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IEEE Guide for Investigating and Analyzing Power Cable, Joint, and Termination Failures on Systems Rated 5 kV through 46 kV

IEEE Power Engineering Society

Sponsored by the
Insulated Conductors Committee

IEEE

3 Park Avenue, New York, NY 10016-5997, USA

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Sponsor

Insulated Conductors Committee
of the
IEEE Power Engineering Society

Approved 9 August 2004

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Abstract: This guide applies to the process of investigating, evaluating, and analyzing field failures. This guide covers the overall format for failure analysis and subsequent guides will specifically address cables, joints, terminations and separable insulated connectors. Included is a recommended flow charting process that can be used to help guide an individual through the failure analysis process.

Keywords: documentation, examination, failures. failure analysis, flow charts, flow charting

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Introduction

This introduction is not part of IEEE Std 1511-2004, IEEE Guide for Investigating and Analyzing Power Cable, Joint, and Termination Failures on Systems Rated 5 kV through 46 kV.

The need for a guide to assist the electric utility industry in the analysis of failures related to system components has existed for many years. Extensive efforts have been made to develop such guides, but these efforts have frequently stalled because of the complexities involved. Many of these efforts have focused on the development of a classification system intended to categorize failures for the purpose of statistical analysis and industry wide data reporting of failure rates. However, the real value of failure analysis is in improving system performance, reliability, and increasing personnel safety.

This guide introduces a new approach that attempts to employ flow-charting techniques to lead an investigator through the steps necessary to identify the cause of a failure. However, the guide is not intended to be either all-inclusive or to be a document that can take the novice investigator through a failure analysis to the point of arriving at a reasonable conclusion regarding the exact cause of failure. Experience is a teacher that opens the mind to other possibilities beyond those that may seem obvious on the surface. As such, this guide is intended to provide documentation of failure mechanisms that have been identified in prior investigations and of the steps that may have led to the conclusions drawn. As investigators contribute new experiences and new instances of analysis, the guide will evolve to address new issues and the evolution of products developed to address the ever-changing needs of the electric utility industry. It will also serve as historic documentation of past shortcomings in engineering, design, application, and maintenance. In this way it is hoped the guide will contribute to continued product improvement and to the prevention of repeating the same mistakes in future product designs and applications.

This guide is the first of what is proposed to be a series of guides related to a common subject. The series will be designated by a common overall number with a point system of additional guides intended to address specific topics in failure analysis of the cable and accessories used on an underground electric utility system. Subsequent guides will specifically address cables, joints, terminations and separable insulated connectors respectively. The present guide attempts to establish a common format, methodology, and procedures for the development of the subsequent guides. It is also intended to provide the background information necessary to introduce an individual to the concepts and principles of failure analysis.

Much credit is to be extended to the Edison Electric Institute for its early efforts to develop a failure analysis guide for laminated insulated power cables. That guide ultimately resulted in a cable system design that was highly reliable and had an enviable history of service. Hopefully, this series of guides will extend that experience into the realm of modern cable systems.

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Contents

1. Overview 1

1.1 Scope 1

1.2 Purpose 1

2. References 2

3. Definitions 2

4. The information gathering process 3

4.1 Determination of what failed 3

4.2 Documentation of the failure event 3

4.3 Transportation and packaging of the failed samples 6

5. The failure analysis process 6

5.1 Steps of the analysis process 6

5.2 Diagramming techniques 8

5.3 Identify effective solutions 13

5.4 Corrective action 13

Annex A (informative) Bibliography 14

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IEEE Guide for Investigating and Analyzing Power Cable, Joint, and Termination Failures on Systems Rated 5 kV through 46 kV

1. Overview

This guide serves as an "umbrella" document for a series of guides intended to cover specific methods of failure classification and analysis for cables, joints, terminations, and separable insulated connectors used on underground electric power systems. To improve or maintain electric system reliability, many companies depend on accurate failure analysis to optimize maintenance budgets and develop improved material specifications. This series of guides will not make the user an expert in failure analysis. It will, however, provide a general background on specific methods that can be used or specified when performing failure analysis.

1.1 Scope

This guide provides an introduction to failure analysis. It is the first in a series of guides covering failure analysis for cables, joints, terminations, and separable insulated connectors used on shielded power cable systems rated 5 kV through 46 kV. Each subsequent guide will address failure analysis of a specific component of the underground power cable system. The following guides are planned for the series.

- Guide for Investigating and Analyzing Shielded Power Cable Failures on Systems Rated 5 kV through 46 kV.
- Guide for Investigating and Analyzing Joint Failures on Systems Rated 5 kV through 46 kV.
- Guide for Investigating and Analyzing Termination Failures on Systems Rated 5 kV through 46 kV.
- Guide for Investigating and Analyzing Separable Insulated Connector Failures on Systems Rated 5 kV through 46 kV.

1.2 Purpose

The purpose of this guide is to provide an introduction to the concepts of failure analysis, how it can be used, and the value that can be obtained. The guide covers some of the commonly used methods employed in failure analysis and how these methods can be applied in determining the cause of failure for the components used in the construction of an underground power cable system. The guide is based on the application of flow charting methods to the analysis of a failure. Ultimately, the guide will serve as a source for documenting known failure mechanisms and will provide a format for the documentation of new failure mechanism once they have been identified.

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2. References

This guide shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

IEEE 48™-1996, IEEE Standard Test Procedures and Requirements for Alternating-Current Cable Terminations 2.5 kV Through 765 kV.[1,2]

IEEE 386™-1995, IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Above 600 V.

IEEE 404™-2000, IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V.

IEEE 592™-1990, IEEE Standard for Exposed Semiconducting Shields on High-Voltage Cable Joints and Separable Insulated Connectors.

IEEE 635™-2003, IEEE Guide for Selection and Design of Aluminum Sheaths for Power Cables.

IEEE 1026™-1995, IEEE Recommended Practice for Test Methods for Determination of Compatibility of Materials With Conductive Polymeric Insulation Shields and Jackets.

IEEE 1210™-1996, IEEE Standard Tests for Determining Compatibility of Cable-Pulling Lubricants With Wire and Cable.

3. Definitions

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition* [B2] should be referenced for terms not defined in this clause.

3.1 contributing cause: A cause that, of itself, may not result in failure.

3.2 contributing factor: A factor that possibly may have contributed to the failure.

3.3 failure: The inability of an item to perform its intended function.

3.4 failure analysis: The logical, systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failures. Statistical techniques may be used to determine failure rates based on the determined cause.

3.5 reliability: The ability of an item to perform a required function under stated conditions for a stated period of time.

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4. The information gathering process

The following information should be tracked for each failure and should be made available to personnel who examine the samples. Many companies develop and use failed material return forms to initiate the information gathering process and track failures using a computerized database to recognize and evaluate trends.

4.1 Determination of what failed

In some cases, it may be difficult to establish exactly what failed. Damage may be present in several locations. An initial failure may have created a cascade of events that led to subsequent failures of other components. In such situations, the most severely damaged area may not be the one where the failure initiated. Similarly, damage may be in a transition area between two components. This raises the question of which component failed or if the failure was the result of something in the interface between the two components. In some cases, it may be difficult to locate or identify any physical evidence that a failure has occurred. Damage may be hidden below the surface or contained within an enclosing medium.

Yet it is important to isolate the failure before repairs can be made and the equipment restored to service. For electrical systems, this may be done through visual observation, reclosing of a circuit, the application of test voltages supplied by portable equipment, or other techniques. The choice of locating technique can have an influence on later efforts to analyze the cause of failure. Some techniques will produce additional damage at the failure site that may obliterate available evidence of the initial cause of failure. It is important to choose location techniques that limit additional damage, yet remain effective at isolating the cause of failure and its location. A number of guides, standards, and references are available that provide recommendations on how to proceed in this area.

Once a failure is located and the components involved are identified, some basic decisions have to be made before any meaningful failure analysis can take place. One of the first of those decisions is what to remove and save for examination. If there is any doubt, submit as much of the material from the failure site as possible.

4.2 Documentation of the failure event

When a failure occurs, it is extremely important to document the event and the details of the failure as completely as possible. There are a number of techniques to apply that will preserve the evidence for future analysis. When the documentation process is thorough, the results of a failure analysis will be more complete and more likely to provide insights into the full sequence of events that took place.

4.2.1 Immediacy

It is extremely important to gather as much information as possible immediately after an event's occurrence. While events are still fresh in the minds of witnesses, details are likely to be clear and vivid. Evidence at the site is likely to be intact and undisturbed. This pristine state of the information can provide additional details that might be lost if the information gathering process is delayed.

4.2.2 Minimum information

The absolute minimum amount of information required to initiate a failure analysis consists of two pieces of information:

- contact information for someone knowledgeable about the event and
- availability of the component(s) involved in the failure.

This basic information can be obtained through the use of a simple form that requires minimal effort on the part of the initiating individual. The simplicity of this initiation process can be a factor in determining

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whether failures are tracked and efforts made to improve a product or if the failure simply ends up in the trash and nothing is learned from the event.

4.2.3 Witnesses and statements

Question witnesses about the event. Make use of the natural senses each person possesses. Ask if there were any unusual sights, sounds, smells, or other sensations prior to or during the failure. At the very least, get names and contact information from each witness present. Have someone take notes of statements made by witnesses or ask those witnesses to write down what took place. If a witness does not object, a voice recorder offers a quick and easy method of documentation when used discretely.

4.2.4 Photography

One of the most valuable tools during a failure investigation can be the camera, whether a conventional film or a digital model. Images capture information that may not be recoverable by any other method. Once objects at the site are moved, the information that may have been provided by the relative location of one item with respect to another is lost forever, unless it is recorded in an image. Photography is an inexpensive means of accumulating a large volume of information. It is much better to take too many pictures than to take too few. Photograph the scene and the failed item from different angles and from different distances away. Some photographs should be close-up while others should provide an overall perspective of the scene. When possible, include an object with known dimensions that can serve as a reference for determining distances and dimensions within the photograph.

4.2.5 Sketches

Only very basic artistic talents are required to provide an overall sketch of the scene where a failure occurred. A sketch can supplement photographic efforts by including direct measurements of dimensions and distances between objects. A sketch could even locate the position of witnesses at the time a failure occurred. A sketch can also provide a convenient place to record nameplate data about the object that failed.

4.2.6 Circumstances

Documentation of the circumstances surrounding a failure can be the key to providing much important data. Develop a record of what took place prior to the failure, what was being done when the failure occurred, and responses to the situation afterward. Actions taken and the resulting events provide many clues that may help resolve apparent conflicts between versions of the situation obtained from different sources.

4.2.7 Other information

Any additional information that can be provided about a failure will be helpful in determining the cause.

4.2.7.1 Location

Record information that can identify the failure, particularly information that ties the failure to a specific location. Location data provides unique tracking information when multiple failures are involved or when several items are submitted within a single analysis request. Location data also allows the failure to be linked to information available through other sources. This may include terrain and circuit maps, average rainfall, nearby industries, sources of pollutants, seismic events, and information from other commercially available data sources.

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4.2.7.2 Date and time of failure

The date and time of a failure can provide insight into the cause. Timing information may allow the correlation of a failure with an environmental event such as lightning or a system event such as a switching transient, a reclose operation, or connection of a capacitor bank. If event recorders are available on the system, a remote recorder may have triggered that could provide detailed information on the sequence of events. Date and time information can be linked to weather data, lightning strike information, and other parameters that are routinely monitored by various agencies and departments within a company or government.

4.2.7.3 Circuit information

Information needed about the circuit associated with a failure can vary. At the least, a circuit identification number, the operating voltage, and the available fault current are frequently useful. Other circuit parameters may prove of interest as an analysis progresses. This could include:

- the circuit configuration
- load current at the time of failure
- maximum load
- load characteristics (starting currents, surges, etc.)
- BIL ratings
- switching events
- fusing
- reclosing sequence
- relaying scheme and types of protective relays
- normally open point locations
- type of grounding and ground resistance
- cable construction and type
  - conductor size and material
  - neutral type, size, and material
  - insulation type and thickness
  - sheath type, size, and material
  - voltage rating
  - operating voltage
- surrounding soil conditions
- manhole or vault presence
- vault ventilation
- level of water in vault or manhole

4.2.7.4 Environmental conditions

Environmental conditions at the time of and immediately prior to a failure can play a role in causing an event. Information on lightning, rainfall, humidity, fog, dew, snow, extreme temperatures, altitude, or common pollutants may be useful and should be recorded.

4.2.7.5 Unusual conditions

Products are often designed with anticipation of certain environments, operating conditions, or methods of usage. How a product is ultimately used can be quite different. Document any unusual conditions that might exist, particularly anything that is outside of the normal specifications, requirements in industry standards, or operating limits noted by the manufacturer. This could include unusual bends in a cable, improper cable positioning or length, an unusual orientation of a product, a powdery or scaly surface finish, rocky or sandy soil or backfill, uneven terrain, exposure to chemicals or contaminants, damage to adjacent objects, or similar conditions.

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4.3 Transportation and packaging of the failed samples

Once the components to be saved and examined from a failure have been identified, it is important to accomplish the following four tasks:

- limit further damage
- isolate from contamination
- seal fluids and gases to prevent leakage or escape
- package for shipment

When packaging an item for shipment and handling, consider the method of transport that will be used. Commercial shipping services may not handle a package gently, even if it is marked fragile. Package the failed item with the intent of surviving rough handling without damage. Consider the fact that damaged items are frequently much more fragile than a similar undamaged item. A material that is charred or burned can be brittle and may fall apart unless proper external support is provided. Items that have some weight develop considerable momentum when moving on a conveyor. Packaging must absorb the energy of this momentum and maintain the integrity of the components contained within.

5. The failure analysis process

Failure analysis is a systematic approach to identifying the cause when a product does not perform as intended. It is a process that is based on the laws of physics, past experience of the analyst and the evidence available from the failure. In its simplest form, failure analysis attempts to reconstruct the events that led up to the failure of a product and determine the most likely cause.

5.1 Steps of the analysis process

5.1.1 Background research

Before starting failure analysis, become familiar with the product(s) involved and the circumstances surrounding the failure. Review the documentation provided from the field, including witness reports, site sketches, circuit configuration information, etc. Contact individuals involved and discuss the event with them. Obtain copies of any product information that may be available, including product catalog pages, installation and operating instructions, and maintenance guides. Compare this product design with designs from other manufacturers and even with current designs from the same manufacturer. Differences can sometime provide clues about product changes that may have been made to eliminate a mode of failure or to improve performance.

5.1.2 Planning

Make preparations before beginning the failure analysis. Begin with a plan that includes contingencies. Determine how you will proceed with the investigation and what steps will be followed. If disassembly of a component will be involved, determine the methods that will be used and the equipment that will be required. If some information may become unrecoverable, determine how that information can be documented before proceeding. If information may be hidden inside that will be disturbed by disassembly, determine if the condition can be documented by non-destructive means, such as x-ray. Be prepared to take an alternate approach if problems are encountered with equipment, procedures, or the nature of the damage discovered. It may even be helpful to search industry literature on the type of product involved, including technical journals, and determine if failures have been experienced by other users.

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5.1.3 Physical examination

Examination of the physical evidence is an extremely important step in the failure analysis process. This step provides many of the most important details that will be discovered and determines what path the investigation will follow. Physical examinations generally involve a detailed visual inspection of the failed product. Start with documentation of the external condition before initiating any disassembly. Documentation should include position markings and orientation on the assembly, should it become necessary to revisit a portion of the analysis. It is extremely important to pay close attention to the immediate area of the failure and the adjoining areas. Look closely for burn marks, tracking, overheating conditions and/or punctures. If dissection of the product is necessary during the examination sequence, take pictures at each stage of the dissection process. Document the removal of individual layers or single components. Photographs should allow you to reconstruct each step of the disassembly. The value of these photographs will become apparent when during the analysis it is necessary to re-examine evidence that may have been destroyed during the disassembly. During this phase of the examination sequence, document as much detail as possible. Take notes during the dissection sequence and document all observations. Note any unusual observations made while examining the samples.

The visual examination may suggest the need to perform other types of testing. This may include chemical analysis or spectral analysis of a possible contaminant or the implementation of a test sequence designed to simulate the mode of failure observed. If results have been inconclusive, it may be time to seek input from a failure analysis expert with more experience.

5.1.4 Analysis and reconstruction

This step requires a great deal of thought. Consideration should be given to all the possible ways in which the product could have failed in a manner that would result in physical details similar to those observed. In this step, various scenarios are developed. Each is a possible sequence of events leading up to the failure. All ideas are equally plausible and none should be rejected. Allowing others to examine the physical evidence and suggest ideas may prove beneficial. Not everyone will view the problem in the same manner. The key is the free flow of ideas with as many solutions as possible. Each scenario, however, must represent a logical sequence of events and consequences based on the applicable physical laws and the available evidence.

Fit the pieces together. Each bit of information gathered will:

- support a theory
- deny a theory
- neither support nor deny the theory

By carefully fitting the pieces of physical evidence together, some theories about the cause of failure will become implausible and should be rejected. Other scenarios will continue to be viable candidates for representing the actual sequence of events. Usually, one sequence of events, or at the most two, will emerge as the most likely cause for the failure.

5.1.5 The process of elimination

Each remaining scenario should be examined for those characteristics that distinguish it from the others. Differences may suggest possible variations that could exist in the physical evidence, distinguishing one theory regarding the cause of failure from another. These differences could direct the investigation toward a single most likely cause of the failure. The differences may also suggest possible tests that could be performed to eliminate a particular theory from consideration. Laboratory testing can become important at this stage of the analysis. Laboratory testing may provide conclusive support that would corroborate a theory or it may provide additional information that would further direct the investigation. It may be necessary to perform simulation tests to recreate the failure or to isolate differences that would more clearly point to one failure scenario over another.

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Finally, re-examine the physical evidence for the details that would distinguish one failure mode from another. This stage of the investigation can serve to reinforce the conclusions drawn and further support the scenario associated with the most likely cause of failure. The re-examination may suggest further testing that could be performed to differentiate failure modes. A single most probable cause and sequence of events should emerge.

5.1.6 Identify the problem

End the analysis sequence by coming to a sound conclusion that will identify the problem and start the proper sequence for corrective actions and preventative measures. All relevant theories that were tried, accepted or denied should point toward a single conclusion, a conclusion that is the exact cause of the failure.

5.1.7 Reporting and feedback

Failure analysis is not successful until the results are used to make positive changes. Drawing a conclusion about the cause of failure is only part of the process. Effective solutions to the problem must also be identified that can prevent future events from occurring or limit the amount of damage inflicted. This part of the process will depend on the value perceived by those initiating the failure analysis. Providing a report of the conclusions drawn in a timely and understandable format is necessary to ensure success. For this reason it is important to turn around results in as short a time as possible.

Close the loop at the end of the failure investigation. If the information developed is not acted upon and distributed back to those involved in the incident, then very little value has been gained from the effort. How this feedback is provided can affect the success of any remedial actions. It is important to approach the situation from a cooperative standpoint. The purpose is not to place blame, but to eliminate the repetition of this event in the future and to improve the products involved or how they are applied to improve reliability and increase value to the user.

5.2 Diagramming techniques

Diagramming techniques provide a visual method of tracing the progress of a failure investigation. There are a variety of diagramming techniques available that can approach the problem from various points of view. Most of these techniques employ flow charting methods to document the failure analysis sequence and all of the possibilities that must be explored and considered. Flow charting is a powerful tool that can help in reaching a sound, undisputed conclusion about the cause of failure. Utilization of diagramming techniques during the entire failure analysis sequence helps to ensure success and to properly document procedures.

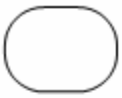
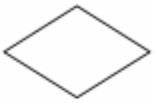
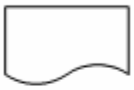
A number of commercial companies offer formal training in failure analysis techniques and in specific flow charting methods. Many of these companies employ the term “root cause analysis” in describing the techniques employed. Variations exist in these approaches and the user of this guide is encouraged to explore the various techniques to determine which method or procedure is most successful for their particular situation.

5.2.1 Flow charting symbols

Flow charts represent a method of block diagramming a process. Like any other process, failure analysis has an optimal sequence that leads to the best possible result. Failure analysis is an investigative process. The steps of the process involve observation, comparison, extrapolation, the formation of hypotheses, the gathering of evidence, the presentation of fact, and the distillation of those facts into a supported conclusion. The flow charts used in this guide employ a number of symbols connected by directional lines to map the process. The symbols and their meaning are described in the symbol chart below.

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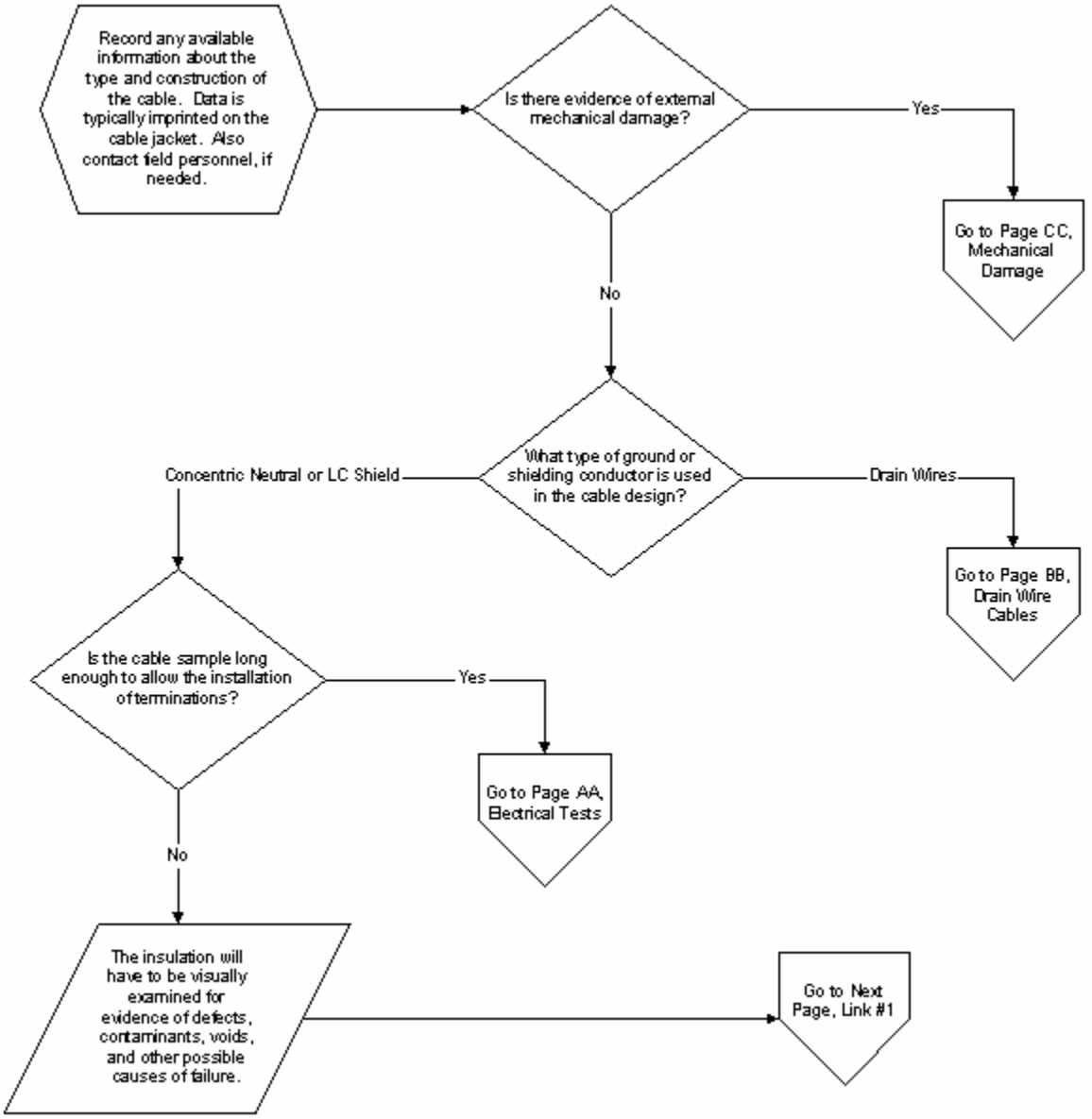
SYMBOL	DEFINITION
	Process—A rectangle or square is used to enclose a verbal statement describing a process or test procedure to be performed.
	Alternate Process—When a problem or question may be approached from two different directions, the flow chart may branch along parallel paths. A square or rectangle with rounded corners identifies the alternate process.
	Decision—The diamond encloses a decision. Various answers to the question may lead to different paths of pursuit. Paths exiting a decision block should be marked with the various possible decision outcomes.
	Data—A slanted parallelogram encloses data. Data for a failure analysis may include descriptive information or pictures that can be used for comparison.
	Document—A rectangle with one wavy side refers to a document. Documents may include references to standards or to technical papers that can provide insight into the problem being analyzed.
	Terminator—The terminator symbol marks the end of a process. For this guide the end of the process should be a cause of failure or a realization that no solution can be reached given the available information.
	Preparation—Steps required to prepare for the following process or test procedure are enclosed in a six-sided polygon.
	Connector—Links or joins a process path across multiple pages or boundaries.
	Off Page Connector—This symbol links the user to another page of the guide where the particular branch of the failure analysis process is continued.
	Summing Junction—A summing junction combines two process paths into a single path.
	Or—An or junction allows a process to split along two parallel paths.
	Delay—The delay symbol can be inserted into a process to slow or delay resolution of the outcome. A delay might be necessary, for example, to allow for receipt of results from an outside laboratory or to allow time for a chemical reaction to occur.
	Manual Operation—The four-sided polygon with a collapsed side is used to indicate a manual operation that must be performed before proceeding to the next step of the process.

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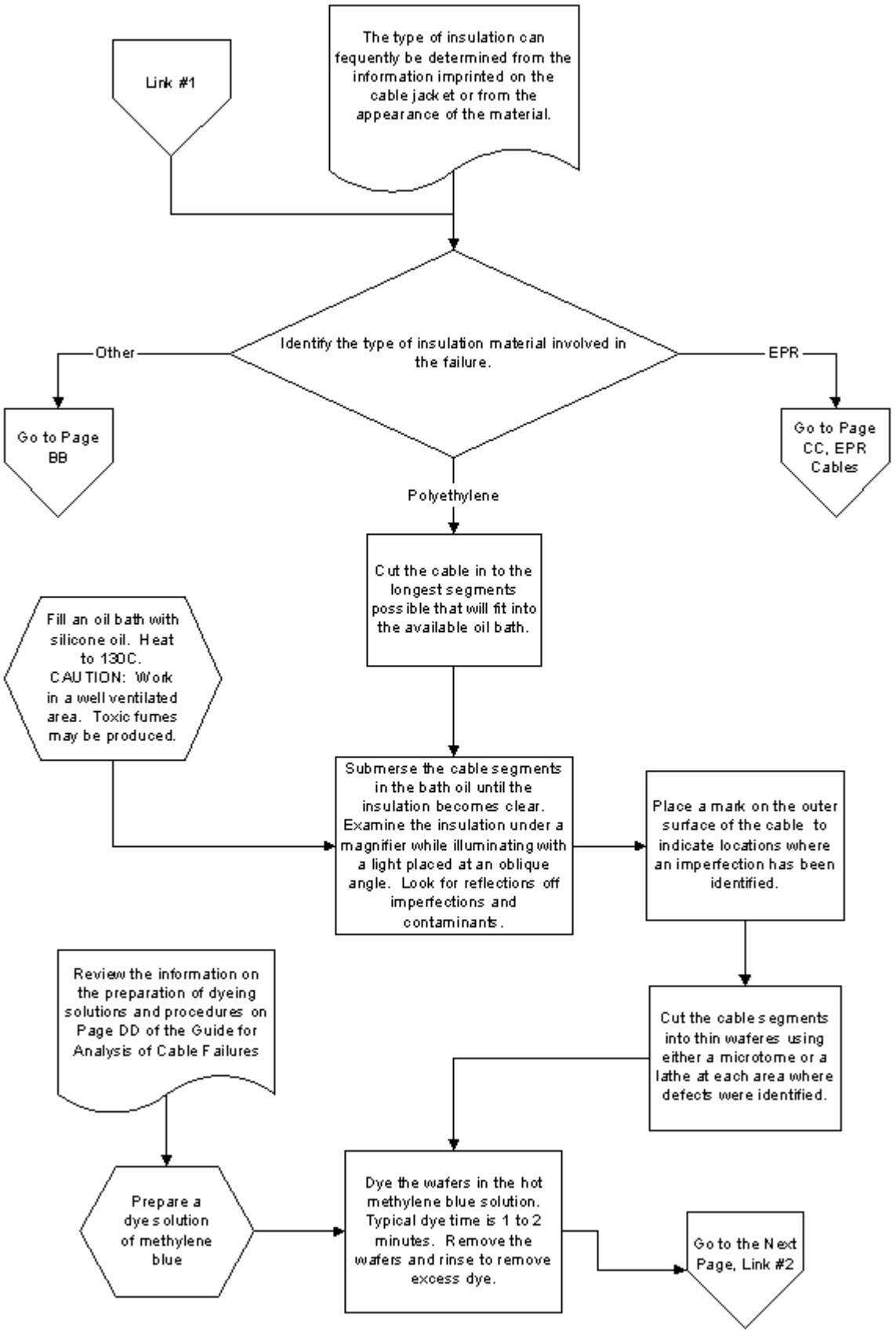
5.2.2 Example Flow Chart

The following example is provided to illustrate how flowcharting techniques might be applied to failure analysis for an underground power cable. The example illustrates the various flowcharting symbols and how they could be used to guide the user through the failure analysis process. The user should consult the specific guides within this series for performing an actual failure analysis on a particular component.



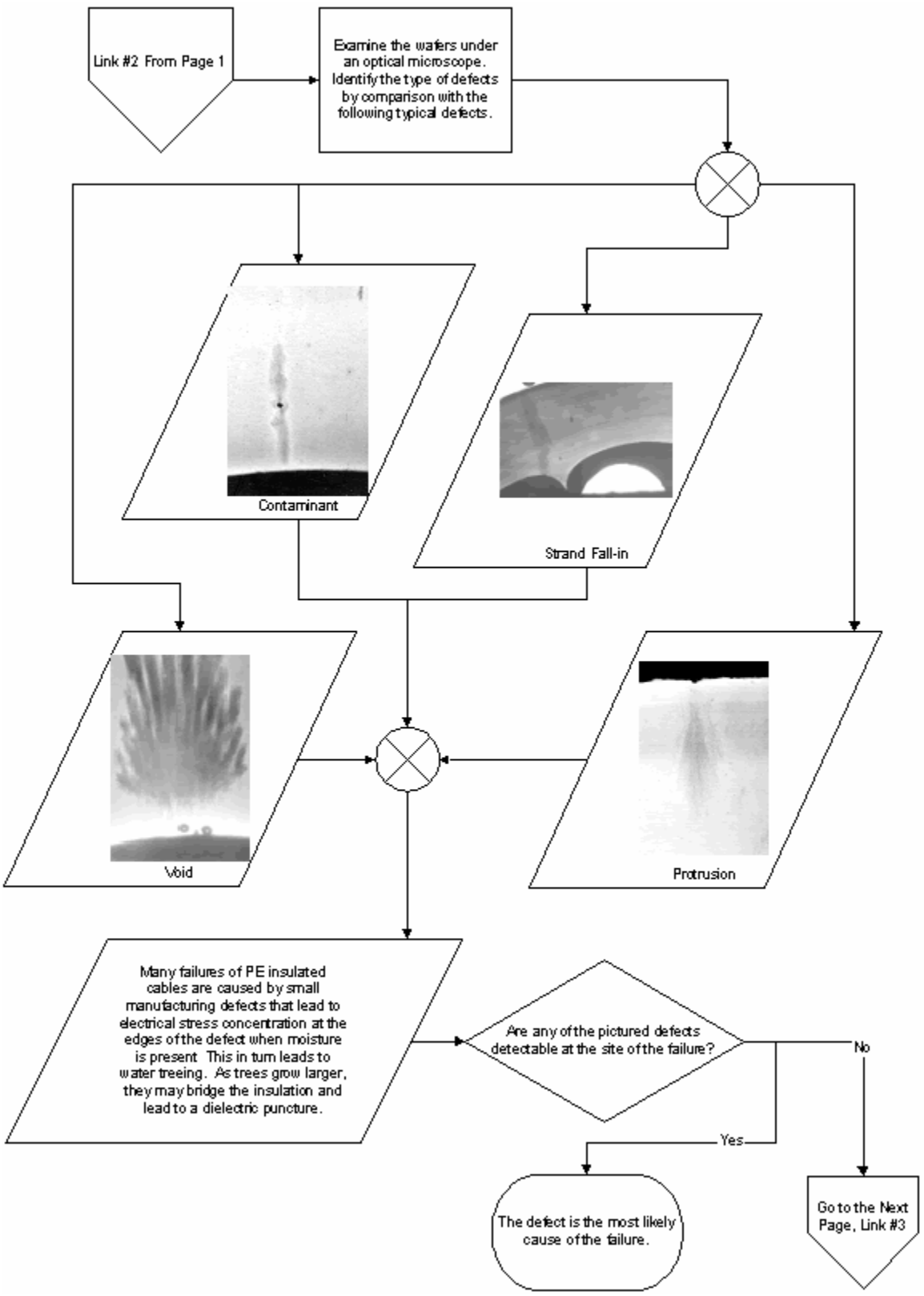
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5.3 Identify effective solutions

The value of failure analysis comes in the form of identifying and implementing corrective solutions that prevent or eliminate the occurrence of future events of a similar nature. Getting those involved in the failure event and involved in developing a solution can significantly improve the chances of success. Brainstorm techniques can ensure that involvement can bring to light some effective solutions that might not have been considered otherwise. Consider solutions that can be implemented immediately and solutions that provide a cost effective means of eliminating further failures.

5.4 Corrective action

After the cause of the failure has been identified and all of the effective solutions documented, carry through with an action plan. Implementation of an appropriate solution and monitoring of its effectiveness are required to ensure a successful resolution of the problem. Success has only been achieved when failures have been eliminated and system reliability has been dramatically improved.

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Annex A

(informative)

Bibliography

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[B2] IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms,* Seventh Edition.

[B3] "Recommended Procedure for the Diagnosis of Cable, Joint, and Termination Troubles, Prepared under the Auspices of the Cable Engineering Section," *Association of Edison Illuminating Companies, and Transmission and Distribution Committee,* Publication No. 60-16, Edison Electric Institute, 1960.

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