebase” or PMBDTK. It is intended to facilitate failure analysis fault table development with failure modes, degradation mechanisms, influences, and corrective actions. See Appendix J for an overview of this new PMBD function. |
| EPRI Nuclear Maintenance Applications Center (NMAC) Hotline can be used to facilitate member collaboration and technical support with guides:<br>- Email directly at nmachotline@epri.com<br>- Home page for additional information is: https://www.epri.com/research/programs/117997 |
| EPRI support email<br>askepri@epri.com |
| Nuclear Regulatory Commission (NRC) - USA<br>(https://www.nrc.gov/) |
| Other Regulator Database<br>- (country and/or regionally dependent) |
| Institute of Nuclear Power Operations (INPO)<br>- OE Database - IRIS (https://iris.inpo.org/) |
| World Association of Nuclear Operators (WANO)<br>- OE Database |
| International Atomic Energy Agency (IAEA)<br>- Incident Reporting System (IRS) (https://www.iaea.org/resources/database/irsni ) |
| Industry Interest Groups, Technical Strategy Groups, Users Groups, Working Groups<br>- (See Appendix I)<br>- Members from these groups can often provide recommended actions or solutions to related problems they have experienced. They are also valuable as third-party reviewers and subject matter experts. |
| Other stations with similar SSCs or processes |
| Industry Bulletins |
| Industry Experts (subject matter experts) |

# F

# VENDOR-SUPPORTED FAILURE ANALYSIS TOOLS

This appendix is provided so members are aware of vendor-supported troubleshooting tools.

It is important to note that EPRI does not recommend vendors directly. The vendors presented below are examples of vendors that provide solutions in the area of troubleshooting identified in EPRI member procedures reviewed during the development of this guide.

## F.1 Kepner-Tregoe Problem Solving and Decision-Making Model [31]

The Kepner-Tregoe Problem Analysis, also known as the “Is, Is Not Table,” is present or referred to within multiple troubleshooting procedures used to develop this guide and was mentioned during communications with members of the technical advisory group (TAG). The Kepner-Tregoe Problem Solving and Decision-Making Model is shown in Figure F-1.

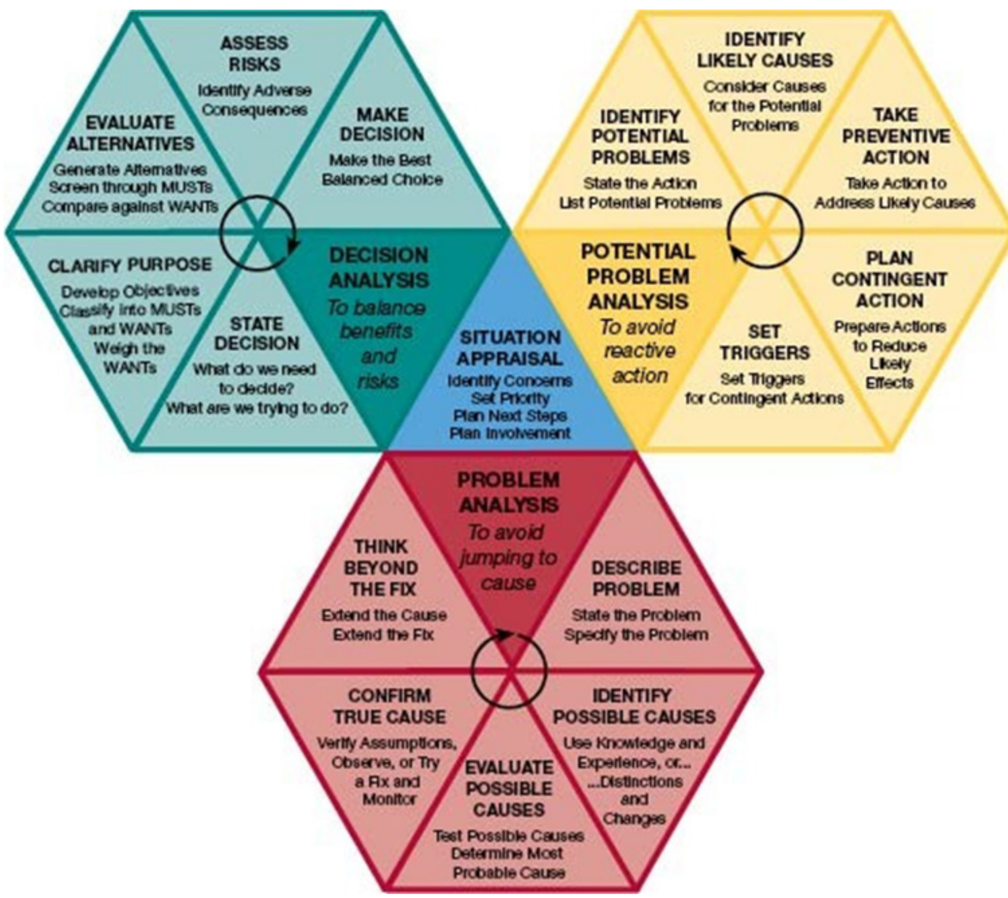



**Figure F-1**
**Kepner-Tregoe Problem Solving and Decision-Making Model (courtesy of Kepner-Trego)**

This appendix provides a brief overview of the Kepner-Tregoe Problem Solving and Decision-Making Process. Additional information can be obtained from the following link: https://www.kepner-tregoe.com/.

The Kepner-Tregoe method is defined as an issue resolution framework that guides the user from initial issue identification and prioritization through identifying root cause, selecting corrective actions or fixes, and ensuring that implementation of these fixes is successful.

As shown in Figure F-1, the Kepner-Tregoe Problem Solving and Decision-Making Model consists of the following approaches:

- Situation Appraisal – Identify and plan for the resolution of high-priority issues.
- Problem Analysis – Conduct failure analysis on complex problems.
- Decision Analysis – Make decisions aligned with operational priorities.
- Potential Problem/Opportunity Analysis – Understand and proactively manage risks and opportunities.

**Note:** The Kepner-Tregoe method does focus on and refer to finding the “root cause” in its material; however, as mentioned previously in this guide, the root cause and troubleshooting process share similar tools. The Kepner-Tregoe methods are introduced here from the perspective of troubleshooting. It is not uncommon for complex troubleshooting events to undergo a root cause investigation following the corrective action to restore functionality to the SSC or process. For the purpose of this guide, EPRI will focus on the value obtained through use of the approaches provided by Kepner-Tregoe in the area of troubleshooting.

### *F.1.1 Kepner-Tregoe Problem Analysis Method, or the “Is/Is Not” Table*

Table F-1 is a sample of the Kepner Tregoe Problem Analysis Table. The problem analysis approach from the Kepner-Tregoe method is used when the following conditions exist:

- There is an abnormal condition or a degrading level of performance exists.
- The cause of an event is unknown.
- The cause needs to be known to take meaningful action.

**Table F-1**
**Kepner-Tregoe Problem Analysis sample table (courtesy of Kepner-Tregoe)**

| **Kepner Tregoe Problem Analysis – Object and Deviation – Data collected during investigation (SAMPLE)** | | | | |
|---|---|---|---|---|
| WHAT IS (Fact) | WHAT IS NOT (similar/related to "Is") | DISTINCTIONS (unique about the "Is") | CHANGES (around the distinction) | CHANGE DATE |
| | | | | |
| | | | | |
| | | | | |
| WHERE IS (Fact) | WHERE IS NOT (similar/related to "Is") | DISTINCTIONS (unique about the "Is") | CHANGES (around the distinction) | CHANGE DATE |
| | | | | |
| | | | | |
| | | | | |
| WHEN IS (Fact) | WHEN IS NOT (similar/related to "Is") | DISTINCTIONS (unique about the "Is") | CHANGES (around the distinction) | CHANGE DATE |
| | | | | |
| | | | | |
| | | | | |

| EXTENT: IS (Fact) | TREND | IS NOT (Similar to "Is," but "IS NOT") |
|---|---|---|
| | | |
| | | |

**LEGEND:**
! = Critical Data that should be found or known
* = Important Data
IS = Factual Information regarding the problem
IS NOT = Similar, closely related, specific, factual date to the IS – "Could be but is not"
DISTINCTION = A Fact that is different, odd, special, or unique about the "Is" compared to the "Is Not" for a specific line.
CHANGE = A change around a distinction, NOT around an "Is" or "Is Not"

Problem analysis is performed by the steps shown in Figure F-2.

Describe Problem:

1. State the problem
    a. List the order based on judgement.
    b. List the object and the deviation.
        i. What object (or group of objects) has the deviation? What deviation does it have?
    c. Specify the problem
        i. Describe as completely, factually as possible.
        ii. WHAT IS
            1. What specific object(s) has the deviation?
            2. What is the specific deviation?
        iii. WHAT IS NOT
            1. What similar object(s) could have the deviation, but does not?
            2. What other deviations could be observed, but are not?
        iv. WHERE IS
            1. Where is the object when the deviation is observed (geographically)?
            2. Where is the deviation on the object?
        v. WHERE IS NOT
            1. Where else could the object be when the deviation is observed, but is not?
            2. Where else could the deviation be located on the object, but is not?
        vi. WHEN IS
            1. When was the deviation observed first (in clock and calendar time)?
            2. When since that time has the deviation been observed? What pattern?
            3. When, in the object's history or life cycle, was the deviation observed first?
        vii. WHEN IS NOT
            1. When else could the deviation have been observed first, but was not?
            2. When since that time could the deviation have been observed, but was not? What could be the pattern?
            3. When else, in the object's history or life cycle, could the deviation have been observed first, but was not?
        viii. EXTENT IS
            1. How many objects have the deviation?
            2. What is the trend in the number of objects with the deviation?
            3. What is the size of a single deviation?
            4. What is the trend in the size?
            5. How many instances of the deviation are on each object?
            6. What is the trend in the number of instances?
        ix. EXTENT IS NOT
            1. How many objects could, but do not? What could be the trend, but is not?
            2. What could be the size, but is not?
            3. What could be the trend, but is not?
            4. How many instances could be on each object, but are not?
            5. What could be the trend in the number of instances, but is not?

**Figure F-2**
**Problem analysis (courtesy of Kepner-Tregoe)**

Advantage of Kepner-Tregoe Problem Solving and Decision-Making Method:

- A guided troubleshooting and root cause analysis process

Limitations of Kepner-Tregoe Problem Solving and Decision-Making Method:

- Training is required to get the full benefit of the Kepner-Tregoe approach.

## F.2 TapRooT® [32]

Part of EPRI's mission is to inform its members about technologies that can improve the processes involved in supporting power generation. The features available within TapRooT®, described here, can be accessed from standard browsers on laptops, desktops, tablets, and even smartphones. TapRooT® also offers options to connect other systems utilized by members using an application programming interface that allows member-owned data and compatible software to integrate with the functionality within TapRooT®. The work performed within the TapRooT® software can be exported into a customizable report that can then be merged with station or fleet report formats. As a function of the software, trends are developed allowing the station or fleet to review past performances and learn from their statistics. These processes are examples of how TapRooT® advances, automates, and streamlines historically labor-intensive processes. These processes are available in hard copy, but the real value of TapRooT® is attained through use of the vendor's software package. The discussion below focuses on the content available in the TapRooT® Software Suite that is relevant to troubleshooting.

The research EPRI performed on System Improvements, Inc., the developers of the TapRooT® Root Cause Analysis System (https://www.TapRooT.com/), revealed a unique and efficient process-driven solution offered through an optional software solution that performs an investigation by asking human performance-based questions that lead to the solution and, once identified, recommends "SMARTER" corrective actions that focus on the immediate fix and preventive measures to prevent reoccurrence. As part of this process, TapRooT® provides the Equifactor® Equipment Troubleshooting module, which provides pre-developed and custom equipment troubleshooting tables to aid in equipment failure recognition. In other words, TapRooT® provides a suite of troubleshooting tools, many of which are described in this guide, that can then be converted into a root cause analysis with little effort.

It is important to note that no EPRI members had referenced TapRooT® in their troubleshooting processes at the time this guide was created; however, EPRI members use the TapRooT® process in their corrective action program to provide a guided progression through an expert-backed investigation process [3].

TapRooT® offers a Simple 6-Step Investigation Process (Figure F-3) that is aligned with the equipment troubleshooting process described in this guide. TapRooT® also offers a Complete 7-Step Investigation Process that aligns with a root cause analysis process to analyze more complex issues (Figure F-4). The 6-Step Investigation Process will be discussed as an example of what TapRooT® offers. More information is available at https://www.TapRooT.com/.

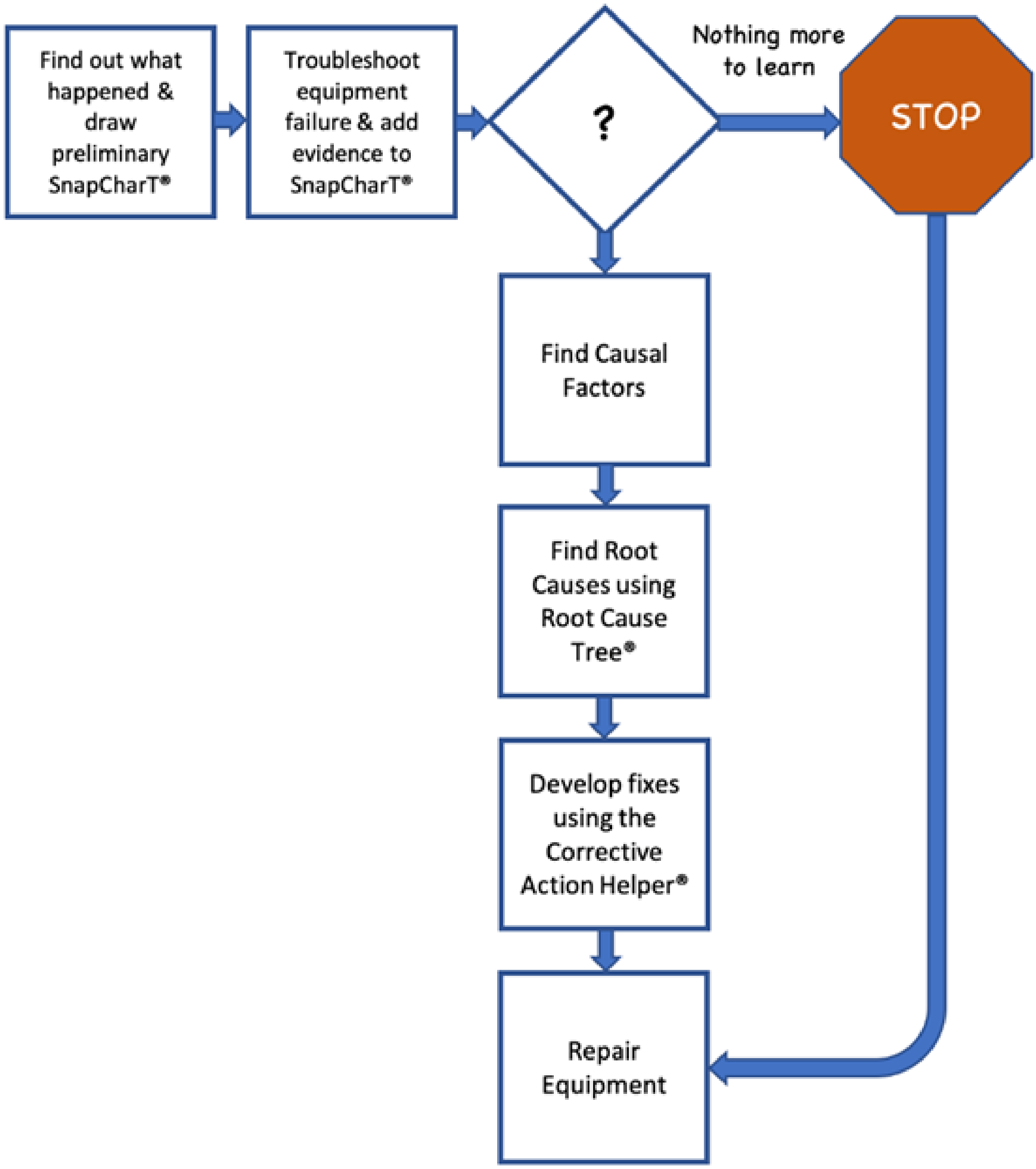



**Figure F-3**
**Simple TapRooT® 6-Step Investigation Process (troubleshooting) (courtesy of TapRooT®)**

**TapRooT® 7-Step Major Investigation Process**

| Phases | Steps | Tools |
|---|---|---|
| Plan ↓ | 1. Plan Your Investigation | **SnapCharT®**<br>*Root Cause Tree®*<br>*Equifactor®* |
| Investigate ↓ | 2. Determine What Happened (Sequence of Events) | **SnapCharT®**<br>*Equifactor®*<br>*CHAP*<br>*Change Analysis* |
| Analyze ↓ | 3. Define Causal Factors | **SnapCharT®**<br>**Safeguard Analysis** |
| | 4. Analyze Each Causal Factor's Root Causes | **Root Cause Tree®** |
| | 5. Analyze Each Root Cause's Generic Causes | **Corrective Action Helper®** |
| Fix ↓ | 6. Develop Fixes | **Corrective Action Helper®**<br>*Safeguard Analysis*<br>**SMARTER** |
| Report | 7. Present/Report for Approval | **SnapCharT®** |

**Figure F-4**
**Complete TapRooT® 7-Step Major Investigation Process (root cause analysis)**
**(courtesy of TapRooT®)**

NOTE: Parenthetical additions "()" have been used to include the terminology used in this guide, in order to provide consistency in the discussion.

**Step 1: Find Out What Happened and Draw a SnapCharT®** (Define the Problem)

The SnapCharT® is a user-friendly approach to creating flow diagrams (and fault trees). Through the use of the SnapCharT® feature, TapRooT® allows the user to establish a sequence of events.

### Step 2: Troubleshoot Equipment Failure and Add Evidence to SnapCharT®

To assist in equipment troubleshooting, TapRooT® offers an additional tool to aid in building the SnapCharT®. The Equifactor® Equipment Troubleshooting Tables provide the user with a preconfigured list of failure symptoms and possible causes for a range of equipment types, These possible causes would be used by the troubleshooting team to quickly identify the actual equipment failure, and then add this information into the SnapCharT® for a more complete description of the chain of failure. Note that these tables can be customized and expanded by the end user.

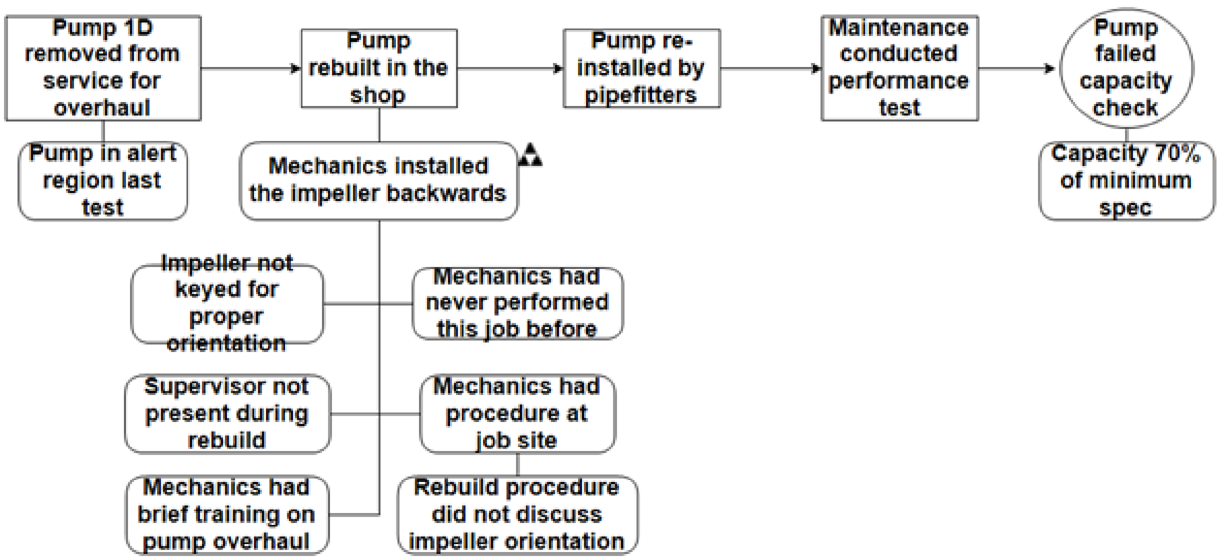



**Figure F-5**
**Example of TapRooT® SnapCharT® (courtesy of TapRooT®)**

### Step 3: Decide If There Is "Nothing More to Learn" Or A "Potential to Learn More"
(Is troubleshooting needed?)

In the same manner in which EPRI recognizes that some processes already exist to address events, TapRooT® recognizes that occasionally after the event is described and understood, additional investigation is not required because the solution is already known. Step 2 is the hold point in the process where the determination is made to perform troubleshooting or use existing normal operation and maintenance processes (Exit the TapRooT® Process).

### Step 4: Find Causal Factors Using Safeguard Analysis

Safeguard Analysis is performed to identify all the causal factors (the human errors or equipment failures) that led to the event. This is the starting point for troubleshooting or root cause analysis. By finding the answers to 5 Safeguard questions and using a new and simplified Causal Factor Worksheet, the causal factors are identified (https://www.taproot.com/using-safeguards-to-find-causal-factors/).

**Step 5: Find Root Causes Using Root Cause Tree®** (Failure Analysis to Identify the Cause(s))

Analyze the root cause of problems guided by the Root Cause Tree® Diagram and TapRooT® Dictionary. Use expert guidance to analyze human errors (including those errors that may have led to an equipment failure) using the Human Performance Troubleshooting Guide. The Root Cause Tree® offers a new enhancement that allows you to select YES or NO to the individual Root Cause Tree® Dictionary questions contained within each individual Basic Cause Category, Near Root Cause, and Root Cause. They are accessed by clicking the question mark icon on the hover menu that appears when you place your mouse over each section. The questions contained with the Root Cause Tree® Dictionary are developed by subject matter experts and industry best practices.

In addition to the Root Cause Tree® Human Performance Troubleshooting Guide to identify human errors, it also utilizes an Equipment Failure section to more easily narrow down equipment failure root causes (Figure F-6).

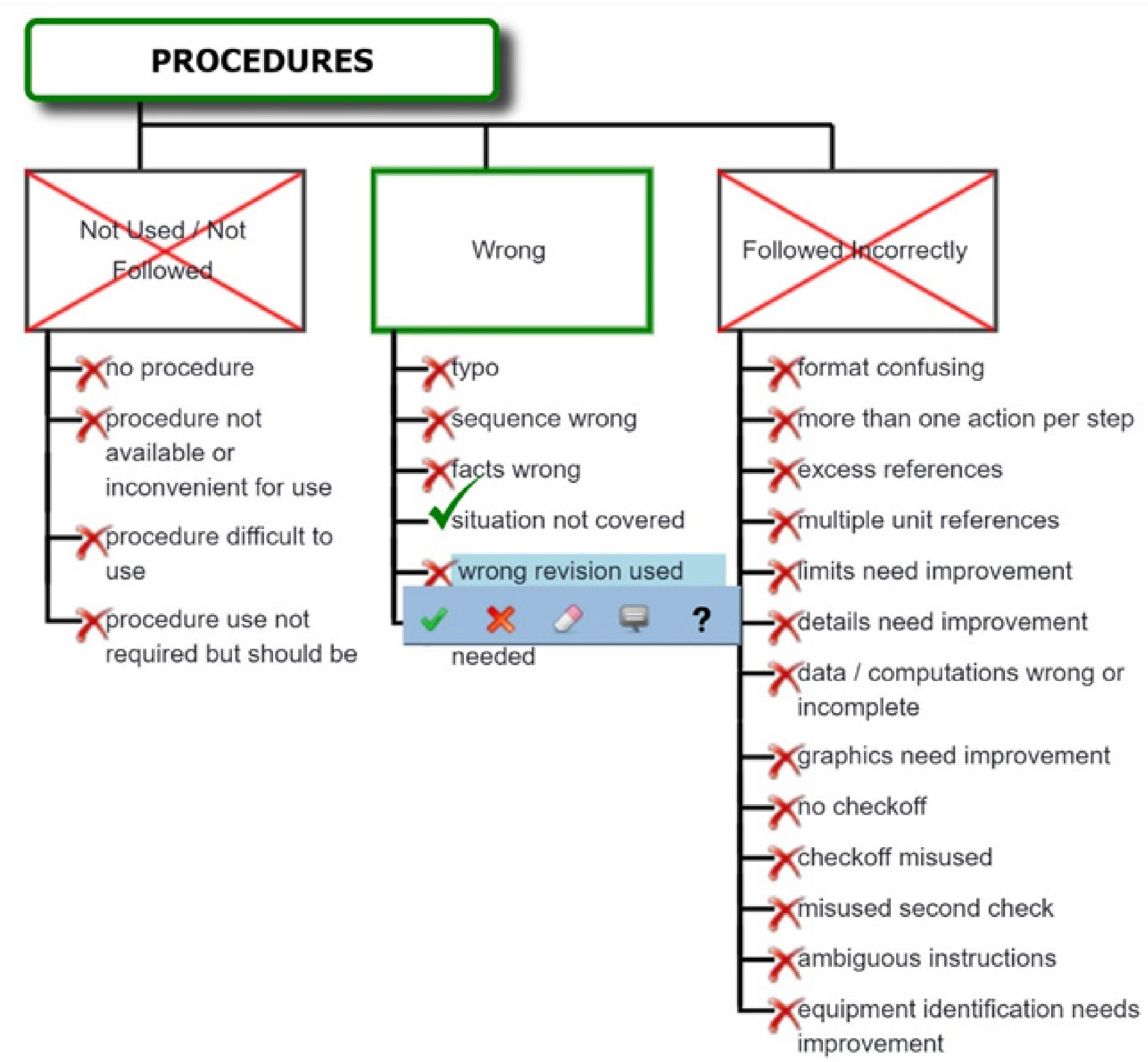



**Figure F-6**
**Example TapRooT® Root Cause Tree® – "Tree View" (courtesy of TapRooT®)**

**Step 6: Develop Fixes Using the Corrective Action Helper® Module**

Develop effective fixes for problems using the Corrective Action Helper® Guide and Safeguard Analysis to stop repeat incidents or significantly reduce their consequences. Through the use of expert guidance to determine corrective actions for human errors using the Human Performance Troubleshooting Guide and equipment failures using the Equifactor® Troubleshooting Tables, the tool offers failure modes and symptoms of common components, while allowing the addition of user input for new components.

No tools that can be immediately applied by members are provided from TapRooT® as part of this guide. This information was provided, as stated above, to share technologies with members that can improve the processes involved with supporting power generation. As fleets and stations advance to a more online and interactive business model, TapRooT® offers an option that could be considered, in lieu of developing their own online tool.

For more information, visit https://www.TapRooT.com/.

**Advantages of TapRooT®**:

- A guided troubleshooting and root cause analysis process
- Large database of subject-matter-developed cause determination questions and failure mechanisms for common components in process plants
- Very applicable to process or SSC troubleshooting from start to finish

**Limitations of TapRooT®**:

- Requires an individual subscription (single user) or company license (multi-user) to use the software features described above. Note that TapRooT® can be used in hard-copy form (supplied with TapRooT® training) without software, but the full value is realized with the software.

# G
# TROUBLESHOOTING THERMAL PERFORMANCE ISSUES

To assist in troubleshooting plant heat rate and thermal performance issues, EPRI developed specific research projects to aid in quickly identifying the cause(s) of lost generation. Table G-1 lists a suite of references that may be used when trying to identify the cause of lost MWe.

**Table G-1**
**EPRI resources for troubleshooting thermal performance issues**

| EPRI User Group or Product ID | EPRI Product Title | Report Contents |
|---|---|---|
| 3002005346 | Thermal Performance Engineering Handbook, Volume 3 | • Discusses the troubleshooting portion of the thermal performance program<br>• Provides detailed information on responding to and creating a troubleshooting strategy for plant thermal performance problems<br>• Includes logic charts and specific questions and actions for diagnosing a thermal performance problem across the plant<br>  ○ Targets the major components in the turbine cycle<br>  ○ Offers general troubleshooting guidance for commonly encountered problems<br>  ○ Provides symptomatic troubleshooting guidance |
| 1025264 | Plant Engineering: Heat Cycle Isolation Valve Leakage Identification and Quantification | • Documents the costs and benefits of implementing a cycle isolation program<br>• Describes various methods for calculating thermal losses due to valve leakages in a steam cycle<br>• Presents two case studies (one BWR and one PWR) capturing thermal loss methods<br>• Assesses cycle isolation activities and programs<br>• Provides an overview of the industry's approach and method descriptions<br>• Provides costs and benefits evaluation |
| P2EP | Plant Performance Enhancement Program | • Thermal Performance User Group<br>• Information exchange and technical support to assist in improving thermal efficiency and electrical output<br>• Website has access to industry peer contacts, a consolidated list of EPRI products, and industry surveys, and provides hotline assistance to member utilities<br>• Oversees a technical library that contains over 900 documents covering 150 subjects relevant to thermal efficiency improvement<br>• User group meets annually in person and three times via webcast throughout the year |

# H TROUBLESHOOTING MEDIUM VOLTAGE CABLE FAULT LOCATION FOR NUCLEAR POWER

## H.1 Cable Faults

Another example of EPRI products focused on troubleshooting is EPRI product 3002016161, *Guide for Troubleshooting Medium Voltage Cable Fault Locating*. This guide is projected to be released in August 2020.

Electrical power outages are expensive and unacceptable to the power utility. Ensuring optimal reliability is a major factor for utilities due to the economic market in the power industry. Expeditious cable fault location is vital, and the utilities are looking for equipment that will efficiently pinpoint the cable fault.

Historically, cable fault location has been an art acquired by only a few over years of hard-earned experience. Many industries/utilities have, over many years, developed very skillful specialists in this field with high degrees of success. These staff are respected, and their skills have resulted in there being a minimum of electrical power outages. However, with the advent of the cross-linked polyethylene (XLPE) and electron paramagnetic resonance (EPR) cables and their high dielectric strength, cable fault location has become more difficult. The approaches used historically (500-watt globes in series or a welding transformer) are no longer effective to locate the fault.

The new method developed by EPRI is a more direct approach to cable testing, unlike the older iterative testing methods known as the Salami Method, where the cable is cut in half and each side is hipot tested, cut in half again, hipot tested, and repeated until the faulted section is identified.

Cable faults can be caused by many factors:

- Mechanical damage
- Water ingress into splices/joints
- Poor splicing/jointing and terminations
- Poor installation and bedding preparation (buried cables)
- Water ingress into the cable via outer sheath damage
- Lightning or switching fault
- Overloading causing thermal stress
- Corrosion of copper tape shield
- Age of cables

- Poor transportation and storage of cables
- Cable defects

The Medium Voltage Cable Fault Location guide will provide the best methods for approaching cable faults ranging from the most common to the rarest fault types encountered, as shown in Figure H-1.

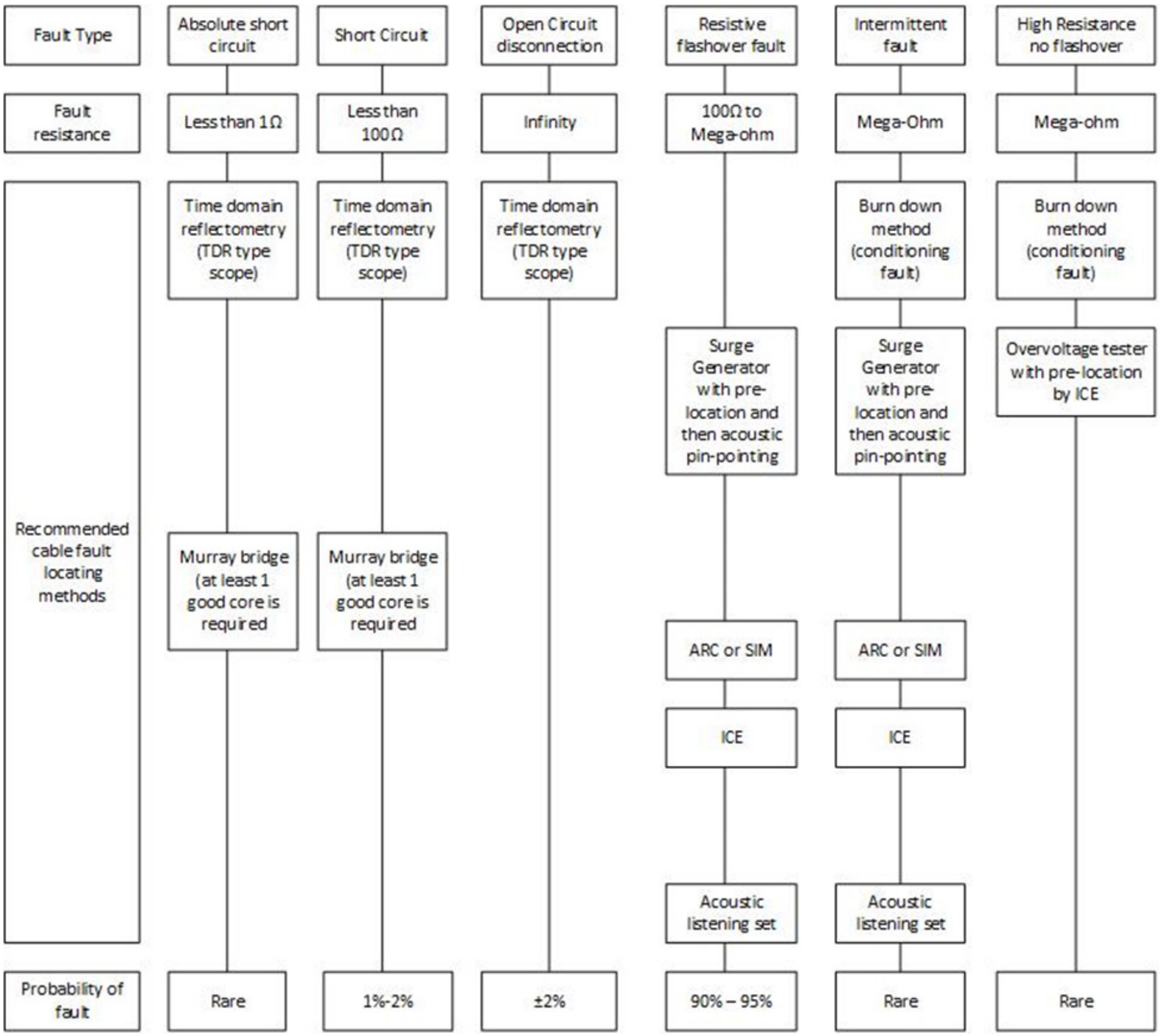



**Figure H-1**
**Cable fault chart by percentage of occurrence**

The guide will also define the steps to be taken, as shown in Figure H-2.

General Steps to Locate Fault in Medium Voltage Cable

1. Locate bus/circuit breaker trip
2. Consult line diagram
3. Locate the far side switchgear/bus/load
4. Identify circuit breaker trip or mv fuse blown
5. Examine protection relay/fuse blown
6. Identify faulty phase
7. Test faulty cable using hot stick
8. Ground faulty cable using grounding stick
9. Isolate and ground far end of cable using hot stick/grounding stick

**Figure H-2**
**General steps to locate faults in medium voltage cable**

In addition, this guide will present various methods of cable fault location and basic tips on ways of making fault locating more successful. The latest methods and equipment will be presented, describing the basic principles of operation and what faults to use the equipment on.

The guide will describe the faults in detail so the user understands how the fault occurs and why the methods suggested are optimal for their discovery.

Examples of testing methods follow.

### *H.1.1 Surge Generator Method*

The surge generator consists of a 110V/220V 60Hz step-up transformer, diode (for half wave rectification), and a high voltage DC capacitor. The input 110V or 220V voltage is varied from 0 to 110V/220V via a Variac, which varies the high voltage (HV) output. The rectified HV DC voltage charges the HV capacitor. Once fully charged, the HV capacitor is discharged via the spark gap into the cable. This sharp-fronted wave then travels down the cable and flashes across from the conductor to the screen at the cable fault.

The flashover causes a loud "thump" at the fault. The output voltage surge can vary from 0 to 30kV, depending on the type of surge generator. Figure H-3 shows a basic surge generator.

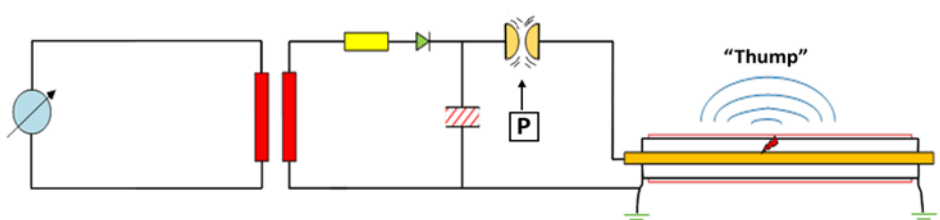



**Figure H-3**
**Example of a basic surge generator**

Acoustic devices are helpful in locating the "thump," as shown in Figure H-4. Acoustic devices can be used above or below ground to pinpoint the location of the fault.

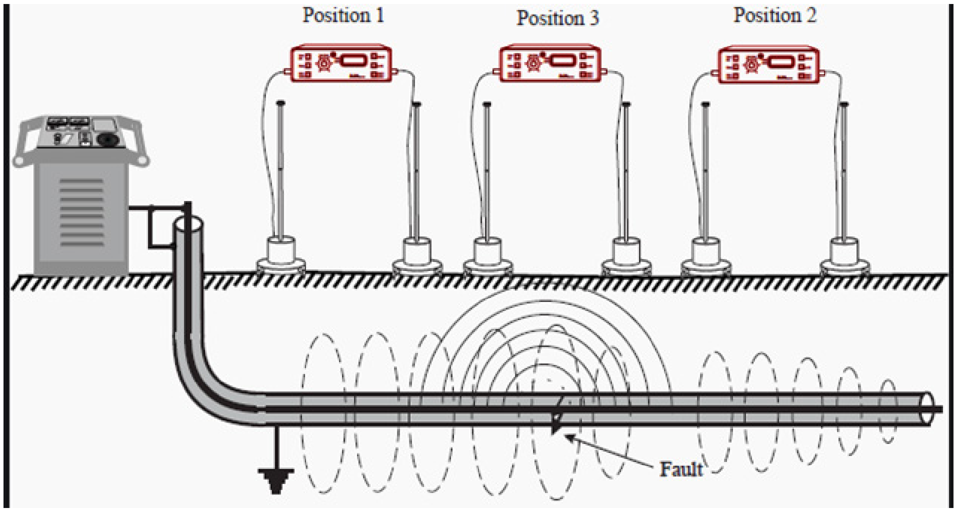



**Figure H-4**
**Example of using acoustic devices to identify an underground fault**

### *H.1.2 Time Domain Reflectometry (TDR) Method*

The time domain reflectometry (TDR) method is also known as the "impulse reflection method" or "scope" method. In this testing method, a cable is treated as a pair of transmission lines in terms of traveling waves. The two cores (the conductor and the screen) present a series and parallel set of impedance to the path of the pulse/surge or traveling wave. The "scope" transmits a low voltage (LV) pulse into the cable, which then causes an incident and reflected wave at the load/fault, as shown in Figure H-5.

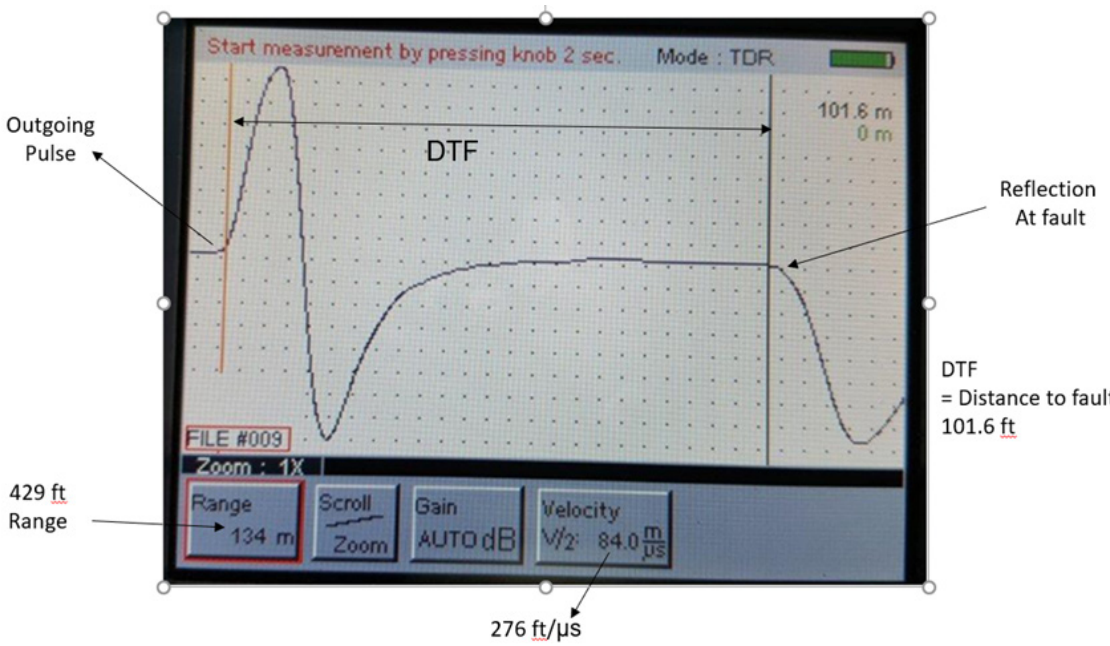



**Figure H-5**
**Example of a TDR echograph of a low-resistance fault**

### H.1.3 Arc Reflection (ARC) or Secondary Impulse Method (SIM) Method

One of the more recent methods of cable fault locating is the pulse arc reflection method. As suggested by the basic block diagram of this method (see Figure H-6), it is by far the simplest of the fault locating methods. This method is also referred to as the secondary impulse method, or SIM.

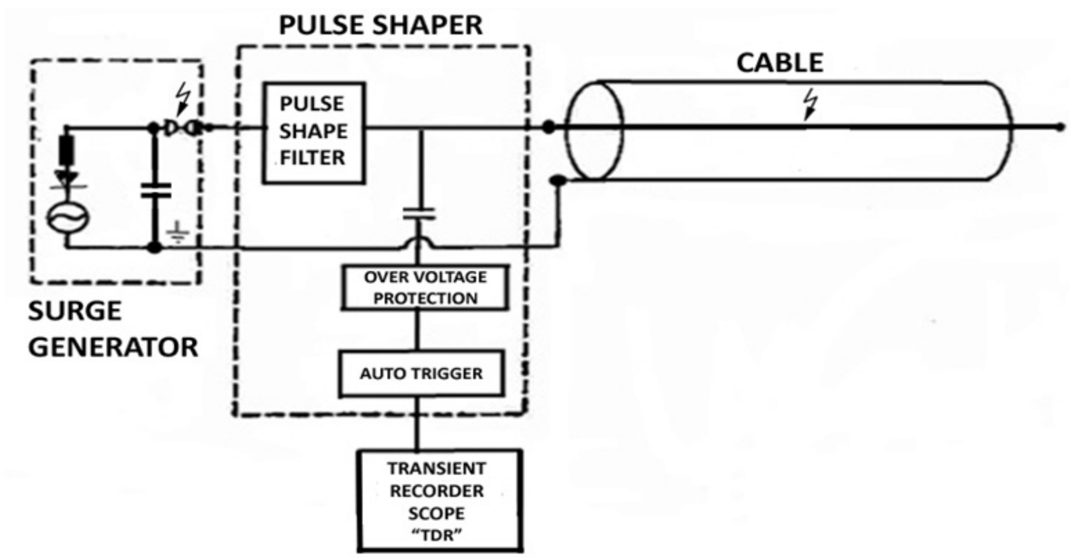



**Figure H-6**
**Example of basic pulse arc reflection method**

With the advent of the ARC/SIM development the time domain reflectometry technology has been extended into faults above 100 ohms. This combination can detect 96% of all faults in MV cables. This method has allowed the operator to simply send one HV surge down the cable, and the scope will record and display the position of the fault.

With the aid of the surge generator, the fault is transferred into a low resistive fault as the flashover occurs. The TDR can now be used to locate the fault. The design of the pulse shaper, pulse width, and capacitive divider is critical in order to quickly dampen out current surges resulting from the flashover and to hold the arc long enough to enable the "scope" to reflect off the flashover.

The surge generator is set to a single-shot operation, and a single surge is sent into the faulty cable. This triggers the scope via the coupling capacitor. The TDR can now send out a pulse and record the fault echogram placed into the TDR's memory. After the arc has extinguished, a second pulse (hence the name "secondary impulse") is sent out from the scope, and the end of the cable echogram is recorded in the memory.

Figure H-7 shows an example of the simultaneous illustration of both of the echograms on the TDR scope, clearly indicating the distance to fault.

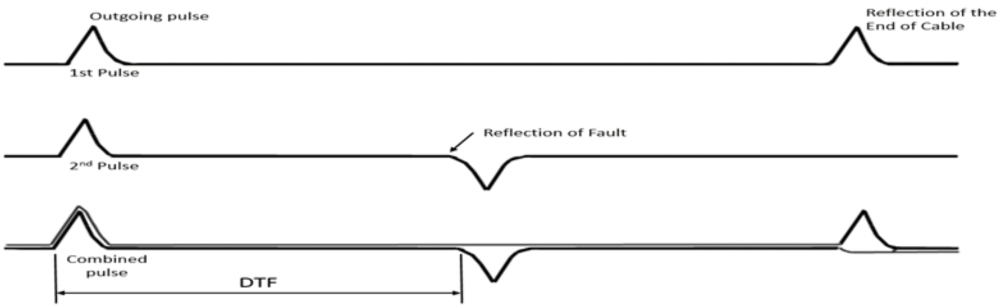



**Figure H-7**
**Example of basic pulse arc reflection method**

### *H.1.4 Surge or Impulse Current Equipment (ICE) Method*

One of the original methods used for cable fault location is the surge/impulse current method (ICE). The equipment is much simpler and less costly, but more difficult to understand. However, the advent of the "smart" surge generator will change this conception. The equipment for the ICE method consists of a surge generator, inductive coupler, and transient recorder (commonly called TDR).

The diagram and pulse reflection lattice shown in Figure H-8 illustrate the basic operation of the impulse current method on a healthy cable with the far end open-circuited. A lattice diagram depicts the surge wave from the surge generator as it travels down the cable, reflects at the far end, and returns through the coupler. The transient recorder/scope/TDR displays the waveform based on amplitude (Y axis) and time (X axis). Notice the voltage doubling at the far end—this doubling is often the cause of the cabling breaking down after the returning wave front from the far end. This doubling in addition enables the operator to use a lower voltage surge to achieve a flashover at the fault.

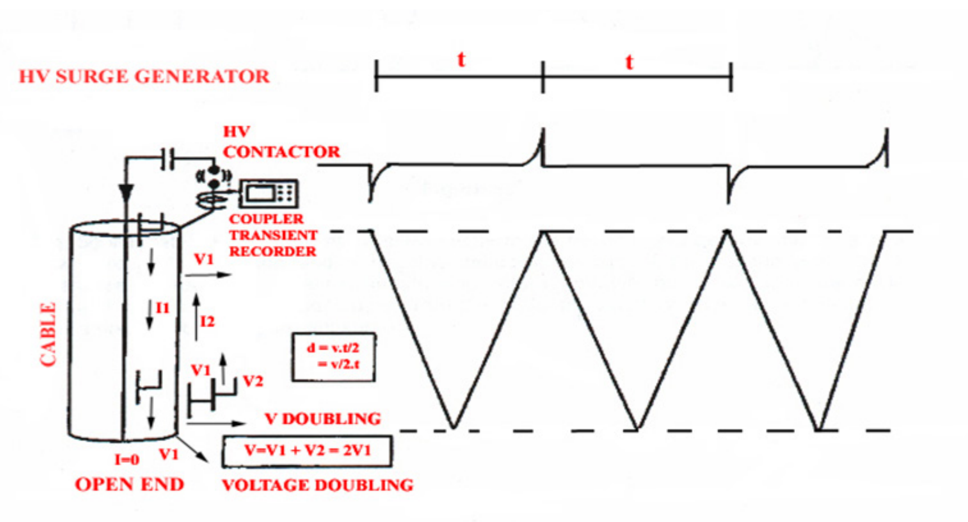



**Figure H-8**
**Example of basic operation of ICE on a healthy cable with an open circuit at the end**

### *H.1.5 Murray Bridge Method*

Another very reliable fault locating method is the Murray bridge method (Figure H-9), sometimes referred to as "Wheatstone" bridge (but incorrectly, as it is a variation of the true Wheatstone). This method is not used very often, but can be very reliable for very high resistant faults and cable shield/sheath faults. Faults from dead short circuits up to megohms can be located with the Murray bridge.

This method uses a low-DC voltage bridge supply, which is typically from 9V and 10kV (DC). As such it is non-destructive and allows for the in-depth diagnostic analysis of the fault.

This method does require that one heathy core be present and the fault must be resistive in nature.

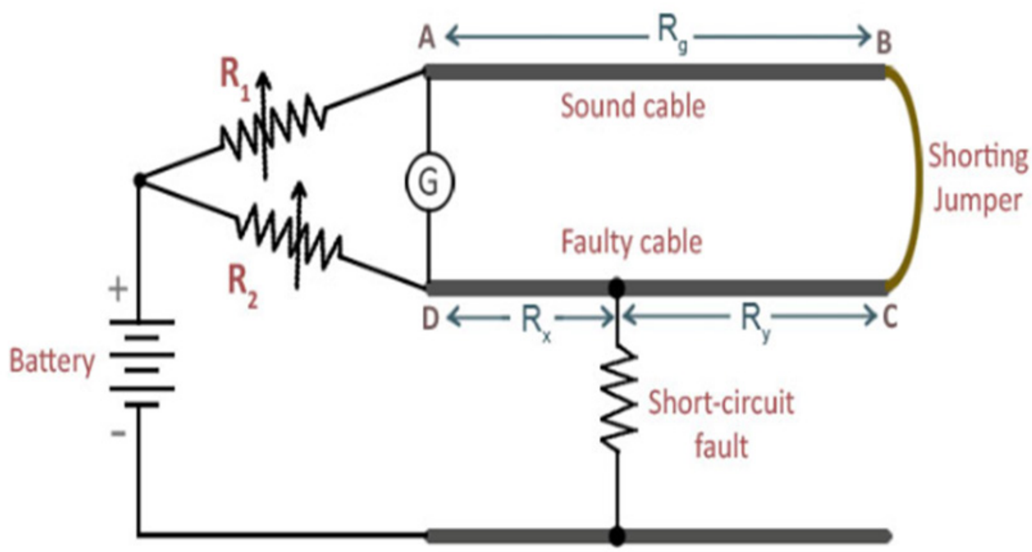



**Figure H-9**
**Typical Murray bridge setup**

# I

# INDUSTRY INTEREST GROUPS, TECHNICAL STRATEGY GROUPS, AND USER AND WORKING GROUPS FOR EXTERNAL RESOUCES

Industry interest groups, technical strategy groups, task groups, working groups, and user groups are collections of personnel involved with the subject matter. The collective experience of the user groups can be very valuable to troubleshooting efforts.

Table I-1 presents a list of the known user groups applicable to the power industry. Home pages contain contact information for the groups that can aid in troubleshooting efforts at the time of this publication.

**Note:** This list is subject to change over time. NMAC will post and update the list on the NMAC Wiki page: https://nmac.epri.com/index.php/Users_Groups.

**Table I-1**
**List of industry user groups**

| Owner | Title | Group Short Name | Home Page |
|---|---|---|---|
| External | American Coal Users' Group | ACUG | https://www.electricpowerexpo.com/prb-centro/ |
| External | Air-Operated Valve Users Group | AOV | http://www.aovusersgroup.com/ |
| External | Boric Acid Users Group (shared with FLMUG) | BAUG | https://www.fluidleak.com/ |
| EPRI | Buried Pipe Integrity Group | BPIG | https://msites.epri.com/ms/research/117997/buried-pipe-integrity-group |
| External | Boiling Water Reactor Owner's Group | BWROG | https://nuclear.gepower.com/service-and-optimize/tools-and-resources/bwrog |
| EPRI | Cable Program | CABLE | https://msites.epri.com/ms/research/117997/cable-program |
| External | Compressed Air Nuclear Users Group | CANUG | https://www.aovusersgroup.com/canug.html |
| EPRI | Condition Based Maintenance User Group | CBMUG | https://nmac.epri.com/index.php/NMAC/CBM |

**Table I-1 (continued)**
**List of industry user groups**

| Owner | Title | Group Short Name | Home Page |
|---|---|---|---|
| EPRI | Circuit Breakers Users Group | CBUG | https://msites.epri.com/ms/research/117997/circuit-breakers-users-group-%28cbug%29- |
| External | Combined Cycle Users Group | CCUG | http://www.powerusers.org/our-groups/ccug-combined-cycle-users-group/ |
| EPRI | CHECWORKS User's Group | CHUG | https://www.epri.com/research/programs/117997/committees/2969 |
| External | CANDU Owners Group | COG | http://www.candu.org/SitePages/Home.aspx |
| EPRI | Cathodic Protection Users Group | CPUG | https://membercenter.epri.com/programs/065756/Pages/Unique%20Pages/CPUG.aspx |
| External | Combustion Turbine Operation s Technical Forum | CTOTF | http://www.ctotf.org/ |
| External | Diesel Fuel Owners Group | DFOG | http://dfog.mpr.com/ |
| INPO | Equipment Reliability Working Group | ERWG | https://web.inpo.org/Pages/Equipment-Reliability.aspx |
| External | Energy System Integration Group | ESIG | https://www.esig.energy/about/user-groups-working-groups/ |
| External | Fluid Leak Management Users Group | FLMUG | https://www.fluidleak.com/ |
| External | Foreign Material Exclusion Industry Working Group (North America) | FME IWG | http://fme-iwg.com/ |
| External | Foreign Material Exclusion International Industry Working Group | FME-IIWG | (in development) |
| EPRI | Fossil Pump Users Group | FPUG | https://membercenter.epri.com/Programs/058771/pages/committees.aspx (no formal page exists. This is a page for EPRI and Member contacts in FPUG) |
| EPRI | Fleet Wide Monitoring Interest Group | FWMIG | https://membercenter.epri.com/Programs/056611/Pages/Unique%20Pages/FWMIG.aspx |
| EPRI | EPRI Nuclear Groundwater Protection Technical Strategy Group | Groundwate r TSG | https://membercenter.epri.com/collaboration/E238399 |
| External | Generator Users Group | GUG | http://www.powerusers.org/our-groups/gug-generator-users-group/ |
| EPRI | Hoisting, Rigging, & Crane Users Group | HCRUG | https://membercenter.epri.com/programs/065755/Pages/Unique%20Pages/HRCUG.aspx |

**Table I-1 (continued)**
**List of industry user groups**

| Owner | Title | Group Short Name | Home Page |
|---|---|---|---|
| EPRI | Heat Exchanger Performance User Group | HXPUG | https://msites.epri.com/ms/research/117997/heat-exchanger-performance-user-group |
| EPRI | Infrared Thermography (IR) Acoustic (A) User Forum | IRAF | https://nmac.epri.com/index.php/NMAC/CBM/Infrared |
| EPRI | Emergency Diesel Generator System Resource Webpage | Joint EDG OG | https://msites.epri.com/ms/research/117997/edg-system-webpage- |
| EPRI | Procurement Technical Assistance Program / Joint Utility Task Group | JUTG | https://epic.epri.com/EPIC_Hom |
| EPRI | Large Electric Motor Users Group | LEMUG | https://msites.epri.com/ms/research/117997/large-electric-motor-users-group-lemug |
| EPRI | Low Level Waste Technical Strategy Group | LLW TSG | https://membercenter.epri.com/collaboration/4000000517 |
| EPRI | NMAC Lubrication Support Program | Lubrication | https://nmac.epri.com/index.php/NMAC/CBM/Lubrication |
| EPRI | Maintenance Managers Conference | MMC | rroberts@epri.com |
| EPRI | Maintenance Rule Users Group | MRUG | https://pr.epri.com/PR/MRUG |
| External | Motor-Operated Valves Users Group | MUG | https://www.movusersgroup.com/index.html |
| External | Nuclear HVAC Utility Group | NHUG | https://www.nhug.org/default.aspx |
| External | Industry Check Valve Group | NIC | https://www.nicusergroup.org/ |
| EPRI | EPRI's Nuclear Maintenance Applications Center Hotline | NMAC | nmachotline@epri.com |
| EPRI | Operations Managers Conference | OMC | dcoffey@epri.com |
| EPRI | Plant Performance Enhancement Program | P2EP | https://msites.epri.com/ms/research/117997/plant-performance-enhancement-program |
| INPO | Preventive Maintenance Working Group | PMWG | https://web.inpo.org/Pages/Equipment-Reliability.aspx |

**Table I-1 (continued)**
**List of industry user groups**

| Owner | Title | Group Short Name | Home Page |
|---|---|---|---|
| External | Power Plant Controls Users Group | PPCUG | http://www.powerusers.org/our-groups/ppcug-power-plant-controls-users-group/ |
| External | Pump Users Group | PUG | https://pumpusersgroup.com/ |
| External | Pressurized Water Reactor Owners Group | PWROG | https://pwrogpublic.westinghousenuclear.com/SitePages/default.aspx |
| External | PWR Reactor Services IWG. | PWRRXS | https://www.pwrrxs.com/ |
| EPRI | Relay Users Group | Relay UG | https://msites.epri.com/ms/research/117997/relay-users-group |
| EPRI | Radiation Management and Source Term Technical Strategy Group | RMST TSG | https://membercenter.epri.com/collaboration/E238454 |
| EPRI | Seismic Qualification Reporting and Testing Standardization Users Group | SQURTS | https://msites.epri.com/ms/research/117997/seismic-qualification-reporting-and-testing-standardization-users-group-%28squrts%29- |
| External | Safety Relief Valve Users Group | SRVUG | https://www.safetyreliefvalveusersgroup.com/index.php |
| EPRI | Standardized Task Evaluation Program | STE | https://www.epri.com/training |
| External | Steam Turbine Users Group | STUG | http://www.powerusers.org/our-groups/stug-steam-turbine-users-group/ |
| EPRI | Service Water Assistance Program | SWAP | https://msites.epri.com/ms/research/117997/service-water-assistance-program-swap |
| EPRI | Turbine Generators User Group | TGUG | https://membercenter.epri.com/Programs/056608/Pages/Unique%20Pages/TurbineGeneratorsUserGroupTGUG.aspx |
| EPRI | Transformer and Switchyard Users Group | TSUG | https://msites.epri.com/ms/research/117997/tsug |
| EPRI | Terry Turbine Users Group | TTUG | https://nmac.epri.com/index.php/NMAC/Terry_Turbines |
| EPRI | Vibration Technology Forum | VTF | https://nmac.epri.com/index.php/NMAC/CBM/Vibration |
| EPRI | Work Planning Users Group | WPUG | https://msites.epri.com/ms/research/117997/wpug |

# J
# PMBD TROUBLESHOOTING KNOWLEDGEBASE OVERVIEW

## J.1 Overview

The EPRI Nuclear Maintenance Applications Center (NMAC) has provided troubleshooting information in technical documents. This information was originally available in an online tool called the NMAC Troubleshooting Knowledgebase, or NMACTK, at https://nmactkb.epri.com/Landing.aspx since its release in 2013. Recent requests from members to update the functionality of this tool prompted NMAC to improve the way information valuable to troubleshooting could be accessed by members and overhaul this web-based tool. In response, NMAC combined the NMACTK troubleshooting information with the extensive failure mode information in the Preventive Maintenance Basis Database (PMBD) to bring a larger dataset to our members within the PMBD.

As a result of this action, members will have access to a consolidated troubleshooting knowledgebase via a familiar web application (the PMBD), known as the PMBD Troubleshooting Knowledgebase or PMBDTK. This capability will be available within the PMBD as part of the PMBD Version 5.0 release. Screenshots in this guide are intended to demonstrate the functionality of the PMBDTK; as additional versions of the PMBD are released, the PMBD Help Page (https://pmbd.epri.com) will be the most up-to-date location to find relevant information.

This troubleshooting knowledgebase tool is intended to provide members with a starting point in the troubleshooting process, specifically in their fault table, support/refute matrix, or failure modes and effect analysis development. The database can be searched based on the component of interest (for example, pump, valve, fan, etc.) and/or the indications presented during an equipment event (for example, high vibrations, leaks, high temperature, noise, etc.).

From the PMBD home page members can access this information via a “Troubleshooting” tab on the PMBD dashboard (Figure J-1). The database will be presented in a spreadsheet-like format on the PMBDTK website. It can be searched and filtered for the component of interest and then exported as a Microsoft Excel spreadsheet (see Figure J-2).

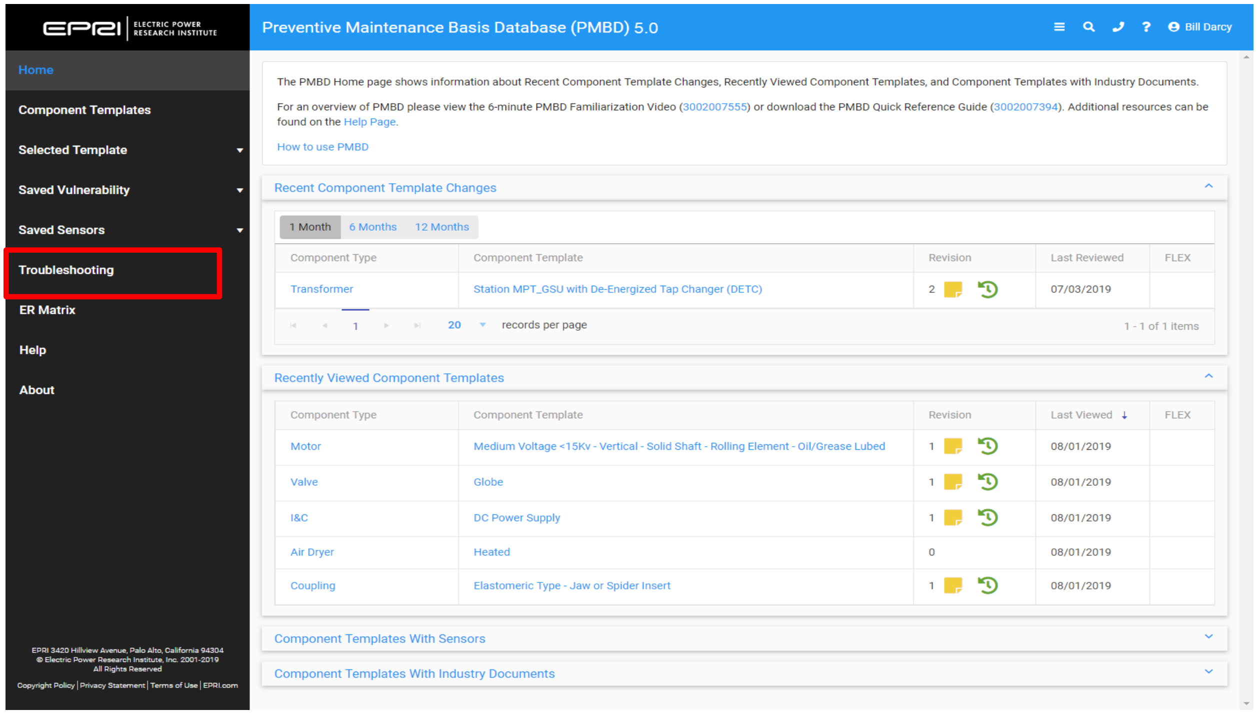



**Figure J-1**
**Accessing the PMBDTK via the PMBD**

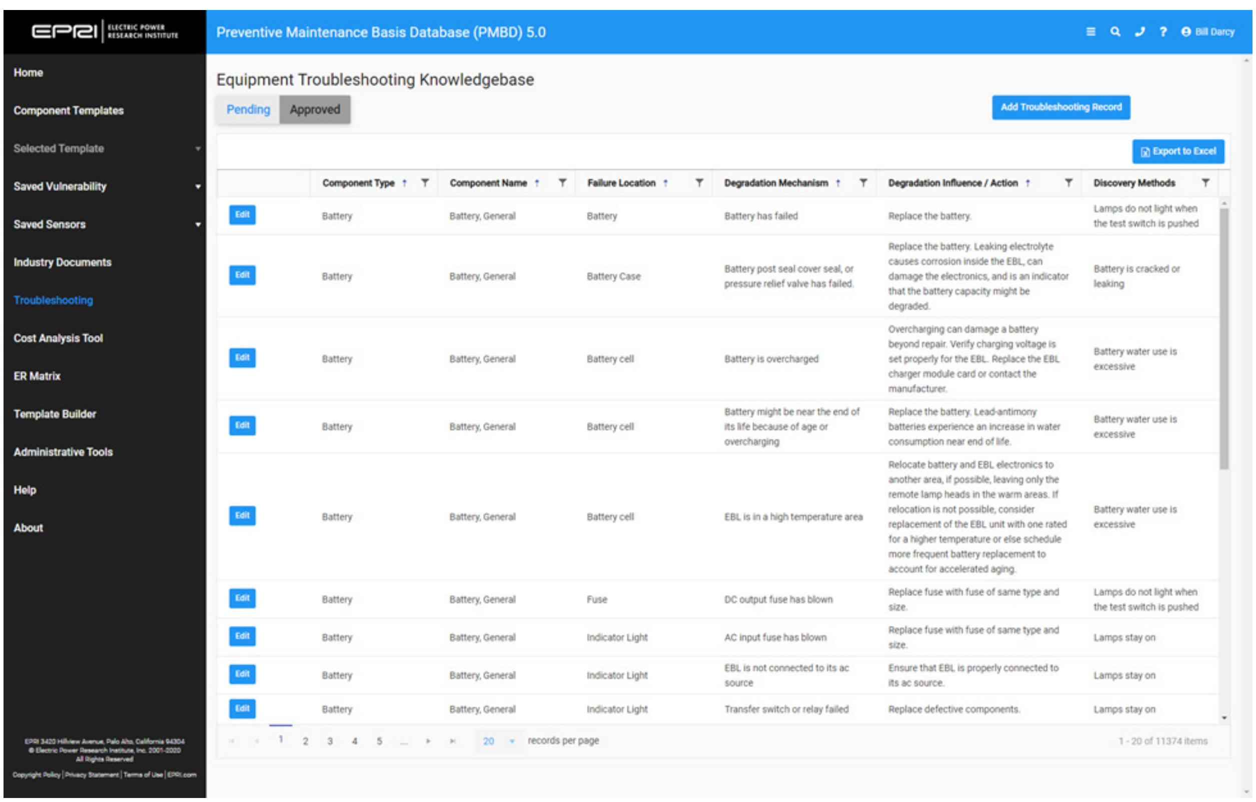



**Figure J-2**
**Interfacing with the PMBDTK via the PMBD**

EPRI members can use the tool as a standalone spreadsheet after exporting results from the PMBD, or it can be integrated with other station/fleet-owned commercially available software programs or custom troubleshooting software. As analytical algorithms improve, the database can be incorporated into member-owned analytical environments to aid in the generation of troubleshooting plans, auto-created failure analysis tables, or performance monitoring programs.

To encourage continuous growth of the PMBDTK, members will be able to perform one of the following two actions to add additional data to the database:

1. Submit troubleshooting plans to NMAC for review and inclusion into this database. Troubleshooting plans and/or failure analyses can be sent to nmachotline@epri.com.
2. Add new line items to the PMBDTK database manually via the "Add Troubleshooting Record" function within the PMBD (See Figure J-3).

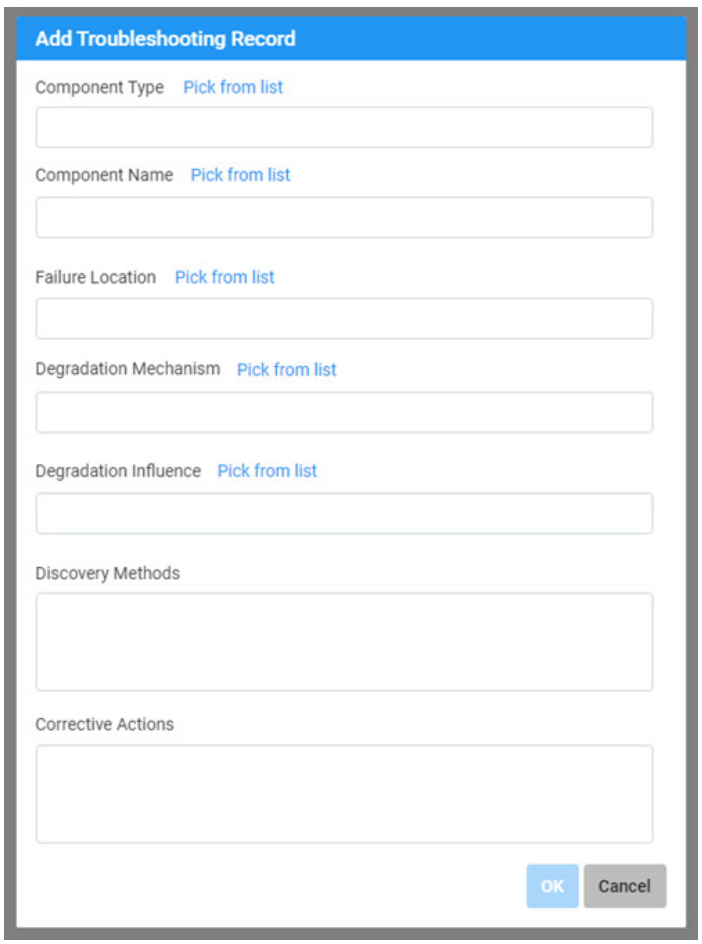



**Figure J-3**
**Adding a new troubleshooting record in PMBDTK – PMBD V5.0**

Once new data is provided to EPRI via email or the "Add Troubleshooting Record" function shown above, it will be reviewed by EPRI NMAC before being incorporated into the PMBDTK for use by members. A similar feature will also be provided if members would like to add suggestions to improve existing records, as shown in Figure J-4.

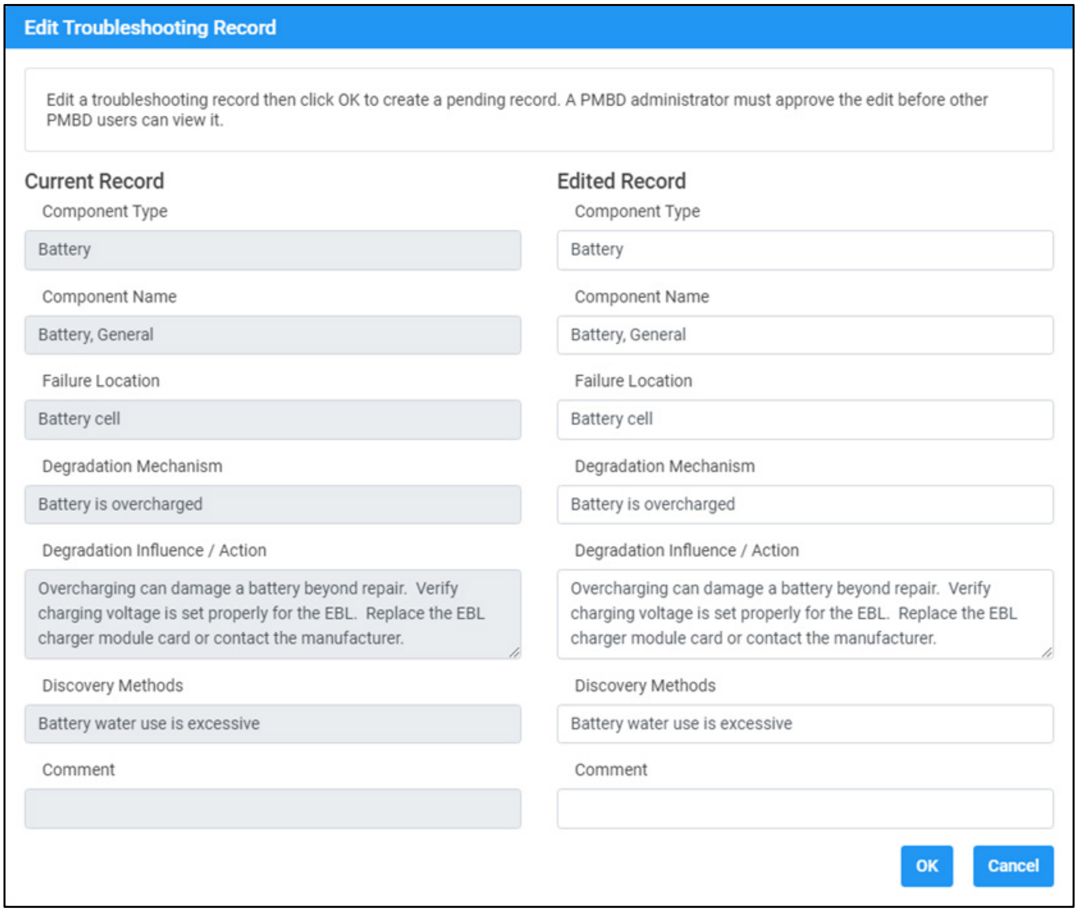



**Figure J-4**
**Editing an existing troubleshooting record in PMBDTK – PMBD V5.0**

NMAC is also available to assist with troubleshooting efforts as a service to EPRI members through the NMAC Hotline at nmachotline@epri.com.

## J.2 Hypothetical Case Study Demonstrating Functionality of the PMBDTK

*Permission provided from originator of the operating experience. This operating experience has been anonymized.*

The following provides a step-by-step example of how the PMBDTK in PMBD can be used to support troubleshooting. The problem statement is from real operating experience from a member, with identifying information anonymized.

### *J.2.1 Initial Problem Statement*

A vertical pump began experiencing reduced flow during a performance test while all other parameters were normal. It is important to note that recent performance tests on this pump were successful.

The problem statement indicated that flow was found to be reduced on a vertical pump during a performance test and all other parameters were stable.

**Step 1: Finding the Component and All Possible Failure Modes in the PMBDTK**

Using the PMBDTK, a search can be performed that provides all of the failure modes contained in the database for vertical pumps. This is done in PMBD by filtering the list down with "PUMP" in the "Component Type" column and all styles of vertical pumps in the "Component" Column. This filtered result provides all of the failures contained in the PMBDTK regarding vertical pumps.

**Note:** In its current state and relationship with the PMBD database, there are several designations of styles of vertical pumps, as is the case for most components. This may provide redundant faults for component types; however, through functions like "remove duplicates" in common spreadsheet programs, these can be quickly eliminated.

A filtered search for "Performance Test" revealed 212 line items within the PMBDTK for the following failure locations:

- Bowls
- Casing and cover
- Column piping
- Discharge bowl and liner
- Gaskets, O-rings
- Impeller
- Suction bell
- Suction strainer
- Wear rings

**Step 2: Filtering the Possible Failure Modes from Information Provided in the Problem Statement**

The problem statement identified that all parameters stayed the same, so the discovery methods or indications that are parameters for a vertical pump will be removed.

The discovery methods that were provided after the initial filter in Step 1 are:

- Vibration
- Audible noise
- Inspection
- Performance test
- Motor current
- Borescope
- Oscillating motor current

- Oscillating flow
- Increased motor current
- Change in motor current
- Hand rotation

Vibration, audible noise, and all faults related to “motor current” will be removed, as these are parameters monitored on this pump.

Hand rotation will be removed because it is coupled with vibration and is an investigation method performed when inspecting for faults in the drive train of a pump/motor.

Oscillating flow is near to the flow issue defined in the problem, so it will be retained.

What remains is:

- Inspection
- Performance test
- Borescope
- Oscillating flow

**Step 3: Developing the Fault Trees**

With the remaining items in the list (shown in Table J-1), essentially what has been created is a fault table.

Note that “Bowls” and “Discharge Bowl and Liner” are identical. “Discharge Bowl and Liner” will be used, as it mentions the “liner” that may or may not be present as a fault location.

**Table J-1**
**Product of filtering PMBDTK for causes**

| Failure Location | Failure Mode | Cause of Failure |
|---|---|---|
| Casing and Cover | Corrosion/Erosion | Fluid quality and chemistry |
| Casing and Cover | Corrosion/Erosion | Improper material |
| Casing and Cover | Erosion | High flow velocities |
| Casing and Cover | Erosion | Improper impeller fit, loose |
| Casing and Cover | Deformation | Thermal shock |
| Column Piping | Loss of Bolting Integrity | Corrosive fluid in presence of incorrect material or installation |
| Column Piping | Corrosion | Fluid quality and chemistry |
| Column Piping | Corrosion | Improper material |
| Column Piping | Corrosion | Loss of protective coating |

**Table J-1 (continued)**
**Product of filtering PMBDTK for causes**

| Failure Location | Failure Mode | Cause Of Failure |
|---|---|---|
| Discharge Bowl and Liner | Corrosion/Erosion | Fluid quality and chemistry |
| Discharge Bowl and Liner | Corrosion/Erosion | Improper material |
| Discharge Bowl and Liner | Corrosion/Erosion | Loss of protective coating |
| Discharge Bowl and Liner | Erosion | High flow velocities |
| Discharge Bowl and Liner | Erosion | Improper impeller fit, loose |
| Gaskets, O-Rings | Leakage | Age |
| Gaskets, O-Rings | Leakage | Contaminated surface |
| Gaskets, O-Rings | Leakage | Improper fit |
| Gaskets, O-Rings | Leakage | Improper torque |
| Gaskets, O-Rings | Leakage | Poor surface condition, warped |
| Gaskets, O-Rings | Leakage | Wrong material |
| Suction Bell | Corrosion/Erosion | Fluid quality and chemistry |
| Suction Bell | Corrosion/Erosion | Improper material |
| Suction Bell | Corrosion/Erosion | Loss of protective coating |
| Suction Bell | Erosion | High flow velocities |

If required by station procedures, this can be converted to a fault tree, as shown in Figure J-5.

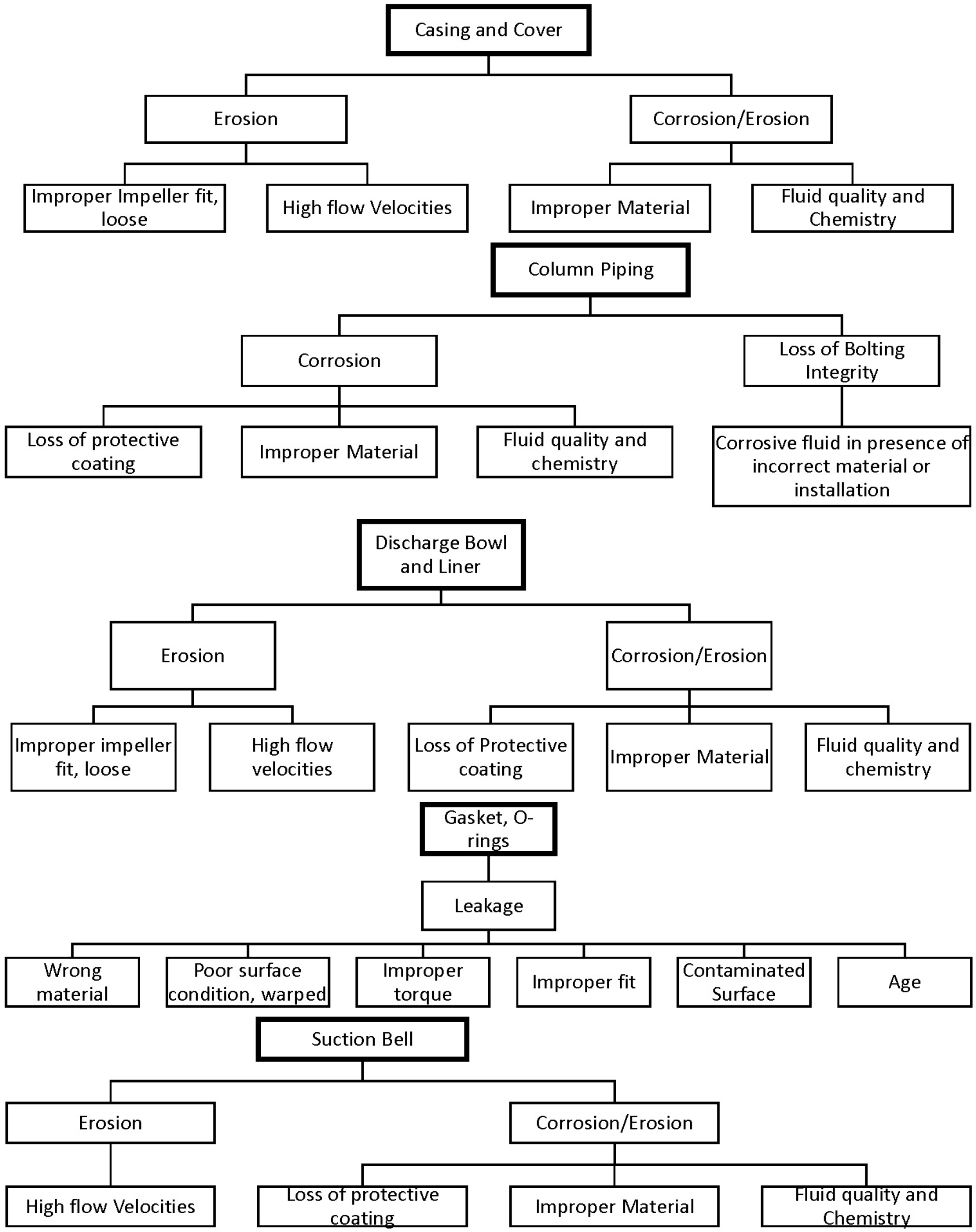



**Figure J-5**
**Filtered PMBDTK information converted into a fault tree**

**Step 4: Building a Support/Refute Table**

As noted in the guide, a support/refute table is the most common tool used in failure analysis in the EPRI members' procedures reviewed for the development of this guide. Table J-2 contains the product of the discussion that follows.

Using the actual operating experience referenced, the investigation revealed that the causes were as follows:

- **Direct Cause**: The flange between the bottom column and the top suction bell exhibited a separation with protruding O-ring, resulting in a loss of differential pressure.
- **Apparent Cause**: Carbon steel bolting is susceptible to corrosion in raw water. This was accelerated by galvanic interactions with silt, copper never-seize, and alloy steel.

It was discovered that the heads of the bolting that connected the bottom column to the top of the suction bell were severely degraded, with significant material loss such that the bearing area of the bolt head yielded and began slipping through the column pipe flange holes. This loss of material and resulting slip caused a separation between the flanges, ranging from 0 to 0.24 inches (0 to 6 mm) around the circumference of the connection, and failure of the O-ring in this flange (see photos in Figures J-6 and J-7). The measurements were taken while the assembly was suspended, as it would have been installed. The condition of the bolt head ranged from approximately 70% to 100% bearing area loss. The resulting gap would result in a loss of differential pressure and would affect the pump performance by leaking flow from the connection. The leak would be apparent in the in-service testing data as a loss of performance.


**Figure J-6**
**Gap between bottom column and suction bell flange**

**Figure J-7**
**Failed O-ring caused by bolting failures**

**Table J-2**
**Support/refute table for PMBDTK example**

| Sequence # [Note 1] | Failure Mode [Note 2] | Supporting Evidence [Note 3] | Refuting Evidence [Note 4] | Troubleshooting Task OR Work Order Number [Note 5] | Notes/Results [Note 6] | FM/CF/I/R [Note 7] |
|---|---|---|---|---|---|---|
| **1. Casing and Cover** | | | | | | |
| 1a | Corrosion/erosion caused by fluid quality and chemistry | None | Casing and cover found in acceptable condition. | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | | R |
| 1b | Corrosion/erosion caused by improper material | None | Casing and cover found in acceptable condition. | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | | R |
| 1c | Erosion from high flow velocities | None | Casing and cover found in acceptable condition. | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | | R |
| 1d | Erosion from improper impeller fit, loose | None | Casing and cover found in acceptable condition. | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | | R |
| **2. Column Piping** | | | | | | |
| **2a** | **Loss of bolting integrity from corrosive fluid in presence or incorrect material or installation** | **Carbon steel corrosion was accelerated by galvanic interactions with silt, copper never-seize, and alloy steel** | **None** | **Work order (WO) 12345678-10 perform full visual inspection camera or divers.** | **Results: Divers found degraded fasteners and extruded O-ring at the flanged joint at the bottom column and top case.** | **FM** |
| 2b | Corrosion caused by fluid quality and chemistry | See Item 2a | None | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | Notes: See Item 2a | CF |
| 2c | Corrosion caused by improper material | See Item 2a | None | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | Notes: See Item 2a | CF |
| 2d | Corrosion caused by loss of protective coating | None | Coatings are still intact. No abnormal corrosion seen. | Work order (WO) 12345678-10 perform full visual inspection camera or divers. | | R |

**Table J-2, continued**
**Support/refute table for PMBDTK example**

| Sequence # [Note 1] | Failure Mode [Note 2] | Supporting Evidence [Note 3] | Refuting Evidence [Note 4] | Troubleshooting Task OR Work Order Number [Note 5] | Notes/Results [Note 6] | FM/CF/I/R [Note 7] |
|---|---|---|---|---|---|---|
| **3. Discharge Bowl and Liner** | | | | | | |
| 3a | Corrosion/erosion fluid quality and chemistry | None | Discharge bowl liner found in acceptable condition. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 3b | Corrosion/erosion improper material | None | Discharge bowl liner found in acceptable condition. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 3c | Corrosion/erosion from loss of protective coating | None | Discharge bowl liner found in acceptable condition. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 3d | Erosion from high flow velocities | None | Discharge bowl liner found in acceptable condition. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 3e | Erosion from improper impeller fit, loose | None | Discharge bowl liner found in acceptable condition. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| **4. Gaskets, O-Rings** | | | | | | |
| 4a | Leakage of joints caused by age | None | No failure caused by age. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 4b | Leakage of joints caused by contaminated surface | None | No failure caused by contaminated surfaces. Bolts were contaminated – see Item 2a. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 4c | Leakage of joints caused by improper fit | None | No leak caused by poor fit. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 4d | Leakage of joints caused by improper torque | None | No leak caused by improper torque. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |

**Table J-2, continued**
**Support/refute table for PMBDTK example**

| Sequence # [Note 1] | Failure Mode [Note 2] | Supporting Evidence [Note 3] | Refuting Evidence [Note 4] | Troubleshooting Task OR Work Order Number [Note 5] | Notes/Results [Note 6] | FM/CF/I/R [Note 7] |
|---|---|---|---|---|---|---|
| **4. Gaskets, O-Rings** | | | | | | |
| 4e | Leakage of joints caused by poor surface condition, warped | None | No leak caused by poor surface condition at flange. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 4f | Leakage of joints caused by use of wrong material | None | O-ring did fail, correct O-ring material used. Incorrect bolting. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| **5. Suction Bell** | | | | | | |
| 5a | Corrosion/erosion caused by fluid quality and chemistry | None | No corrosion or erosion found on suction bell from fluid or chemistry. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 5b | Corrosion/erosion caused by Improper material | None | No evidence of corrosion or erosion from suction bell material. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 5c | Corrosion/erosion caused by Loss of protective coating | None | Coatings were present and intact on suction bell. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |
| 5d | Erosion caused by high flow velocities | None | No signs of erosion caused by high flow velocities. | Work order (WO) 123456-10 perform full visual inspection with camera or divers. | | R |

**Notes:**

1. Sequence does not represent priority but represents sequence of execution and may change based on results.
2. Insert the possible credible failure that could cause the problem identified in the Problem Statement.
3. Provide Supporting Evidence for the condition if the Failure Mode IS present.
4. Provide Refuting Evidence for the condition if the Failure Mode IS NOT present.
5. Troubleshooting Tasks are basic instructions to aid in planning of task. Option to use Troubleshooting Task Sheet as attachment in Work Order if additional detail is needed. Not required for every task.
6. Quantitative evidence is used to support or refute a failure mode. Qualitative or soft wording is avoided. Can also contain notes collected during tasks.
7. Determined to be Failure Mode (FM), Contributing Factor (CF), Indeterminate (I), or Refuted (R).

### Example Conclusion

Although the solution was known at the start of the example, it provided a real-world illustration of how the PMBDTK can be used to support troubleshooting investigations. It is understood that not all failure modes may be captured within the PMBD and PMBDTK, so member support is requested if new failure modes are discovered or are identified as missing. All suggestions, comments, or corrections can be sent to NMACHotline@epri.com.

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