

1413.1™

IEEE Guide for Selecting and Using Reliability Predictions Based on IEEE 1413™

IEEE Standards Coordinating Committee 37

IEEE Standards Coordinating Committee 37 on
Reliability Prediction



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on
Reliability Prediction

Approved 12 September 2002

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Abstract: A framework for reliability prediction procedures for electronic equipment at all levels is provided in this guide.

Keywords: baseline, classic reliability, constant failure rate, estimation, failure, goal, item, operating environment, reliability prediction, requirement, system life cycle

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Introduction

(This introduction is not part of IEEE Std 1413.1™-2002, IEEE Guide for Selecting and Using Reliability Predictions Based on IEEE 1413™.)

IEEE Std 1413-1998, IEEE Standard Methodology for Reliability Predictions and Assessment for Electronic Systems and Equipment, provides a framework for reliability prediction procedures for electronic equipment at all levels. This guide is a supporting document for IEEE Std 1413-1998. This guide describes a wide variety of hardware reliability prediction methodologies.

The scope of this guide is processes and methodologies for conducting reliability predictions for electronic systems and equipment. This guide focuses on hardware reliability prediction methodologies, and specifically excludes software reliability, availability and maintainability, human reliability, and proprietary reliability prediction data and methodologies. These topics may be the subjects for future IEEE 1413 guides.

The purpose of this guide is to assist in the selection and use of reliability prediction methodologies satisfying IEEE Std 1413. The guide also describes the appropriate factors and criteria to consider when selecting reliability prediction methodologies.

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Contents

1.	Overview	1
1.1	Scope	1
1.2	Purpose	1
1.3	Glossary	1
1.4	Contents	1
2.	References	2
3.	Definitions, abbreviations, and acronyms	8
3.1	Definitions	8
3.2	Abbreviations and acronyms	9
4.	Background	10
4.1	Basic concepts and definitions	10
4.2	Reliability prediction uses and timing	16
4.3	Considerations for selecting reliability prediction methods	18
5.	Reliability prediction methods	18
5.1	Engineering information assessment	19
5.2	Predictions based on field data	23
5.3	Predictions based on test data	33
5.4	Reliability predictions based on stress and damage models	41
5.5	Reliability prediction based on handbooks	49
5.6	Assessment of reliability prediction methodologies based on IEEE 1413 criteria	55
6.	System reliability models	67
6.1	Reliability block diagram	68
6.2	Fault-tree analysis (FTA)	76
6.3	Reliability of repairable systems	77
6.4	Monte Carlo simulation	80
	Annex A (informative) Statistical data analysis	83
	Annex B (informative) Bibliography	90

IEEE Guide for Selecting and Using Reliability Predictions Based on IEEE 1413

1. Overview

IEEE Std 1413-1998 [B5]¹ provides a framework for reliability prediction procedures for electronic equipment at all levels. This guide is a supporting document for IEEE Std 1413-1998. This guide describes a wide variety of hardware reliability prediction methodologies.

1.1 Scope

The scope of this guide is processes and methodologies for conducting reliability predictions for electronic systems and equipment. This guide focuses on hardware reliability prediction methodologies, and specifically excludes software reliability, availability and maintainability, human reliability, and proprietary reliability prediction data and methodologies. These topics may be the subjects for additional future IEEE guides supporting IEEE Std 1413-1998.

1.2 Purpose

The purpose of this guide is to assist in the selection and use of reliability prediction methodologies satisfying IEEE Std 1413-1998. The guide accomplishes this purpose by briefly describing a wide variety of hardware reliability prediction methodologies. The guide also describes the appropriate factors and criteria to consider when selecting reliability prediction methodologies.

1.3 Glossary

Many of the terms used to describe reliability prediction methodologies have multiple meanings. For example, the term *reliability* has a specific mathematical meaning, but the word is also used to mean an entire field of engineering study. Clause 2 contains definitions of the terms that are used in this document, taken primarily from *The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition* [B3]. The terms *reliability* and *failure* are discussed in more detail in Clause 4.

1.4 Contents

Clause 4 provides background information for reliability prediction methodologies. This background information includes basic reliability concepts and definitions, reliability prediction uses, reliability prediction relationship with a system life cycle, and factors to consider when selecting reliability prediction methodologies. Clause 5 describes reliability prediction methodology inputs and reliability prediction methodologies for components, assemblies, or subsystems. These methodologies include reliability predictions based on field data, test data, damage simulation, and handbooks. Clause 6 describes methodologies for combining the predictions in Clause 5 to develop system level reliability predictions. These methodologies include reliability block diagrams, fault trees, repairable system techniques, and simulation.

¹The numbers in brackets correspond to those of the bibliography in Annex B.

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3. Definitions, abbreviations, and acronyms

3.1 Definitions

3.1.1 baseline: The set of data values selected as reference for comparing other similar sets of future data values.

3.1.2 Bx life (e.g., B10): Time until a specified percent of a device population will have experienced a failure (B10 means the time duration when 10% of a device's population will have experienced a failure).

3.1.3 Cx confidence level (e.g., C90): Confidence level (C90 means confidence of 90%).

3.1.4 classic reliability: The probability that an item will perform its intended function for a specified interval under stated conditions.

3.1.5 constant failure rate: A hazard (see 3.1.14) rate that is constant or independent of time (applies only to exponentially distributed failure assumption—see 4.1.4.1).

3.1.6 estimation: A systematic procedure for deriving an approximation to the true value of a population parameter.

3.1.7 failure: The termination of the ability of an item to perform a required function.

3.1.8 failure cause (root cause): The circumstances during design, manufacture, or use which have led to a failure.

3.1.9 failure criticality: The combined effect of the qualified consequences of a failure mode and its probability of occurrence. *Syn:* **risk**.

3.1.10 failure mechanism: The physical, chemical, or other process that results in failure.

NOTE—The circumstance that induces or activates the process is termed the root cause of the failure.

3.1.11 failure mode: The effect by which a failure is observed to occur.

3.1.12 failure site: Failure site is the specific location where a failure mechanism occurs.

3.1.13 goal: An objective that is desirable to meet, but it is not mandatory to meet.

3.1.14 hazard rate: The hazard rate is the instantaneous rate of failure of the product.

3.1.15 item: An all-inclusive term to denote any level of hardware (or system) assembly.

3.1.16 item characteristics: The set of technical parameters that comprehensively define an item, including its goals and performance.

3.1.17 Lx life (e.g., L60): Time until a specified percent of a device population will have experienced a failure (L60 means the time duration when 60% of a device's population will have experienced a failure). Lx is the same as Bx.

3.1.18 operating environment: The natural or induced environmental conditions, anticipated system interfaces, and user interactions within which the system is expected to be operated.

3.1.19 operating profile: A set of functional requirements that are expected to apply to the system during its operational life.

3.1.20 requirement: A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification, or other formally imposed documents.

3.1.21 system life cycle: The period of time, that begins when a system is conceived and ends when the system is no longer available for use.

3.2 Abbreviations and acronyms

AFR	annualized failure rate
ASIC	application specific integrated circuits
BOM	bill of materials
CCA	circuit card assembly
CDF	cumulative distribution function
CNET	The Centre National d'Etudes des Telecommunications
CSP	chip scale package
CTE	coefficient of thermal expansion
DOA	dead on arrival
DRAM	dynamic random access memory
DSIC	Defense Standards Improvement Council
EEPROM	electrically erasable programmable read-only memory
EOS	electrical overstress
EPROM	erasable programmable read-only memory
ESD	electrostatic discharge
ESD	electrostatic discharge
FAIT	fabrication, assembly, integration, and test
FFOP	failure-free operating period
FITs	failures per billion hours
FMEA	failure modes and effects analysis
FMECA	failure modes, effects and criticality analysis
FPMH	failures per million hours
FRACAS	Failure Reporting and Corrective Action System
FTA	fault tree analysis
HALT	highly accelerated life tests
LCC	leadless ceramic capacitor
LCR	leadless ceramic resistor
MCBF or MCTF	mean-cycles/miles-between/before-failure
MFOP	maintenance-free operating period
MIRADCOM	The U.S. Army Missile Research and Development Command
MLE	maximum likelihood estimation
MTBF	mean-time-before/between-failure
MTBR	mean-time-between-return/repair/replacement
MTBSC	mean-time-between-service call
MTBSI	mean-time-between-service interruption
MTBWC	mean-time-between-warranty claim
MTTF	mean time to failure
NFF	no failure found
NTT	Nippon Telegraph and Telephone Corporation
ORT	ongoing reliability tests
OST	over-stress tests
PCB	printed circuit board

PLCC	plastic leaded chip carrier
PROM	programmable read-only memory
RAC	Reliability Analysis Center
ROBOC	Regional Bell Operating Companies
RDT	reliability demonstration tests
ROM	read-only memory
SAE	Society of Automotive Engineers
SDDV	stress driven diffusive voiding
SRAM	static random access memory
TDDDB	time-dependent dielectric breakdown
UTE	Union Technique de L'Electricité

4. Background

Background information on basic reliability concepts and definitions are provided in this clause. Subclause 4.1 provides basic reliability concepts and definitions commonly used in reliability engineering such as failure and hazard rate, bathtub curve, statistical distributions, and reliability metrics. It also introduces repairable and non-repairable system concepts. Subclause 4.2 describes some of the uses of reliability predictions and how reliability predictions fit into the system life cycle. Subclause 4.3 describes factors that should be considered when selecting a reliability prediction method.

4.1 Basic concepts and definitions

This subclause provides background information on basic reliability concepts and definitions. Subclause 4.1.1 discusses common usage and definitions of the terms reliability and failure and associated concepts. Subclause 4.1.2 describes the bathtub curve. Subclause 4.1.3 provides the characteristics of statistical distributions commonly used in reliability prediction. Subclause 4.1.4 describes reliability metrics. Subclause 4.1.5 is a brief discussion of the concepts for repairable and non-repairable system reliability.

4.1.1 Reliability and failure

The word reliability is used in many different ways. It can be used to broadly describe an engineering discipline or to narrowly define a specific performance metric. Classic reliability is the probability that an item will perform its intended function for a specified interval under stated conditions (see Pecht, [B11]). In classical reliability, a single product, unit, or component is generally considered to have two states, operational and failed. The assumption is made that the product can only transition from the operational to the failed state (no repair). The state of the product is represented by a random variable that takes a value of one when it is operational and zero when it is failed. Classic reliability, $R(t)$, is the probability that the product is in the operational state up to time t . At time 0, the product is assumed to be good, and the product must eventually fail, so $R(0) = 1$, $R(\infty) = 0$, and $R(t)$ is a non-increasing function. If there is a mission with duration T , the classic reliability for that mission is $R(T)$.

A failure occurs when an item does not perform a required function. However, in practice, the word failure is often used to mean whatever the customer considers as a failure. There is also the concept of transient or intermittent failures, in which an item does not provide the specified performance level for a period, and then once again provides the specified performance level, without repair of the item and sometimes without any intervention.

Although reliability theory is based on the concept of failures, the definitions of a failure may be very different from different perspectives. To a hardware engineer, a “failure” means a component replacement and verification of the replaced component failure. To a manufacturing repair depot, a “failure” is a returned component. To the finance department, a “failure” is a warranty claim. To a service organization, a “failure”

is a service call for corrective maintenance (as opposed to planned or preventive maintenance). To a customer, a “failure” is a degradation of service or capability of the system (a failure that is tolerated without service interruption is considered a degradation of the product capability since it is then less able to tolerate future failures). These various definitions of “failure” lead to various types of metrics, such as replacement rate or service call rate, in addition to the classic reliability metric of constant failure rate. For reliability predictions and discussions, it is important to make clear the system hierarchy level to which a failure applies. For example, a component failure may not cause a system failure, particularly in systems that include redundancy or fault tolerance.

When testing or tracking a subsystem, assembly, or component, the definition of failure becomes important. For a simple unit under test with a binary response, defining failure is relatively easy: either the unit operates or it doesn’t. However, even digital devices may experience degraded modes such as changes in the timing of critical signals or signal bounce under certain switching conditions, which will affect the system performance. Similarly, analog devices may show a slowed response or excessive drift from nominal. How far can it drift before the device is considered failed? If a pull-up resistor on a digital circuit drifts from 10,000 ohms to 7,000 ohms, it may still provide the intended function even though the magnitude of the change is 30% decrease in resistance. For an electronic control system, the failure criteria may be the number of milliseconds delay in system response. Acceptable levels of drift or change should be established.

4.1.2 Bathtub curve

The idealized bathtub curve, shown in Figure 1, represents three phases of product hazard rates. The vertical axis is the hazard rate, and the horizontal axis is time from initial product operation. The first phase, often called “infant mortality,” represents the early life of the product when manufacturing imperfections or other initial failure mechanisms may appear. The hazard rate decreases during this time as the product becomes less likely to experience failure from one of these mechanisms. The second phase, sometimes called the “useful life,” represents the majority of the product operating time. During this period of time, the hazard rate of the product appears to be constant, i.e., a constant failure rate. The third phase, often called “wear-out,” occurs near the end of the expected product life and often represents failure mechanisms caused by cumulative damage. Electronic components are subject to wear-out due to electromigration, material degradation, and other mechanisms. Weibull, lognormal, or other statistical distributions can be used to describe hazard rates during both “infant mortality” and “wear-out.” Mathematically, the idealized bathtub curve is actually the composite of 3 distinct distributions representing the 3 product behavior phases—an initial decreasing hazard rate distribution in the early operation, an exponential distribution (constant failure rate) the useful life, and an increasing hazard rate distribution for end of life. However, in practice, the bathtub curve will not be so simple, may be a combination of many distributions representing many different failure modes, and may not have the characteristic shape shown in Figure 1 (see Wong, K. L., and Lindstrom, D. L., “Off the Bathtub onto the Roller-Coaster Curve (Electronic Equipment Failure),” *Proceedings of the Annual Reliability and Maintainability Symposium*⁶).

⁶Information on references can be found in Clause 2.

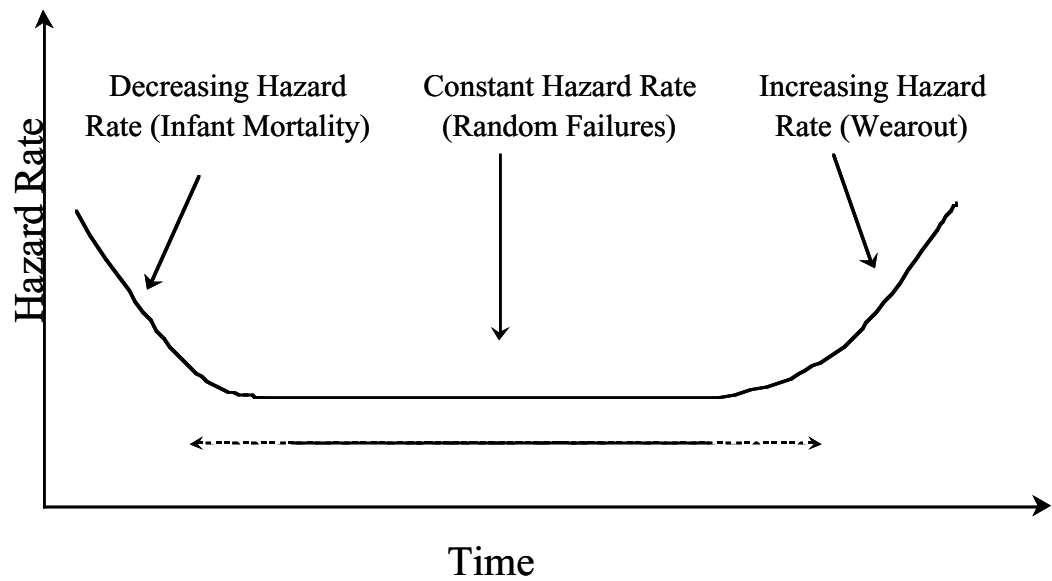


Figure 1—Idealized bathtub curve

4.1.3 Statistical distributions

Many different statistical distributions are used in reliability prediction (see Table 1). These statistical distributions are sometimes called “life” distributions and usually represent the probability that an item is operating at a particular time. Classic reliability, hazard rate, mean life, and other reliability metrics can be calculated from these distributions. A more detailed discussion of these distributions can be found in several textbooks (e.g., Montgomery, D. C. and Runger, G. C., *Applied Statistics and Probability for Engineers*, and Pecht, M., Nguyen, L. T., and Hakim, E. B., *Plastic Encapsulated Microelectronics*).

Table 1—Example distributions used in developing reliability predictions
[see Alvarez, M. and Jackson, T., “Quantifying the Effects of Commercial Processes on Availability of Small Manned-Spacecraft”]

Distribution name	Density function, f(t)
Binomial	$\text{Comb}\{n;x\}p^xq^{n-x}$, where n is the number of trials, x ranges from 0 to n, p is the probability of success and q is 1–p.
Exponential	$\lambda\exp(-\lambda t)$, where λ is the constant failure rate and the inverse of MTBF. Applies to middle section of idealized bathtub curve (constant failure rate).
Gamma	$(1/\alpha!\beta^{\alpha+1})t^{\alpha}\exp(-t/\beta)$, where α is the scale parameter and β is the shape parameter.
Lognormal	$(2\pi t^2 \sigma^2)^{-1/2}\exp\{-(\ln(t)-\mu)/\sigma\}^2/2\}$, where μ is the mean and σ is the standard deviation.
Normal	$(2\pi\sigma^2)^{-1/2}\exp\{-(t-\mu)/\sigma\}^2/2\}$, where μ is the mean and σ is the standard deviation.
Poisson	$(\lambda t)^x\exp(-\lambda t)/x!$, where x is the number of failures and λ is the constant failure rate. Appropriate distribution for number of failures from a device population in a time period when the devices have an exponential distribution and are replaced upon failure.
Weibull	$(\beta/\alpha)(t/\alpha)^{\beta-1}\exp(-(t/\alpha)^{\beta})$, where a is the scale parameter and β is the shape parameter. Infant Mortality (shape parameter < 1); Wear-out (shape parameter > 1); constant failure rate (shape parameter = 1).

4.1.4 Measuring reliability

The classical definition of reliability is the probability of providing a specified performance level for a specified duration in a specified environment. This probability is a useful metric for mission-oriented, low volume products such as spacecraft. However, reliability metrics for most high-volume products measure the reliability of a product population rather than the performance of a single system or a mission. Specifying a single value such as MTBF is not sufficient for a product that exhibits a time-dependent hazard rate (i.e., non-constant failure rate). In this case, a more appropriate metric is the probability of mission success. This metric may be time dependent, e.g., the probability of mission success may vary depending on the length of the mission, or number of cycles, e.g., the probability of mission success may vary depending on the number of uses. For “one-shot” devices, where the mission is a single event such as a warhead detonation, the probability of success will be a single number. Constant rate metrics are discussed in 4.1.4.1. Probabilities of success metrics are described in 4.1.4.2.

A useful reliability function is the cumulative hazard function, $H(t)$, that can be derived from the Equation $H(t) = -\ln(R(t))$. The derivative of the cumulative hazard function is the hazard rate, $h(t)$ (see Pecht [B11]).

4.1.4.1 Constant rate reliability metrics

The hazard rate is the instantaneous rate of failure of the product. When the hazard rate is constant, or independent of time, it is usually designated by a parameter λ . Since

$$H(t) = \int_0^t h(t)dt = \lambda t$$

for a constant failure rate, the previous equation becomes the familiar $R(t) = \exp(-\lambda t)$, the exponential distribution. The constant parameter λ is usually called the constant failure rate, although sometimes the function $h(t)$ is also called the “failure rate,” and there are many references in the literature to increasing or decreasing failure rates.⁷

A constant failure rate has many useful properties, one of them is the mean value of the product’s life distribution is $1/\lambda$. This mean value represents the statistically expected length of time until product failure and is commonly called the mean life, or mean-time-before/between-failure (MTBF). Another useful property of the constant failure rate is that it can be estimated from a population as the number of failures divided by time without having to fit a distribution to failure times. However, it should be noted that the exponential distribution is the only distribution for which the hazard rate is a constant and that the mean life is not $1/h(t)$ when the hazard rate is not a constant.

MTBF is sometimes misunderstood to be the life of the product rather than an expression of the constant failure rate.⁸ If a product has an MTBF of 1,000,000 hours, it does not mean that the product will last that long (longer than the average human lifetime). Rather, it means that, on the average, one of the products will fail for every 1,000,000 hours of product operation, i.e., if there are 1,000,000 products in the field, one of them will fail in one hour on the average. In this case, if product failures are truly exponentially distributed, then 63% of the products will have failed after 1,000,000 hours of operation. Products with truly exponentially distributed failures over their entire lifetime almost never occur in practice, but a constant failure rate and MTBF may be a good approximation of product failure behavior.

⁷Since failure rate is so often implicitly interpreted as a constant parameter, the term *constant failure rate* is used throughout this guide to mean the constant parameter λ of the exponential distribution. The term *hazard rate* is used whenever the derivative of the hazard function varies with time, e.g., decreasing hazard rate or increasing hazard rate.

⁸The use of mean time to failure (MTTF) and MTBF is not standard in either reliability literature or industry practice. In some contexts, MTTF is used for non-repairable items, and MTBF is used for repairable items. In some contexts, either or both MTTF and MTBF are implicitly assumed to imply a constant failure rate. For convenience and to help minimize confusion in this guide, MTTF is used in conjunction with non-repairable items, MTBF is used in conjunction with repairable items, and both are used only in conjunction with a constant failure rate. When the hazard rate is not a constant, the mean value of the reliability distribution is referred to as the mean life rather than the MTBF or MTTF.

If the constant rate is represented by the parameter λ , the mean value of the exponential distribution is $1/\lambda$, as discussed in the preceding subclause. Therefore, constant rate metrics can be described either as a rate or as a mean life, e.g., constant failure rate or MTBF. Constant rate reliability metrics are approximations based on the assumption of the exponential distribution. Predictions for these alternative types of reliability metrics are discussed in 5.2. The term *constant rate* is used throughout this document to refer to this collection of metrics that includes, but is not limited to, constant failure rate. Constant rate metrics other than constant failure rate are collectively referred to as “non-failure metrics.” Table 2 contains a list of constant rate metrics and their equivalent mean life inverses along with an indication of when these metrics might be appropriate.

Table 2—Example Constant Rate Reliability Metrics (Note—Equivalent non-constant versions of these metrics can also be used, e.g. hazard rate in place of constant failure rate)

Constant rate metric	Mean life equivalent	Definition	Use
Constant failure rate	Mean-Time-Between/Before-Failure (MTBF) or Mean-Time-To-Failure (MTTF)	Total failures divided by total population operating time; can be expressed as failures per year – annualized failure rate (AFR), failures per billion hours (FITs), failures per million hours (FPMH).	Standard metric for reliability predictions; measure of inherent system hardware reliability.
Constant failure rate using cycles or distance instead of time	Mean-Cycles/Miles-Between/Before-Failure (MCBF) or MCTF	Total failures divided by total population number of cycles or distance, e.g., miles.	Standard metric for reliability predictions when usage is more relevant than time. These metrics are sometimes converted to time-based metrics by specifying an operating profile.
Constant return/repair rate	MTBR (Mean Time Between Return/Repair)	Total returns/repairs divided by total population operating time.	Useful for sizing a repair depot or manufacturing repair line.
Constant replacement rate	MTBR (Mean Time Between Replacement)	Total replacements divided by total population operating time.	Used as surrogate for constant failure rate when no failure analysis is available; useful for warranty analysis.
Constant service or customer call rate	MTBSC (Mean Time Between Service Call)	Total service/customer calls divided by total population operating time.	Customer perception of constant failure rate; useful for sizing support requirements.
Constant warranty claim rate	MTBWC (Mean Time Between Warranty Claim)	Total warranty claims divided by warranted population operating time.	Useful for pricing warranties and setting warranty reserves.
Constant service interruption rate	MTBSI (Mean Time Between Service Interruption)	Total service interruptions divided by total population operating time.	Customer perception of constant failure rate; may be an availability metric.

There are several equivalent ways of expressing the constant rate metrics in Table 2. For example, a constant failure rate of 1% per year is equivalent to 0.01 failures per unit per year, 1.1 failures per million hours, 1100 FITs, and 10 failures per 1000 products per year (assuming replacement, 9.95 failures per 1000 products per year without replacement).

Constant rate reliability metrics may be used as surrogates for time-dependent metrics by specifying different constant failure rates for different periods of time such as the Infant Mortality phase. For example, a constant failure rate goal might be stated as 3λ , for first 3 months of production or operation, 2λ , for next 3 months, and λ , after 6 months, where λ , is the constant failure rate during the “useful life” phase. Another approach for replacing a time-dependent metric with a constant failure rate is to determine the expected number of failures for a certain time period and to specify a constant failure rate during that time period. For example, a product that follows the idealized bathtub curve might be expected to have 50 failures in a population of 1,000 in the first year, 30 failures in each of the next 3 years, and 60 failures in the 5th year. This product’s reliability may be approximated with an average constant failure rate of 4.6 failures per million hours (4,600 FITs) for 5 years, equivalent to 200 failures in a population of 1,000 in 5 years.

4.1.4.2 Probability of success metrics

For non-exponential life distributions, i.e., when the failure rate is not constant, metrics other than failure rates may be more meaningful. An easier to manipulate metric for non-exponential distributions is classic reliability, i.e., the probability of success. This metric can be a point on one of the reliability distributions shown in Table 1 or can be a convolution of many distributions.

Another way of expressing probability of success is the percentage of a population that survives a specified duration. For this metric, percentiles of the distribution may be used. These percentiles may be stated as a “B” life or an “L” life. For example, an L10 life of 300,000 hours means that 10% of the product population would have experienced a failure by 300,000 hours of operation, and a B50 life of 5 years means that 50% of the product population would have experienced a failure by 5 years of operation. Some metrics may be stated with a confidence level, e.g., R96C90 in the automotive industry means a reliability of 96% with 90% confidence. Table 3 contains a list of probability of success metrics along with their definitions and uses.

Table 3—Example probability of success metrics

Metric	Definition	Example use
Classic reliability	Probability that a product performs a required function under stated conditions for a stated period of time.	Classic reliability metric.
Lx life, e.g., L10 life	Time until 10% of a device population will have experienced a failure.	Mechanical items, e.g., fans. Electronic components with wearout, e.g., electrolytic capacitors.
Bx life, e.g., B10 life	Same as Lx life.	Automobile industry.
Failure-Free Operating Period (FFOP)	An operating period where a product performs a required function under stated conditions without failure.	Application where a period of time without failure is required.
Maintenance-Free Operating Period (MFOP)	An operating period where a product performs a required function under stated conditions without a failure or maintenance action.	Applications where no failure or maintenance is allowed or possible.
Mean mission duration	Integral of the reliability function R(t) from 0 to the specified design life.	Spacecraft.

4.1.5 Repairable and non-repairable system concepts

A repairable item is one that can be restored to functionality after failure, e.g., a system can be restored by repair or replacement of a component(s) either physically or functionally. Examples of repairable items are cars and computers. A non-repairable item is one that cannot be restored to functionality after failure (or one for which an organization's maintenance policy does not restore after failure). Examples of non-repairable items are light bulbs and fuses. Note that a repairable item may contain non-repairable lower-level items. For example, if a circuit card assembly is repaired by replacing a resistor that is thrown away, the circuit card assembly is repairable while the resistor is non-repairable.

Repair can affect the reliability prediction. Some redundant systems permit repair of a failed component that restores the component to an operational state while the system continues to operate. Reliability distributions are calculated from multiple failures of the same item in field or test data. If repair of the item does not return it to a "good as new" condition, these multiple failures represent different life distributions, and they cannot be used to estimate the parameters of the original life distribution. When the repaired component has the same statistical life distribution as the original component, it may be considered "good as new."

Examples of techniques for analyzing repairable systems are Poisson processes (homogeneous and non-homogeneous), renewal theory, and Markov analysis. Repairable system concepts are described briefly in Clause 6. If additional information is desired, sources such as Asher, H. and Feingold, H., "Repairable Systems Reliability: Modeling, Inference, Misconceptions and Their Causes" may be consulted.

4.2 Reliability prediction uses and timing

As stated in 1.2, the purpose of this guide is to assist in the selection and use of reliability prediction methodologies satisfying IEEE Std 1413-1998. However, before selecting a reliability prediction method, the desired uses of the prediction (why), the appropriate time in the system life cycle to perform the prediction (when), the item(s) for which the reliability prediction is to be performed (what), and the factors that should be considered in selecting the appropriate reliability prediction method (how) should be considered. Subclause 4.2.1 describes some of the uses for a reliability prediction to help define why a prediction is being performed. Subclause 4.2.2 explains how reliability predictions fit into the product life cycle, which helps to identify the appropriate time to use a certain reliability prediction method. The factors that should be considered in selecting the appropriate reliability prediction method are discussed in 4.3 and 5.1.

Predictions can be made using data obtained during engineering development phases. Not only is the raw data useful to determine the reliability but the rate of change in reliability can also be used to show additional improvements. Reliability improvement (growth) models available in literature include the Gompertz, Lloyd-Lipow, Logistic Reliability Growth, Duane and AMSAA for non-homogeneous Poisson processes (see Kececioglu, B. D., *Reliability Engineering Handbook, Vols. 1 and 2*).

4.2.1 Reliability prediction uses

Subclause 1.3 of IEEE Std 1413-1998 lists the uses of a reliability prediction. Those uses are also listed below followed by text that expands upon the usage and describes the associated value.

- Reliability goal assessment: Reliability predictions are used to help assess if the system will satisfy its reliability goals.
- Comparisons of designs and products: Most systems have design implementation options. Trade-offs must be made among the various options, and reliability prediction is an important input in these trade-offs. These options may even affect the system architecture, e.g., the amount and level of redundancy. Since trade-offs must often be made early in the design process, the reliability prediction may be very preliminary. However, it is still useful since the important information may be the relative reliability and ranking of design choices rather than a precise quantitative value.

- Method to identify potential reliability improvement opportunities: Reliability improvement activities should generally focus on the areas with the greatest opportunity for improvement. A reliability prediction quantifies the opportunity by identifying the relative reliability of various units and by predicting the reliability improvement obtained from a reliability improvement activity.
- Logistics support: Reliability predictions are a key input into spare parts provisioning and calculation of warranty and life cycle costs.
- Reliability and system safety analyses: Design and process analyses such as failure modes, effects and criticality analysis (FMECA), event tree analysis, and fault tree analysis (FTA) may be performed to uncover items associated with reliability or safety related risk.
- Mission reliability estimation: Missions may have multiple phases with different equipment configurations and system reliability models can be used to predict reliability for the entire mission.
- Prediction of field reliability performance: A reliability prediction provides an estimate of how reliably a product will perform in future field usage based on how it performed in past field usage. This information may impact operational concepts, contingency planning, and other support planning activities.

4.2.2 Reliability predictions in the system life cycle

There are five system life cycle phases defined in IEEE Std 1220-1998 [B4]. These phases are listed below along with the appropriate reliability prediction output of each phase:

- a) System Definition Phase—Defines the system requirements, including system interface specifications. In the requirements definition phase, existing reliability data can be used for a reliability prediction based on similarity with existing design(s) or in-service product(s). Although this reliability prediction will only be a rough estimate, it may be useful to help establish reliability goals, make reliability allocations, use in trade-off studies, and/or aid in defining the high level system architecture. The output of this phase is reliability metrics and goals.
- b) Preliminary Design Phase—Defines the subsystem requirements and functional architecture. The preliminary reliability prediction, which is the output of this phase, is based on a well-defined functional description and a somewhat less well-defined physical description of the system.
- c) Detailed Design Phase—Completes the design and requirement allocation to the lowest level. The design reliability prediction, which is the output of this phase, is more precise than the earlier ones because it is based on documentation that defines the ready-to-manufacture system, such as design and performance specifications, parts and materials lists, and circuit and layout drawings.
- d) Fabrication, Assembly, Integration, and Test (FAIT) Phase—Verifies that the system satisfies its operational requirements, which may require building prototypes or conducting tests. The operational reliability prediction, which is the output of this phase, includes the anticipated effects of the manufacturer's processes on the field reliability of the system.
- e) Production/Support Phase—Manufactures, ships, and supports the system in the field, including resolution of any deficiencies. The field reliability prediction, which is the output of this phase, is based on the field reliability data collected, possibly combined with other predictions. When changes are made to the system's design or manufacturing process, the field reliability prediction is updated. An example of a production change that may affect the field reliability prediction is parts obsolescence. Parts that are available in the Detailed Design phase may not be available in the Production/Support phase, and the subsequent change in the Bill of Materials (BOM) may significantly affect the field reliability of the system.

The reliability prediction methodologies that are described in Clause 5 of this guide may be used in any phase of the system life cycle, as long as the required engineering information is available. However, because of the progressive nature of the system life cycle, there may be times when certain reliability prediction methods are preferred due to the type and quality of the available engineering information. For example, field data necessary for a reliability prediction based on field data usually becomes available in the Production/Support Phase. However, field data from similar in-service systems can be used for reliability predictions earlier in the life cycle. Similarly, the test data necessary for a reliability prediction based on test data

usually becomes available in the FAIT Phase. The engineering information necessary for each type of reliability prediction is explained in more detail in Clause 5.

4.3 Considerations for selecting reliability prediction methods

Subclause 5.1 describes the characteristics and required input data for reliability prediction methods. These characteristics and input data are important criteria for selecting appropriate reliability prediction methods, but there are also other factors that may influence the choice of a reliability prediction method. These additional factors include product technology, consequences of system failure, failure criticality and available resources.

- Product technology: Product technology may influence the selection of a reliability prediction method in several ways. If the product technology is similar to that used in previous products, reliability prediction methods that make use of historical data or analyses may be appropriate. If the product technology is new, it may be necessary to develop new models.
- Consequences of system failure: The desired reliability prediction precision is a function of the social or business consequences of a system failure. In general, the higher the risk, the higher is the desire for accurate predictions, where risk includes both business risk and social risk. The risks include financial losses caused by delays in certification, fines emanating from regulatory requirements, delay in time-to-market, loss of customer confidence, costs and results of litigation, safety, and information privacy and security. Social risk refers to the potential for human injury or environmental disruption.
- Failure criticality: Failure of an item contained in a system does not necessarily imply system failure. The consequences of each item's failure modes can be variable, ranging from system failure to unnoticeable. The probability of occurrence of each failure mode can also be variable. It may be important to spend more resources evaluating those failure modes with the most severe consequences of failure and/or the highest probability of occurrence.
- Available resources: The choice of reliability prediction method may be affected by available resources, including time, budget, and information. Some reliability prediction methods may require engineering information or data that is unavailable, e.g., historical or test data. Time or budget limitations may prevent necessary data from being gathered. The skill levels and familiarity with certain prediction types of the available personnel may influence reliability prediction method selection.
- External influences: External influences may impact the selection of a reliability prediction. An organization may have a specified reliability prediction method used for all products or all products of a certain type. Customers and regulators may dictate the type of reliability prediction method used or may require a precision that can only be obtained by certain methods. In addition, a bias for or against certain types of prediction methods on the part of the customers or development organization may influence reliability prediction method selection. The available information on operating environment and profile may limit the applicable reliability prediction methods. The selection of a reliability metric may also limit the applicable reliability prediction methods since some methods are useful for only certain types of metrics, e.g., constant failure rate. The engineering information available from a vendor may only support certain types of reliability prediction methods, or a vendor may only have the capability to perform certain types of reliability prediction methods.

5. Reliability prediction methods

This clause provides information for selecting and using reliability prediction methods. Subclause 5.1 discusses the engineering information that should be considered in selecting a reliability prediction method and performing a reliability prediction. Subclauses 5.2 and 5.3 describe the prediction methods that are based on field data and test data, respectively. Subclause 5.4 discusses reliability predictions based on stress and damage models. Subclause 5.5 describes reliability prediction methods based on reliability handbooks. Subclause 5.6 describes the assessment of different reliability prediction methodologies based on IEEE Std 1413-1998.

5.1 Engineering information assessment

The engineering information used in developing a reliability prediction may be collected from many different sources, including the manufacturer's database, the customer's database, in-house database, or public domain literature and databases. It is necessary to consider the available resources, in terms of time, money, and labor, for collecting this information and using it to develop a reliability prediction with the desired degree of precision. Engineering information includes the following:

- Reliability requirements
- System architecture
- Operating environment
- Operating profile
- Failure modes, mechanisms, and causes

Prior to the selection of a reliability prediction method(s), the type and quality of the engineering information that is available should be examined. Generally, the level of confidence in the engineering information is commensurate with the life cycle maturity of the system for which it applies (see 4.2).

5.1.1 Reliability requirements and goals

Reliability requirements define the *specified* system reliability and reliability goals define the *desired* system reliability. Reliability requirements and goals may be stated either as a single value, e.g., a minimal level of reliability below which the predicted system reliability is unacceptable, or a range of values, e.g., the 3 sigma values for a normal distribution that is centered at a specific time. Different reliability requirements or goals may be defined for different system functions, e.g., when a system is in a high-power mode or a low-power mode. Reliability predictions may be useful in defining reliability requirements and goals, and conversely, reliability requirements and goals may impact the selection of reliability prediction methods.

A single reliability goal may be sufficient for a simple system. However, for a complex system, it is useful to allocate the system level reliability goal to lower levels, such as a subsystem, assembly, or component level. These lower-level goals provide guidance for design engineers that are responsible for a specific portion of the system, and provide reliability input to supplier specifications. The way in which lower-level goals are allocated depends on the metric. If the metric is classical reliability for a series system, then the product of the reliabilities of lower-level units must be greater than or equal to the system goal. If the metric is constant failure rate then the sum of the lower-level unit constant failure rates must be less than or equal to the system goal.

5.1.2 System architecture

The system architecture consists of both the physical and logical system hierarchy structure. There are several different levels in the system hierarchy structure, such as, component, assembly, and subsystem. A component or assembly in one application may be a system in another application. The system hierarchy from IEEE Std 1220-1998 [B4] is used throughout this document:

- System
- Product
- Subsystem
- Assembly
- Component
- Subassembly (optional)
- Subcomponent
- Part

The physical architecture defines the basic system hierarchy and the association of lower-level parts and components with higher-level assemblies and systems. A set of bills of materials (BOM), also called indented parts lists, is an example of a physical architecture. The level of physical architecture detail that is available may influence the selection of the reliability prediction method. Some reliability prediction methods require only indented parts lists while others require the interconnection of the parts as well.

The logical architecture describes the partitioning of physical units into functional units and is often depicted as a functional block diagram. The reliability prediction may include a transformation of the system logical architecture into a reliability model such as a reliability block diagram or a fault tree. This reliability model defines the system success/failure criteria and the level and type of redundancy. It may also identify the failure modes for components and/or assemblies and the effects of those failure modes on system operation. Some systems have missions with multiple phases and different logical architectures for each phase. Therefore, the reliability model should define all the different logical architectures for the system.

5.1.3 Operating environment

The operating environment consists of both the physical environment and the human interaction with the system. The physical environment describes the operating conditions and loads under which the system operates. It includes temperature, humidity, shock and vibration, voltage, radiation, power, contaminants, and so forth. It also includes loads applied in packaging, handling, storage, and transportation. The human interaction with the system includes human interfaces, skill level of the operators, opportunities for corrective and preventive maintenance, and so forth. If a system has a mission with multiple phases, the operating environment for each phase needs to be identified. These data are used to estimate the reliability of the system.

5.1.4 Operating profile

The operating profile (referred to as the mission profile by some industries) is a set of functional requirements that are expected to apply to the system during its operating life. A system may have multiple operating profiles with different functional requirements and operating environments. For example, a reusable spacecraft may have operational phases with different requirements and environments such as, launch, flight, re-entry, and landing. Electronic equipment may have a non-operating profile (such as, shipping, transportation, and storage) as part of its operating profile. Sometimes system failures can occur during the transition from one operating profile to another (see Jackson, T., "Integration of Sneak Circuit Analysis with FMEA"), e.g., a reverse current path that initiates an unwanted function. The reliability prediction should incorporate the operating profile for the system.

5.1.5 Failures, modes, mechanisms, and causes

IEEE Std 1413-1998 specifies the need to identify the failure site, failure mode, failure mechanism, and failure cause(s). The definitions of these terms are given in Clause 3. For every failure mode, there is an initiating failure mechanism or process that is itself initiated by a root cause. In general, the failure mode at one level of the system becomes the failure cause for the next higher level. This bottom-up failure flow process applies all the way to system-level, as illustrated in Figure 2. This is a generalized and simplified picture assuming a linear hierarchical nature of connections between system elements. In reality, the source of a system failure can be at interactions between various system elements.

Failures can be described by their relation to failure precipitation.

- Overstress failure: A failure that arises as a result of a single load (stress) condition. Examples of load conditions that can cause overstress failures are shock, temperature extremes, and electrical overstress, under-voltage input signals, mismatched switching speeds, and sneak paths.
- Wearout failure: A failure that arises as a result of cumulative load (stress) conditions. Examples of load conditions that cause cumulative damage are temperature cycling, abrasion and material aging.

- System functional failure: A failure that arises as a result of an anomalous condition of the system output. Examples of anomalous conditions that cause system functional failure are under-voltage input signals, mismatched switching speeds, and sneak paths.

The root cause is the most basic causal factor or factors that, if corrected or removed, will prevent the recurrence of the failure (see ABS Group, Inc., *Root Cause Analysis Handbook, A Guide to Effective Incident Investigation*). One of the purposes of determining the root cause(s) is to fix the problem at its most basic source so it doesn't occur again, even in other products, as opposed to merely fixing a failure symptom. Identifying root causes is the key to preventing similar occurrences in the future. Another purpose of determining the root cause(s) is to predict the probability of occurrence of the failure. Examples of sources of root causes of failures are given as follows:

- Design process induced failure causes: Such as design rule violations, design errors resulting from overstressed parts, timing faults, reverse current paths, mechanical interference, software coding errors, documentation or procedural errors, and non-tested or latent failures.
- Manufacturing process induced failure causes: Such as workmanship defects caused by manual or automatic assembly or rework operations, test errors, and test equipment faults.
- Environment induced failure causes: Such as excessive operating temperature, humidity or vibration, external electromagnetic threshold exceeded, and foreign object damage or mishandling damage.
- Operator or maintenance induced failure causes: Such as operator errors, incorrectly calibrated instruments, false system operating status, and maintenance errors or fault maintenance equipment.

Many methods are used for root cause analysis, including cause and effect diagram (Ishikawa diagram- fish-bone analysis), failure modes and effects analysis (FMEA), cause factor chart, fault tree analysis (FTA), and Pareto chart. Readers are referred to the following references: ABS Group, Inc., *Root Cause Analysis Handbook, A Guide to Effective Incident Investigation*; Dew, John R., "In Search of the Root Cause;" Latino, R. L., and Latino, K. C., *Root Cause Analysis: Improving Performance for Bottom Line Results*; Mobley, R. K., *Root Cause Failure Analysis (Plant Engineering Maintenance Series)*; and Wilson, P. D., Dell, L. D., and Anderson, G. F., *Root Cause Analysis: A Tool for Total Quality Management*; as well as EIA/JEP131 [B6] and MIL-STD-1629A [B8], for more information on these methods. The reliability prediction process should use these methods for improved product development.

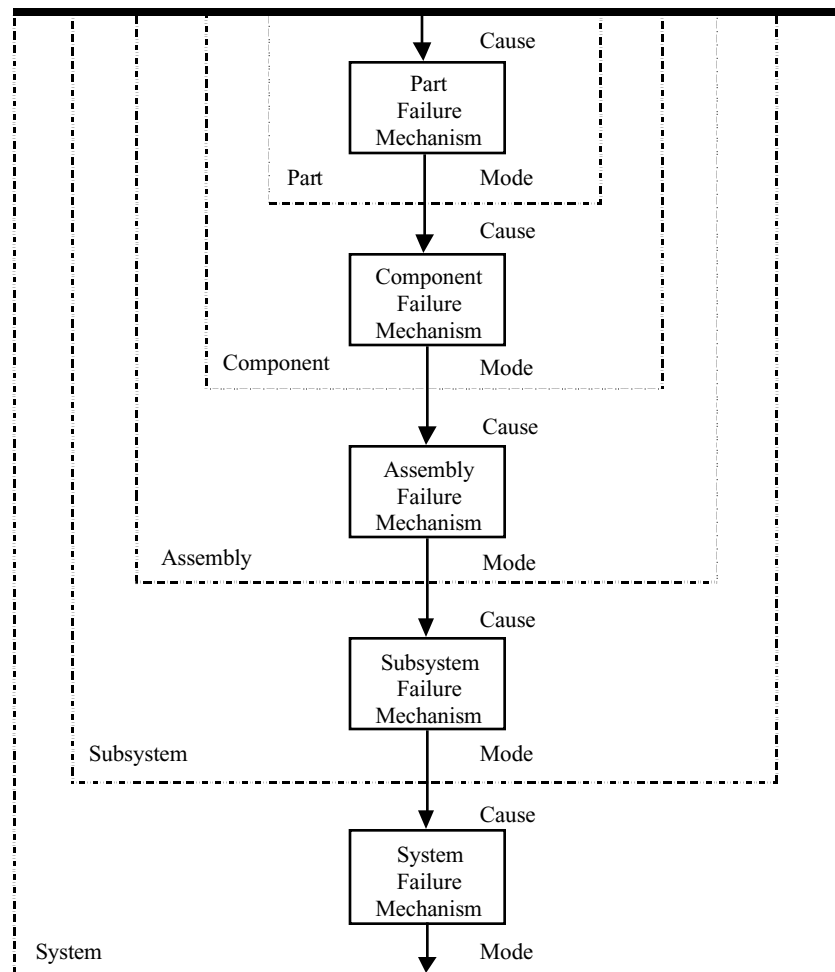


Figure 2—Failure Process Flow

5.1.6 Engineering information quality

The quality of a reliability prediction is generally dependent on the quality of the available engineering information. It is advantageous to determine the quality of the input data as early as possible in the planning stages of the reliability prediction. The following is a list of characteristics that can be used to evaluate the information quality:

- Accuracy: Representing the data value with error bounds.
- Applicability: Suitableness of data for its intended use.
- Completeness: Degree to which all needed attributes are present in the data.
- Consistency: Agreement or logical coherence among data that measure the same quantity.
- Precision: Degree of exactness with which the data or error bounds are stated.
- Relevance: Agreement or logical coherence of the data attributes to the quantity of interest.
- Timeliness: Data item or multiple items that are provided at the time required or specified for the data to be valid.
- Trustworthiness: Degree of confidence in the source of the data.
- Uniqueness: Data values that are constrained to a set of distinct entries where each value is the only one of its kind.

- Utility: Degree to which the data is available in a form that facilitates using it in the manner desired.
- Validity: Conformance of data values to known facts or sound reasoning.
- Verifiability: Degree to which the data can be independently verified.

5.2 Predictions based on field data

Field data represents the actual reliability performance of an item in its actual operational environment. Thus, a reliability prediction based on field data is appropriate for an item already in service, (e.g. for logistics planning, warranty reserve, repair department sizing or future corrective action). Field data is also used when comparing reliability predictions based on test data or analysis and the actual reliability performance of the equipment. The type and quality of field data can range from simple factory ship and return data to sophisticated tracking of installation times, operating hours, and failure times for every unit in service. The ideal data to use for an item's reliability prediction is the field reliability data for that item in the same operating environment. If some information is missing, similar items or similar environments may be found for reliability predictions.

This subclause describes the collection and analysis of field reliability data for reliability predictions. Subclause 5.2.1 describes types of field reliability data, including approximations and adjustments to the data. Subclause 5.2.2 describes field reliability data collection. Field reliability data analysis is the subject of 5.2.3. Subclause 5.2.4 describes how to use field reliability data from existing systems to predict the reliability of new designs. The use of non-failure field reliability data, such as replacements or returns, is described in 5.2.5. Subclause 5.2.6 contains an example of using field reliability data to perform a reliability prediction.

5.2.1 Field reliability data

Reliability predictions based on field data require an estimate of the operating time before failure for failed items and the accumulated operating time for all items that have not failed. This implies that three things are known for each unit: 1) initial operation time, 2) life cycle history and operating profile (along with the operating environment), and 3) failure time (or current time if the item has not failed).⁹ Field reliability data usually consists of failed units with different failure times intermingled with non-failed units, all of which may have had different installation times.¹⁰ In addition, the failures may be due to a number of different causes. This situation is shown in Figure 3. In this figure, the time 0 is the starting time for the operation of unit 1. Units 1 and 5 fail at different operating times due to failure cause X. Unit 3 fails due to failure cause Y. Units 2 and 4 are still operating at the current time although their initial operating times are different. Unit 4 also is in a non-operating condition for a period of time as shown by the dashed line in the figure.

⁹If the aggregate operating time on installed units and number of failures are the only data available, then an exponential distribution (constant failure rate) is the distribution that must be applied.

¹⁰This type of data is called multiply censored. Units that have not failed are often called suspended items. See Nelson [B10] for more information on censored data.