

IEEE Std 3006.8™-2018

Recommended Practice for
Analyzing Reliability Data
for Equipment Used in
Industrial and Commercial
Power Systems



IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

Sponsor

**Technical Books Coordinating Committee
of the
IEEE Industry Applications Society**

Approved 27 September 2018

IEEE-SA Standards Board

Abstract: Data supporting the reliability evaluation of existing industrial and commercial power systems are described. This recommended practice is likely to be of greatest value to the power-oriented engineer with limited experience in the area of reliability. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

Keywords: availability, IEEE 3006.8™, mean down time (MDT), mean time between failures (MTBF), mean time to maintain (MTTM), mean time to repair (MTTR), reliability analysis, reliability data

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2018 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 17 October 2018. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-5029-4 STD23333
Print: ISBN 978-1-5044-5206-9 STDPD23333

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.” They can also be obtained on request from IEEE or viewed at <http://standards.ieee.org/IPR/disclaimers.html>.

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (“IEEE-SA”) Standards Board. IEEE (“the Institute”) develops its standards through a consensus development process, approved by the American National Standards Institute (“ANSI”), which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE Standards are documents developed through scientific, academic, and industry-based technical working groups. Volunteers in IEEE working groups are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE Standards do not guarantee or ensure safety, security, health, or environmental protection, or ensure against interference with or from other devices or networks. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. A current IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every ten years. When a document is more than ten years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit IEEE Xplore at <http://ieeexplore.ieee.org/> or contact IEEE at the address listed previously. For more information about the IEEE-SA or IEEE's standards development process, visit the IEEE-SA Website at <http://standards.ieee.org>.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE-SA Website at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this IEEE recommended practice was submitted to the IEEE-SA Standards Board for approval, the Power Systems Reliability Working Group of the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society had the following membership:

Robert G. Arno, *Chair*
Neal Dowling, *Vice Chair*

Timothy Coyle
Peyton S. Hale

Masoud Pourali
Robert Schuerger

Michael Simon
Christopher C. Thompson

At the time this IEEE recommended practice was completed, the Power Systems Reliability Working Group had the following membership:

Christopher C. Thompson, *Chair*

Timothy Coyle
Neal Dowling

Peyton S. Hale
Masoud Pourali

Robert Schuerger
Michael Simon

The following members of the individual balloting committee voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

Ali Al Awazi
Robert G. Arno
Louis Barrios
Wallace Binder
Thomas Bishop
Frederick Brockhurst
Gustavo Brunello
Demetrio Bucaneg, Jr.
William Byrd
Paul Cardinal
Dion Caves
Steven Chen
Michael Chirico
Greg Clement
Terry Conrad
Daryld Crow
Glenn Davis
Davide De Luca
Gary Donner
Neal Dowling
H. Landis Floyd
Mietek Glinkowski
Waymon Goch
Edwin Goodwin
Lou Grahor
Randall Groves
Scott Hietpas

Werner Hoelzl
Robert Hoerauf
Gary Hoffman
Richard Holub
Christel Hunter
Gerald Irvine
John Kay
Yuri Khersonsky
Yoonik Kim
Jim Kulchisky
James Lagree
Wei-Jen Lee
Duane Leschert
Albert Livshitz
William Lockley
Daleep Mohla
William Moylan
Jerry Murphy
Daniel Neeser
Dennis Neitzel
Arthur Neubauer
Joe Nims
Gearold O. H. Eidhin
Howard Penrose
Jim Phillips
Masoud Pourali
Iulian Profir

John Rama
James Reilly
John Roach
Tim Rohrer
Ryandi Ryandi
Daniel Sabin
Vincent Saporita
Bartien Sayogo
Robert Schuerger
Kenneth Sedziol
Michael Simon
Jerry Smith
Gary Smullin
Wayne Stec
Thomas Stewart
David Tepen
Wayne Timm
Timothy Unruh
James Van De Ligt
Van Wagner
Keith Waters
Kenneth White
Dean Yager
Jian Yu
David Zech
Shuhui Zhang
Gaetano Zizzo

When the IEEE-SA Standards Board approved this recommended practice on 27 September 2018, it had the following membership:

Jean-Philippe Faure, *Chair*
Gary Hoffman, *Vice Chair*
John Kulick, *Past Chair*
Konstantinos Karachalios, *Secretary*

Chuck Adams
Masayuki Ariyoshi
Ted Burse
Stephen Dukes
Doug Edwards
J. Travis Griffith
Michael Janezic

Thomas Koshy
Joseph L. Koepfinger*
Kevin Lu
Daleep Mohla
Damir Novosel
Ronald C. Petersen
Annette D. Reilly

Robby Robson
Dorothy Stanley
Adrian Stephens
Mehmet Ulema
Phil Wennblom
Howard Wolfman
Yu Yuan

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 3006.8-2018, IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems.

IEEE 3000 Standards Collection™

This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society, as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000™:

- Power Systems Design (3001 series)
- Power Systems Analysis (3002 series)
- Power Systems Grounding (3003 series)
- Protection and Coordination (3004 series)
- Emergency, Standby Power, and Energy Management Systems (3005 series)
- Power Systems Reliability (3006 series)
- Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3006.8™

Knowledge of the reliability of electrical equipment is an important consideration in the design and operation of industrial and commercial power distribution systems. Each of the hundreds of components installed at a facility has an operational signature defined by its failure statistics. When these signatures are analyzed in the context of their relationship in a power system, designers and operators can understand—and more importantly, predict—system performance over time. In response, this recommended practice offers the best facility equipment data currently available. The data that follow represent five decades, millions of dollars, and thousands of hours of labor in the collection of data from more than 300 diverse facilities.

Contents

1. Overview	11
1.1 Scope	11
2. Normative references.....	11
3. Definitions	11
4. Introduction	12
5. Part 1: Mechanical and electrical equipment data, 1994 and 2005.....	13
5.1 Database development	13
5.2 Results	16
5.3 Introduction	34
5.4 1979 switchgear bus reliability data	34
5.5 1980 generator survey data.....	35
5.6 1979 survey of the reliability of transformers.....	36
5.7 1983 IEEE survey on the reliability of large motors	42
6. Part 3: Equipment reliability surveys conducted prior to 1976	52
6.1 Introduction	52
6.2 Reliability of electrical equipment (1974 survey).....	54
Annex A (informative) Bibliography	68

IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to analyze reliability data for equipment used in industrial and commercial power systems. Equipment reliability data collected over the years is presented. This is followed by a discussion of key equipment reliability metrics, such as failure rate, downtime to repair in hours per failure, and probability of starting (operating).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Historical Reliability Data for IEEE 3006 Standards: Power System Reliability^{TM, 1,2}

IEEE Std 3006.2-2016TM, Recommended Practice for Evaluating the Reliability of Existing Industrial and Commercial Power Systems.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.³

¹ The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

² IEEE publications are available from The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

For definitions of terms pertaining to power system reliability used in this standard, refer to IEEE Std 3006.5TM-2014.

4. Introduction

Knowledge of the reliability of electrical equipment is an important consideration in the design and operation of industrial and commercial power distribution systems. Each of the hundreds of components installed at a facility has an operational signature defined by its failure statistics. When these signatures are analyzed in the context of their relationship in a power system, designers and operators can understand—and more importantly, predict—system performance over time. In response, this recommended practice offers the best facility equipment data currently available. The data that follow represent five decades, millions of dollars, and thousands of hours of labor in the collection of data from more than 300 diverse facilities.

The failure characteristics of individual pieces of electrical equipment can be partially described by the following basic statistics: mean time to repair (MTTR) and mean time between failures (MTBF). From these, most failure statistics can be calculated, including and especially, reliability (r) and inherent availability (a_i). Data on other factors (e.g., cause and type of failures, maintenance procedures, repair method, etc.) are also required to characterize the performance of electrical equipment in service (refer to *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 1 and page 61 for more information).

Availability is a key measure of facility performance. Many facilities operate for long periods of time, providing power to perform critical functions. Balancing the cost of design, construction, and maintenance against the requirement for continuous and reliable operation is of the utmost importance. Understanding both component-level and system-level failure statistics is essential to achieving this balance.

The data in this recommended practice are used to model power system performance. The analytical models required for estimating power system performance are presented in IEEE Std 3006.3TM-2017 [B21], IEEE Std 3006.5TM-2014, and IEEE Std 3006.9TM-2013 [B23].

The recommended practice is divided into three parts, which together cover data collection programs spanning more than 45 years. Each part consists of a large collection of equipment reliability and availability statistics.

Part 1 includes data from two major collection efforts conducted by the U.S. Army Corps of Engineers Power Reliability Enhancement Program (USACE-PREP). The 1994 data collection program was extensive, including information for many types of commercial facilities within the United States. The 2005 program replicated and expanded upon the 1994 program, respecting its standards for data integrity. Together, these efforts created the most comprehensive facility equipment reliability database in existence.

Part 2 is a collection of equipment surveys conducted between 1976 and 1994. The resolution is remarkable, as it specifically divulges cause of failure, a valuable piece of knowledge for facility managers.

Part 3 is a collection of equipment surveys conducted before 1976. The data in this collection reveal detail about failure modes, time of failure discovery, and how failures were repaired following discovery. The data also give failure data for utility providers in a variety of configurations and voltage classes.

Each of the three parts complements the others, providing focused data to key indicators of equipment performance. Details of the survey data (Part 2 and Part 3) are unavailable to statistically merge with the data collected in Part 1; the raw individual component information from the data collection has been lost over time.

³IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.

An additional archive of data can be found in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*. This document contains information according to Table 1.

Table 1—Historical reliability data for IEEE 3006 Standards reference guide

Electrical equipment types	<i>Historical Reliability Data for IEEE 3006 Standards: Power System Reliability</i>
Motors, > 50 hp (37.3 kW)	pages 1, 61, 124
Motor starters	pages 1, 61
Generators	pages 1, 61, 187
Circuit breakers	pages 1, 61, 161, 170, 266
Disconnect switches	pages 1, 61
Bus duct	pages 1, 61
Switchgear bus, insulated	pages 1, 61, 100
Open wire	pages 1, 61
Cable	pages 1, 61, 151
Transmission lines, 230 kV and above	page 221
Electric utility power supplies	pages 1, 61, 95

The IEEE Industry Applications Society (IAS) has also conducted surveys on the reliability of electrical equipment in industrial and commercial installations (see Aquilino [B4], Dickinson [B6], IEEE Committee Reports [B11], [B12], [B13], [B29], and O'Donnell [B28], [B30]).

5. Part 1: Mechanical and electrical equipment data, 1994 and 2005

5.1 Database development

5.1.1 Summary of contents

The data presented in this section is the culmination of more than 50 000 h of effort to collect operational and maintenance data on 280 power generation, power distribution, and HVAC equipment items, including generators, switchgear assemblies, cables, boilers, piping, valves, and chillers.

A database was developed to assist technical staff in organizing, tracking, analyzing, and reporting all of the technical and contact information during the execution of these projects. The database contains:

- a) Contact and site records. These records ensure data is unique by keeping accurate accounts of what information has been accepted and what has been rejected from different sites. These records also allow data analysts the opportunity to follow-up with facility managers to complete or update data records. Nearly 400 sites have been contacted or surveyed to provide data; approximately 300 have provided data that meets the standards for inclusion in the database.
- b) Equipment records. These include all of the specific reliability and maintainability information for each component. The database contains information for 280 component types. This includes some 370 000 individual pieces of equipment, 900 000 failure and maintenance event records, and 1 900 000 unit-years of equipment operation. In many cases, records also contain more detailed information, such as failure mode, cause of failure, manufacturers, operating modes, etc.

A comprehensive database system allowed the program to record site information, prioritize site visits, collect and organize data, input and verify data, summarize and analyze data, and produce reports. The output record generator contains several canned reports designed for data summary and availability

calculations. Some of the reports are designed to allow the user the flexibility to select a multitude of query topics.

The database software and structure has evolved as the database has grown. The current version is contained in a common software package with a user-friendly front-end graphical user interface. Recent design changes allowed new data to be automatically uploaded, reducing manual labor and increasing accuracy.

5.1.2 Data collection

Contacts were the key to the success of this program. The cooperation and support of the people involved from the many facilities is demonstrated in the quality of data received to support the data collection.

A concerted effort was employed to develop an extensive contact database using manufacturers, facilities, societies, and locations of any potential data contributor utilizing key electrical, mechanical, and control components. The collection teams sought manufacturers for contacts as well as warranty information, 25 of which participated. A total of 25 professional societies were also contacted, including:

- a) American Gas Association
- b) National Association of Power Engineers
- c) American Society of Mechanical Engineers
- d) Association of Physical Plant Administrators
- e) Association of Energy Engineers

The final list of sites includes universities, government facilities, prisons, utilities, office buildings, and other types of facilities. Specifics of these contributors are withheld to protect the confidentiality of the sources.

Building and managing the database requires a broad focus, looking into how each additional site contributes to the database as a whole. In order to collect statistically valid data it was important that a stratified survey of different facility categories, applications, and operating conditions be conducted. Guidelines were developed to assist in the selection of potential sites that vary in (a) degree of maintenance, (b) facility type, (c) component size, and (d) equipment age.

Collecting diversified data was critical to covering the spectrum of how equipment may operate and fail. To locate sites with equipment and data collection policies that conform to the standards of the database, surveys were first issued to hundreds of candidate facilities. Those that responded with potential for inclusion were visited by the data collection team. The team then copied the data, to be later pushed through the rigorous quality assurance process. The procedure for conducting the survey is given in *Historical Reliability Data for IEEE 3006 Standards: Power System Reliability*, page 109. Information on the determination and analysis of reliability studies is presented in IEEE Std 500™-1984 [B18].

5.1.3 Data summarization and classification

As with every data collection program, there are varying degrees of completeness in the data gathered. Some data sources had complete records and could give statistics on operational characteristics on every piece of equipment from the installation date through the collection date. More often, the only items tracked were major items, such as cooling towers and generators. Other problems included incomplete or non-current versions of the equipment drawings.

It became important to categorize the different levels of data completeness to ensure that the final data collection included fair data representation for each component. In other words, it is important to avoid a bias stemming from record quality. To quantify this data completion (or quality) index, the collection team identified these four levels:

- a) *Perfect data*: Data needed for a valid, complete reliability study, including a parts list, failure history data with time-to-failure statistics, parts description data, operational periods, and five continuous years of recorded data. No engineering judgment or data extrapolation is required. The USACE-PREP equipment record database is composed of 10% to 20% of this type of data.
- b) *Imperfect data*: Data without serious flaws, but the data collection process demanded additional time to ensure useful information was gathered. Examples include parts list determined by inspection, incomplete drawings, or less than five years of data. The USACE-PREP equipment record database contains 35% to 40% of this type of data.
- c) *Verbal/inspection data*: Data with serious gaps that required additional documentation and verification prior to its inclusion in the database. Items included were typically major items, such as generator sets and boilers. Senior maintenance personnel were interviewed to extract the necessary information to fill the data gaps. These interviews were used as support documentation of recorded data, not as data source information. About 25% of this type of data exists in the USACE-PREP equipment record database.
- d) *Soft data*: Data that relied on the memories of experienced maintenance personnel from the participating facility; it was often extracted from log books containing maintenance personnel entries, filing cabinets with work order forms, and repair records when outside repair support was needed. Engineering judgment was often used to determine numerous performance parameters. This type of data was the most difficult and time consuming to summarize, and was only used when other data sources were unavailable and when it could be sufficiently completed to meet the input standards. The USACE-PREP equipment record database is composed of 10% to 15% of this type of data.

These levels helped determine the effort required to identify and categorize the components at the site. Engineers prepared all candidate data for analysis through a process called *summarization*. The database requires all information to be imported in correct and consistent format. Engineers assemble all known data for a subject component in tables, including nameplate information, such as make, model, serial number, install/removal date, etc., and failure and maintenance event information, such as date of incident, outage duration, cause of event, type of event, etc. Engineers purged data for other types of equipment outside of the database scope.

5.1.4 Maintenance policy

One objective of the data collection effort was to minimize the effects of maintenance policies and procedures on the calculated availability values by collecting data from a variety of locations having various maintenance policies. The database team developed a code to categorize each facility's maintenance policies and procedures into one of three levels:

- a) Code 1: Above average maintenance policy. The facility not only followed a scheduled, preventive maintenance policy that was equivalent or similar to the manufacturer's suggested policy, but also went beyond it, such as using redundant units, specialized equipment tests (thermograph, vibration analysis, oil analysis), complete spare parts kits for equipment, and so on. The USACE-PREP equipment database is composed of 25% of this type of data.
- b) Code 2: Average maintenance policy. The facility used either in-house maintenance crews performing scheduled, preventative maintenance according to the equipment manufacturer's

suggested preventive maintenance schedule, or a combination of in-house maintenance crews and outside contractors. In both cases, it was verified that they did actually follow a fairly rigid schedule. The USACE-PREP equipment database is composed of 58% of this type of data.

- c) Code 3: Below average maintenance policy. The facility's actual policy was slightly lower than average. It may have instituted a scheduled maintenance policy but not followed it, or it may have had no maintenance policy. Symptoms such as leaky valves with rags tied around them, dirty air filters, squeaky bearings, loose belts, and lax general housekeeping because of unavailable labor were typical signs that maintenance policies were less than desirable. The USACE-PREP equipment database is composed of 17% of this type of data.

Each location was then compared to each other and to the average maintenance policy. Overall, the facilities that the collection teams visited practiced an average level of maintenance; that is, they adhered to the manufacturer's recommended maintenance policies. The team looked at approximately the same number of facilities that had below average maintenance policies as those facilities that had an above average maintenance policy.

5.1.5 Analysis and inclusion

Engineers used test statistics (goodness-of-fit, Weibull) to compare candidate data to established populations of reliability data. Significant outliers warranted a review of the data set being considered. If the new data set was both an outlier and showed suspicious site data (e.g., data gaps, mistakes) the data set was rejected. A statistical outlier alone was not a sufficient reason to reject candidate data.

Following the analysis, engineers made accept/reject decisions for every candidate data set. A computer algorithm processed all accepted data, verifying formatting, data types, and other information. Engineers reviewed an output file for each submission, confirming that data was incorporated into the database as expected.

5.2 Results

5.2.1 USACE-PREP equipment reliability database

The final USACE-PREP database includes the 280 different components. A hierarchical structure provides the analyst with options to use a specific type of component or data for a general category of components. As an example, the *category* of Accumulator comprises two *classes* (pressurized and unpressurized). Reliability data are presented for each class and for the entire category of Accumulators.

Some categories of equipment are more complete than others. Though not a perfect proxy, unit-years can be used to interpret the confidence in a data point. A few components have less than 10 unit-years of information available; many have more than 10 000. When using information from the database, the analyst may opt to use a data point for a category of equipment, which may be a more reliable statistic than a data point for a specific class.

Table 2 displays the average failure and maintenance statistics of the data collection described in Part 1.

Table 2—USACE-PREP equipment reliability database

Category			Class	Unit-years	Failures	Failure rate (failures/year)	MTBF (hours)	MTTR (hours)	MTTM (hours)	MDT (hours)
Accumulator				1463.2	10	0.006 834 233	1 281 782	7.80	0.94	0.98
	Pressurized	H01-100	Accumulator, pressurized	1072.8	7	0.006 525 131	1 342 502	10.29	0.96	1.01
	Unpressurized	H01-200	Accumulator, unpressurized	390.4	3	0.007 683 510	1 140 104	2.00	0.33	0.42
Air compressor				5124.5	1592	0.310 662 877	28 198	12.20	1.55	4.24
	Electric	H02-100	Air compressor, electric	4534.6	1492	0.329 029 093	26 624	11.80	1.48	4.16
	Fuel	H02-200	Air compressor, fuel	590.0	100	0.169 499 396	51 682	17.45	2.72	5.71
Air conditioner	All types	H03-000	Air conditioner	4947.4	781	0.157 860 257	55 492	5.95	1.59	2.63
Air dryer	All types	H04-000	Air dryer, all types	2307.2	170	0.073 681 948	118 889	9.11	1.44	5.36
Air handling unit				12 173.7	2650	0.217 681 964	40 242	5.06	1.99	3.27
	Humid			379.1	68	0.179 375 438	48 836	2.55	2.53	3.21
		H05-110 ^a	Air handling unit, humid, pan humid, w/o drive	25.0	0	0.027 695 536	429 882	0.00	0.00	0.00
		H05-130	Air handling unit, humid, pan humid, with drive	212.8	30	0.140 975 629	62 138	3.02	2.73	2.94
		H05-120 ^a	Air handling unit, humid, spray humid, w/o drive	38.1	0	0.018205276	653 976	0.00	0.00	0.00
		H05-140	Air handling unit, humid, spray humid, with drive	103.2	38	0.368 256 160	23 788	2.27	1.59	4.31
	Multizone system	H05-310	Air handling unit, multizone system, packaged	1103.7	448	0.405 891 785	21 582	6.18	4.34	9.97
	Non-humid			10 690.9	2134	0.199 609 243	43 886	4.75	1.67	2.38
		H05-210	Air handling unit, non-humid, without drive	7821.1	1734	0.221 709 225	39 511	4.95	1.88	2.40
		H05-220	Air handling unit, non-humid, with drive	2869.8	400	0.139 380 939	62 849	4.18	1.51	2.36
Air separator	All types	H06-000	Air separator, all types	84.7	9	0.106 272 848	82 429	6.31	0.88	3.35
Surge arrester	Surge and lightning	E01-000	Surge arrester, surge and lightning	1863.4	12	0.006 439 803	1 360 290	9.50	12.28	11.66
Battery	Rechargeable			13 228.7	121	0.009 146 782	957 714	13.40	0.16	0.45
		E02-110	Battery, gel cell-sealed	3106.8	53	0.017 059 514	513 496	2.00	0.13	0.15
		E02-120	Battery, lead acid	5022.6	65	0.012 941 467	676 894	24.08	0.25	4.31
		E02-130	Battery, nickel-cadmium	5099.3	3	0.000 588 315	14 889 985	10.33	0.16	0.16

IEEE Std 3006.8-2018
IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

Blower				4307.0	239	0.055 490 708	157 864	9.44	0.17	0.63
	Without drive	H07-100	Blower, without drive	3947.4	189	0.047 880 115	182 957	10.75	0.17	0.32
	With drive	H07-200	Blower with drive	359.7	50	0.139 016 903	63 014	3.79	1.04	24.95
Boiler				5125.6	2190	0.427 265 681	20 502	17.69	6.61	8.72
	Hot water	H08-100	Boiler, hot water	2566.6	688	0.268 055 191	32 680	3.94	6.35	6.89
	Steam			2559.0	1502	0.586 952 425	14 925	24.40	6.70	9.37
		H08-210	Boiler, steam, high pressure, > 103.4 kPa (15 psig)	942.7	781	0.828 434 093	10 574	39.77	5.52	6.84
		H08-220	Boiler, steam, low pressure, ≤ 103.4 kPa (15 psig)	1616.2	721	0.446 097 568	19 637	13.25	48.03	40.86
Bus duct or busway	All types	E03-000	Bus duct or busway, all types, per 30.5 m (100 ft)	2462.3	143	0.058 075 621	150 838	1.65	1.08	1.26
Cabinet heaters	Forced air flow			14 053.8	64	0.004 553 920	1 923 618	3.10	1.23	1.56
		E04-100	Cabinet heaters, forced air flow, steam or hot water	13 931.1	64	0.004 594 025	1 906 825	3.10	1.23	1.56
		E04-200 ^a	Cabinet heaters, forced air flow, electric	122.7	0	0.005 649 689	2 107 341	0.00	0.67	0.67
Cable				736 799.6	1366	0.001 853 964	4 725 011	5.59	4.34	4.43
	AC			698 824.2	924	0.001 322 221	6 625 216	7.29	4.35	4.50
		E06-111	Cable, ac, 0 V to 600 V, above ground, in conduit, per 305 m (1000 ft)	29 442.9	2	0.000 067 928	28 959 932	8.00	13.06	13.01
		E06-112 ^a	Cable, ac, 0 V to 600 V, above ground, in trays, per 305 m (1000 ft)	15.9	0	0.043 545 391	273 412			
		E06-113	Cable, ac, 0 V to 600 V, above ground, no conduit, per 305 m (1000 ft)	33 286.3	4	0.000 120 170	72 896 904	2.50	0.05	0.08
		E06-121	Cable, ac, 0 V to 600 V, below ground, in duct, per 305 m (1000 ft)	40 000.4	5	0.000 124 999	70 080 730	16.40	0.73	2.79
		E06-122	Cable, ac, 0 V to 600 V, below ground, in conduit, per 305 m (1000 ft)	24 426.8	49	0.002 005 991	4 366 919	11.22	87.71	28.22
		E06-123	Cable, ac, 0 V to 600 V, below ground, insulated, per 305 m (1000 ft)	3095.3	80	0.025 845 534	338 937	7.60		7.60

IEEE Std 3006.8-2018
IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

		E06-211	Cable, ac, 601 kV to 15 kV, above ground, in conduit, per 305 m (1000 ft)	523 356.6	281	0.000 536 919	16 315 315	8.56	40.51	16.11
		E06-212 ^a	Cable, ac, 601 kV to 15 kV, Above ground, in trays, per 305 m (1000 ft)	180.1	0	0.003 849 060	3 093 176			
		E06-214	Cable, ac, 601 kV to 15 kV, above ground, in trays, in conduit, per 305 m (1000 ft)	2646.0	2	0.000 755 852	11 589 564	4.00		4.00
		E06-221	Cable, ac, 601 kV to 15 kV, below ground, in conduit, per 305 m (1000 ft)	19 525.5	46	0.002 355 896	3 718 331	15.70	211.43	41.55
		E06-222	Cable, ac, 601 kV to 15 kV, below ground, in duct, per 305 m (1000 ft)	78.1	1	0.012 799 383	684 408			
		E06-223	Cable, ac, 601 kV to 15 kV, below ground, insulated, per 305 m (1000 ft)	22 770.3	454	0.019 938 292	439 356	5.13	3.97	4.01
	Aerial			37 500.3	439	0.011 706 565	748 298	2.03	0.35	1.91
		E07-200	Cable, aerial, > 15 kV, per 1.6 km (1 mile)	30 884.9	127	0.004 112 048	2 130 325	2.54	0.35	2.08
		E07-100	Cable, aerial, 0 kV to 15 kV, per 1.6 km (1 mile)	6615.5	312	0.047 162 173	185 742	1.82		1.82
	DC	E08-100	Cable, dc, insulated, per 305 m (1000 ft)	475.1	3	0.006 313 969	1 387 400	2.00		2.00
Cable connection	Underground	E05-100	Cable connection, underground, duct, ≤ 600 V	21 574.5	8	0.000 370 808	23 624 073	0.75		0.75
Capacitor bank	All types	E10-000	Capacitor/capacitor bank, all types	2041.1	104	0.050 951 857	171 927	2.37	4.27	3.13
Charger	Battery	E11-000	Charger, battery	666.0	26	0.039 040 966	224 380	7.46	0.72	2.29
Chiller				3607.7	1283	0.355 626 726	24 633	8.57	1.86	3.33
	Absorption	H10-100	Chiller, absorption	587.7	93	0.158 231 093	55 362	11.40	0.68	0.72
	Centrifugal			1054.5	529	0.501 674 408	17 462	7.73	11.29	24.68
		H10-210	Chiller, centrifugal, ≤ 600 tons (2110 kW)	152.1	298	1.959 149 120	4471	5.75	29.58	140.30
		H10-230	Chiller, centrifugal, > 1000 tons (3517 kW)	242.9	152	0.625 733 105	14 000	9.23	35.17	35.44

		H10-220	Chiller, centrifugal, 600 tons to 1000 tons (2110 kW to 3517 kW)	659.4	79	0.119 797 371	73 123	11.81	5.28	5.51
	Reciprocating			1193.5	192	0.160 868 248	54 455	10.77	1.65	2.21
		H10-321	Chiller, reciprocating, closed, with drive, 50 tons to 200 tons (176 kW to 703 kW)	881.8	139	0.157 633 096	55 572	11.11	1.53	2.06
		H10-331	Chiller, reciprocating, open, w/o drive, 50 tons to 200 tons (176 kW to 703 kW)	285.7	53	0.185 495 934	47 225	10.02	2.98	3.80
		H10-311 ^a	Chiller, reciprocating, with drive, < 50 tons (176 kW)	26.0	0	0.026 651 082	446 729		1.00	1.00
	Rotary			122.5	15	0.122 477 741	71 523	7.33	8.47	9.47
		H10-420	Chiller, rotary, < 600 tons (2110 kW)	32.0	1	0.031 244 650	280 368	1.00	1.63	1.60
		H10-410	Chiller, rotary, 600 tons to 1000 tons (2110 kW to 3517 kW)	90.5	14	0.154 754 694	56 606	8.60	8.74	9.79
	Screw			649.5	454	0.698 994 807	12 532	7.83	8.12	10.69
		H10-510	Chiller, screw, ≤ 300 tons (1055 kW)	499.0	380	0.761 497 960	11 504	5.37	27.44	15.71
		H10-520	Chiller, screw, > 300 tons (1055 kW)	150.5	74	0.491 734 634	17 814	23.24	6.37	7.97
Circuit breaker				180 935.2	1437	0.007 942 070	1 102 987	15.11	7.99	11.33
	Air			9012.4	93	0.010 319 132	848 909	11.65	73.27	60.16
		E12-111	Circuit breaker, air, 3-phase, > 600 V, > 600 A, normally closed (NC)	8885.8	90	0.010 128 467	864 889	11.65	73.27	60.16
		E12-112	Circuit breaker, air, 3-phase, > 600 V, > 600 A, normally open (NO)	126.5	3	0.023 707 970	369 496			
	Fixed (includes molded case)			150 305.9	10	0.000 066 531	31 667 972	25.36	8.29	9.74
		E12-211	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, ≤ 600 A, normally closed (NC)	34 569.2	4	0.000 115 710	75 706 529	23.25	3.09	9.64

IEEE Std 3006.8-2018
IEEE Recommended Practice for Analyzing Reliability Data for Equipment Used in Industrial and Commercial Power Systems

		E12-212	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, ≤ 600 A, normally open (NO)	26 607.0	3	0.000 112 752	77 692 576	18.67	8.61	8.73
		E12-221	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, > 600 A, normally closed (NC)	88 546.5	1	0.000 011 294	75 667 016		13.62	13.62
		E12-222	Circuit breaker, fixed (includes molded case), 3-phase, ≤ 600 V, > 600 A, normally open (NO)	583.2	2	0.003 429 339	2 554 428	37.50	2.69	3.03
	Fixed (molded case)	E12-311	Circuit breaker, fixed (molded case), 600 V, single phase, normally closed (NC)	7027.5	1	0.000 142 299	61 560 528	1.00		1.00
	Metal clad (drawout)			9529.8	179	0.018 783 250	466 373	9.58	2.12	4.33
		E12-411	Circuit breaker, metal clad (drawout), ≤ 600 V, ≤ 600 A, normally closed (NC)	5705.6	18	0.003 154 788	2 776 732	6.50	2.02	2.02
		E12-412	Circuit breaker, metal clad (drawout), ≤ 600 V, ≤ 600 A, normally open (NO)	911.2	4	0.004 389 750	1 995 558	6.00	2.93	2.94
		E12-421	Circuit breaker, metal clad (drawout), ≤ 600 V, > 600 A, normally closed (NC)	2290.1	153	0.066 809 897	131 118	9.90	2.56	26.74
		E12-422	Circuit breaker, metal clad (drawout), ≤ 600 V, > 600 A, normally open (NO)	622.9	4	0.006 421 989	1 364 063	2.00	2.38	2.37
	Oil filled			1573.9	640	0.406 641 344	21 542	19.01	28.83	30.54
		E12-512	Circuit breaker, oil filled, > 5 kV, normally closed (NC)	1392.3	631	0.453 204 694	19 329	18.98	28.84	30.56
		E12-511	Circuit breaker, oil filled, > 5 kV, Normally open (NO)	181.6	9	0.049 569 941	176 720	23.75	8.00	20.60
	SF6 filled	E12-610	Circuit breaker, SF6 filled, normally closed (NC)	315.2	418	1.326 315 057	6605	12.81	51.03	42.52
	Vacuum			3170.7	96	0.030 277 684	289 322	10.71	0.61	2.91
		E12-711	Circuit breaker, vacuum, < 15 kV, < 600 A, normally closed (NC)	514.4	3	0.005 832 348	1 501 968	5.33	0.05	0.06

		E12-712 ^a	Circuit breaker, vacuum, < 15 kV, < 600 A, normally closed (NC)	458.2	0	0.001 512 626	7 870 965		1.84	1.84
		E12-721	Circuit breaker, vacuum, < 15 kV, > 600 A, normally closed (NC)	1476.2	65	0.044 031 239	198 950	11.58	2.60	14.89
		E12-722	Circuit breaker, vacuum, < 15 kV, > 600 A, normally closed (NC)	716.8	28	0.039 061 903	224 259	9.39	0.35	0.49
		E12-730 ^a	Circuit breaker, vacuum, > 15 kV	5.0	0	0.138 553 516	85 929			
Compressor	Refrigerant			1344.2	19	0.014 134 513	619 760	8.69	0.93	1.02
		H11-010	Compressor, refrigerant, ≤ 1 ton (3.52 kW)	74.7	2	0.026 780 146	327 108	9.00	1.31	1.53
		H11-020	Compressor, refrigerant, > 1 ton (3.52 kW)	1052.0	5	0.004 752 765	1 843 138	3.50	0.91	0.93
		H11-100	Compressor, refrigerant, screw	217.5	12	0.055 165 812	158 794	10.83	0.94	1.15
Computer				406.3	100	0.246 142 641	35 589	4.30	4.82	23.48
	Control system server	C02-200	Computer, control system server	156.9	94	0.598 997 888	14 624	4.52	4.65	27.62
	Personal computer (PC) workstation	C02-100	Computer, PC workstation	249.3	6	0.024 063 554	364 036	1.90	5.09	4.09
Condenser				3972.6	305	0.076 775 438	114 099	8.10	2.83	4.91
	Double tube	H12-100	Condensers, double tube	298.7	8	0.026 781 865	327 087	2.50	2.63	2.63
	Propeller type fans/coils	H12-200	Condensers, propeller type fans with coils, direct expansion (DX)	2097.2	267	0.127 309 780	68 809	8.18	1.98	4.91
	Shell and tube	H12-300	Condenser, shell and tube	1576.7	30	0.019 027 462	460 387	9.50	6.86	7.06
Control center	Motor/load center	C03-100	Control center, motor/load center	1109.4	12	0.010 816 417	809 880	5.03	6.40	6.38
Control panel				6247.8	73	0.011 684 020	749 742	2.86	4.29	4.36
	Generator	C04-100	Control panel, generator, w/o switchgear	1808.4	30	0.016 589 350	528 050	4.38	0.62	1.45
	Heating, ventilation, and air conditioning (HVAC)/chillers/air-handling unit (AHU)	C04-200	Control panel, HVAC/chillers/AHU, w/o switchgear	3841.9	32	0.008 329 286	1 051 711	2.07	1.41	1.45
	Switchgear controls	C04-300	Control panel, switchgear controls	597.6	11	0.018 407 130	475 903	1.27	7.01	6.96