An Introduction to Reliability Engineering

可靠性工程概论

蒋　平　邢云燕
程文科　郭　波　编著

国防工业出版社
National Defense Industry Press

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·北京·

内容简介

本书主要介绍了可靠性的基础知识以及相关的理论体系。首先，介绍了可靠性的基本概念和常用指标、可靠性工程的基本内容；然后，介绍了常用的可靠性模型，包括典型的模型和最新的性能可靠性模型；可靠性的分析方法，包括 FMECA 和 FTA 技术；从降低寿命周期费用的角度出发介绍了可靠性设计的内容，包括可靠性的预计与分配、常用的可靠性设计方法等；进一步介绍了常用的可靠性试验；另一个重要的部分是可靠性的评估方法，介绍了可靠性数据的收集与分析、单元及系统的可靠性评估方法等；最后，介绍了在可靠性工程中起着重要作用的可靠性管理。全书由 7 章组成。

本书主要作为国内外高等院校和科研机构开展可靠性教学和培训的参考用书，也可供科研机构的可靠性工程技术和管理人员阅读参考。本书的出版得到了国家自然科学基金(71371182 和 71401170)的资助。

图书在版编目(CIP)数据

可靠性工程概论/蒋平等编著. —北京：国防工业出版社，2015.9

ISBN 978-7-118-10376-2

Ⅰ. ①可...　Ⅱ. ①蒋...　Ⅲ. ①可靠性工程—概论　Ⅳ. ①TB114.3

中国版本图书馆 CIP 数据核字(2015)第 234915 号

※

国防工业出版社出版发行

(北京市海淀区紫竹院南路 23 号　邮政编码 100048)

北京嘉恒彩色印刷有限责任公司

新华书店经售

*

开本 710×1000　1/16　**印张** 15¾　**字数** 302 千字

2015 年 9 月第 1 版第 1 次印刷　**印数** 1—2000 册　**定价** 50.00 元

国防书店：(010)88540777　　发行邮购：(010)88540776

发行传真：(010)88540755　　发行业务：(010)88540717

Preface

This century has become a new era of rapid development of economy propelled by emerging technologies. This leads to a fiercer competitive globe market than before, as modern techniques such as Internet, make it convenient for customers to compare and choose products with high qualities in terms of features, cost, reliability, service, and many other factors. It is not surprising to find that the best-informed customers always choose the products that work better and cost less. Reliability is defined as "the probability that a system will perform satisfactorily for at least a given period of time when used under stated conditions". So reliability will help products keep their competitiveness against others. To survive in such a competitive market environment, manufacturers must deliver products with high reliability, at lower cost, and in much less time. Since product reliability has received increasing attentions from both manufacturers and customers, it has become a critical success factor for business in current competitive world. Hence, to achieve high reliability, manufacturers are pressing reliability engineers as well as providing opportunities to improve reliability, shorten design period, and reduce costs of production and warranty, to increase customer satisfactions. Therefore, manufacturers in various fields need more reliability engineers to be trained to help them assure product reliability. Reliability engineers are professionals in reliability practice, which requires mastering basic concepts of reliability, as well as effective techniques to assure product reliability throughout the product lifecycle.

This book is designed to provide guidelines for reliability engineers, with reliability concepts, and up-to-date techniques to assure product reliability throughout product lifecycle consisting of stages of product planning, design and development, design verification and process validation, production, field deployment, and disposal. In particular, we will introduce techniques translating customer expectations, into building reliability into products in the design and development stage, for testing products more efficiently before design release, in the production stage for screening out defective products, and in the field for monitoring reliability performance. The book is comprised of seven chapters organized as follows.

In Chapter 1, we briefly introduce some basic terms of reliability, some important indices often used to evaluate reliability, the concepts of reliability engineering and some failure distributions that reliability engineers may encounter in engineering practice. Chapter 2 delineates the reliability modeling procedures, and some frequently used reliability models, within which the degradation models are attracting more and more attentions and hence are addressed here. In Chapter 3, we introduce techniques for reliability analysis, such as Failure Mode Effects Analysis (FMEA) and Failure Tree Analysis (FTA). Chapter 4 covers robust reliability design techniques aiming at building reliability and robustness into products in the design and development stage, including reliability prediction and allocation and other approaches. Chapter 5 is one of the most important chapters in the book, presenting typical reliability testing methods including environmental stress screening, acceptance testing, accelerated life testing, reliability growth testing and so on. In Chapter 6, reliability evaluation methods are introduced which covertesting data analysis methods, reliability evaluation methods for units and systems, respectively. The last chapter, Chapter 7, is dedicated to reliability management, which is important for implementing reliability engineering in product lifecycle.

We compose this book to be useful to reliability engineers as well as university students subject in industrial engineering and management. Readers are supposed to have learned basic statistical modeling and inference and ideas of Bayesian method.

We would like to thank the many researchers, who have produced massive books and papers on reliability topics. This book includes their research contributions. Our special thanks to Ms. Junying Xing of National Defense Industrial Publication House for helping us to work on writing this book. Finally, we are most grateful to our families, for their constant love, understanding and support during recent years in which we worked many evenings and weekends to accomplish our researches.

The publishing of this book is supported by the National Science Foundation Council with granted number 71371182 and 71401170.

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Chapter 1 Introduction

Over the past decades, there have been increasing interests in improving quality and reliability of products from both customers and manufacturers. This leads to global competition and higher customer expectations for reliability, safety and so on. Now reliability is generally regarded as the feature that has the potential to provide a product with a distinct advantage in current competitive world. The manufacturers' concernsare developing better processes to move rapidly from the very beginning of product conceptualization to a cost-effective highly reliable end-user product. To meet this end, design engineers and manufacturing engineers are requested to the appropriate use of designed experiments and statistical process monitoring/control. Moreover, reliability engineers are encouraged to take part in the product design and development stage, to help improve product reliability before delivered to users, as a reputation for unreliability can doom a product, even the manufacturing company.

Reliability means quality over the long run. A product that "works" for a long period of time is regarded as reliable. If not, it is unreliable. Let us illustrate some examples of unreliable systems.

Case one: Indian submarine "Sindurakshak"

Sindurakshak is a diesel and electricity-powered Kilo-class submarine in Indian Navy. It exploded on morning of Aug. 14, 2013, which caused a devastating fire. It finally sank at the harbor near Mumbai. The explosion caused 18 death of the crew. Primary investigation indicates that the disaster was caused by misloading of some missiles and a short circuit resulted in the launches of two missiles, one flied out the submarine and exploded on the wall of harbor and the other one exploded immediately inside the sub and caused the catastrophic disaster. This was the first submarine which was destroyed by a missile which was fired by itself.

Figure 1. 1　Indian Navy submarine "Sindurakshak"

Case two: USSR N1 Moon Rocket

The rocket was designed to explore the Moon by the Soviet Union. The Soviet government planned four launches but all failed. The second launch in 1969 even destroyed the launch field. The plan was cancelled after the last failure of lauch in 1970s. From Figure 1. 2 we can see that its character is the 30 engines installed at the rear. The remaining engines were kept in storage in good condition that some of them were later sold to U. S. and succeeded in subsequent rocket launches. From the perspective of reliability, the more engines they installed in the rocket, the more chances the rocket will fail. So, despite of the high reliability of single engine, the rocket is unreliable.

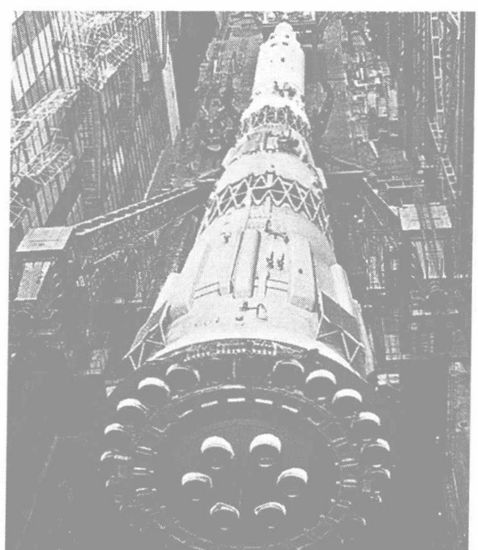

Figure 1. 2　USSR N1 Moon Rocket

Case three: Missile HAWK

Middle-range anti-air missile HAWK was deployed in 1959. At that time, reliability was not an imperative requirement in military equipment. There were many vacuum tubes in the guidance system, which required frequent test and maintenance. When testing in field, the environment was usually severe and those fragile components failed very quickly. In 1977, the US ARMY in Europe had no qualified missiles in storage due to the cause. The storage period was usually short in those days. For example, the storage period for HAWK was 5 years, and it was 3 years for TOW, according to American file published in 1967. Nowadays, the reliability of anti-air missileis was greatly improved. For example, the Russian C-300 can be remained in storage without any inspections for 10 years, and still has high successful launch capability.

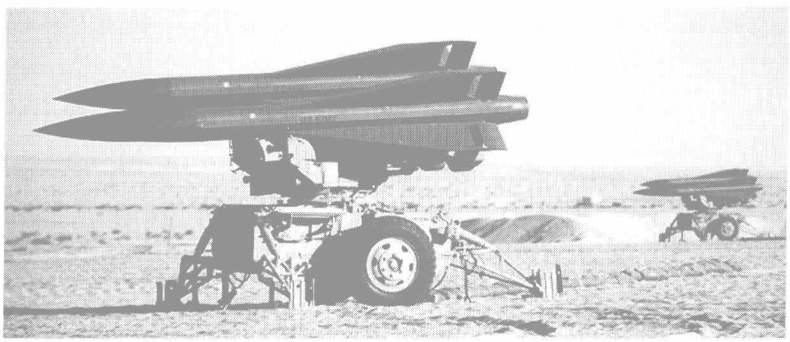

Figure 1. 3 US missile HAWK

From these cases, we can see that reliability is very important for military equipments. With poor reliability, an equipment will fail very quickly and cannot accomplish its task.

1. 1 Terms of Reliability

1. 1. 1 Reliability

Since all products will fail at their respective times, reliability is a probability. Reliability is a time dependent characteristic. Technically, reliability is often defined as the probability that a component or system will perform a required function for a given period of time when used under stated operating conditions.

The definition contains three important elements: (1) *intended function*, (2) *specified period of time*, (3) *specified conditions*.

(i) Intended function

The definition of reliability indicates that product reliability depends on specification of the intended function (defined according to user's concerns) or, complementarily, the failure criteria. For a binary-state product, the intended function is usually objective and obvious. For example, lighting is the intended function defined for a light bulb. Then a failure occurs when the light bulb is blown out. For a multistate or deteriorating product, the definition of an intended function is often subjective. For example, the remote key to a car is required to command the operations successfully at a distance up to, say 30 meters. In this example, the specification of the threshold, 30 meters, is somewhat arbitrary while largely determines the level of reliability. If a product is the component to be installed in a system, the intended function is dictated by the system requirements. So, when used in different systems, the same components may have different failure criteria. For example, a battery in a pocket flashlight may be regarded as failed if used for some months due to insufficient electricity output. But it may still be operational in a clock as the output requirement for the battery of a clock is lower than that of the flashlight.

(ii) Specified period of time

Reliability is a function of time. In the reliability definition, the period of time specified may be the calendar time, warranty length, design life, mission time, or other period of interest. The design life should be related to customers' expectations and be competitive in the marketplace. For example, when defining the reliability of a passenger car, the length of time specified is either 10 years or 150,000 miles, which defines the useful life for most customers' expectations for a vehicle.

It is worth noting that the scales of time vary in different products, for example, calendar time, mileage, and rotation cycles. The life of some products can be measured on more than one scale. A typical example is the automobile, whose lifetime is usually measured by either age or mileage, or both. Sometimes, it is difficult to choose from different scales because all appear to be relevant and of interest. In such situation, the guide is that the scale selected should reflect the underlying failure mechanism. For example, the deterioration of the body paint of a car is more likely related to age instead of mileage because deterioration of it is due to the chemical reaction which takes place continuously even when the vehicle is not running. In some cases, more than one scale is needed to characterize the life.

(iii) Specified conditions

Reliability is also a function of operating conditions. The conditions may include stress types and levels, usage rates, operation profiles, and others. Mechanical, electrical, and thermal stresses are most common stress typies. Usage rate (frequency of operation) is also an important operating condition that affects the reliability of many products. Its effects on some products have been widely studied. For example, the number of cycles to failure of a microrelay is larger at a high usage rate than at a low rate. Rotation speed is a factor that influences revolutions to failure of a bearing. The different effects in respective usage rates inspired the accelerated stress testing method which we will introduce in Chapter 5.

Most products are used in a wide range of conditions. The conditions specified should represent the real-world usage of most customers. In practical cases, it is usually difficult or impossible to address all operating conditions that a product will encounter during its lifetime. However, the stresses to which a product is most sensitive should be included. For example, the engine of T90 tank is designed to be operated in Russian environment where the air is mostly dry and cool. So it is reliable in Russia, while it failed many times in India where the temperature is always high. Therefore, when evaluating the reliability of tank engine, the operational condition should first be specified.

It is worth addressing here that the reliability definition for a specific product should be operational. In other words, the reliability, intended function, specified condition, and time must be quantitative and measurable. To achieve this goal, qualitative and uninformative terms should be avoided. If the product is a component to be installed in a system, the reliability should be defined according to the system's requirements. For example, the reliability of a car can be defined as the probability that it will meet customer expectations for 10 years or 150,000 miles under a usual usage profile. Then the 10 years or 150,000 miles should be translated into the design life of the components within the automobile. This will be further discussed in the reliability allocation of Chapter 3.

1.1.2 Availability

Availability is used for evaluating repairable systems. It is the probability that the system is operational at any given time t. It can also be specified as a proportion of time that the system is available for use in a given interval $(0, T)$. The definitions of availability and reliability may cause confusion as sometimes the two terms are interchangeable with each other. But they are not the same. For example, a plane is reliable at time t may means it is available at time t, while if it is in scheduled inspection, it is not available at time t.

1.1.3 Maintainability

Maintainability is also a time dependent characteristic. It is the ability of a product, under stated conditions of use, to be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources. The definition of maintainability is similar to that of reliability, in required function, stated conditions of use, but different in the condition that it requires the maintenance following prescribed procedures and using resources. Maintainability is a main factor determining the availability of a product.

RAM is often used as an acronym for reliability, availability, and maintainability.

1.1.4 Safety

Safety is the freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property. Safety is a special property of product, a sit is difficult to be quantified, if only referring to this definition. However, safety is a wildly used term especially for military equipments that deserve extensive attentions. People usually evaluate a product's safety by assess the risk of accidents which may caused by the product. Risk is further assessed by the probability of the occurrence of certain accident and by the severity of consequence caused by the accident.

Most people may think that something reliable means it is safe. In fact, even high reliability can not ensure safety. For example, in the test of the famous spacecraft, Apollo, the two subsystems, propeller and brake parachute, are reliable but the brake parachute was burnt by the propeller when ejecting remaining fuel during its returning course, due to the wrong operation sequence of the two subsystems. This accident might cause unendurable collision of the spacecraft. Fortunately, it is an unmanned test. Then the engineers changed the sequence, and avoided such accident. So safety should be an independent factor to be considered for important equipments even they or the components are highly reliable.

1.2 Reliability Indices

In this section we introduce some indices wildly used to measure reliability quantitatively. In practice, the appropriate and effective indices for a specific product must be determined based on product uniqueness and use.

1.2.1 Probability Density Function (pdf)

The pdf, often denoted by $f(t)$, indicates the failure distribution over the entire time range and represents the absolute failure speed. The larger the value of $f(t)$ is, the more failures may occur in a small time interval around time t. Although $f(t)$ is rarely used to measure reliability, it is the basic tool for deriving other metrics and for conducting in-depth analytical studies.

1.2.2 Cumulative Distribution Function (cdf)

The cdf, denoted by $F(t)$, is the probability that a product will fail by a specified time t. It is the probability of failure, often interpreted as the population fraction failed by time t. Mathematically, it is expressed as

$$F(t) = P(T \leqslant t) = \int_0^t f(s)\mathrm{d}s,$$

which is equivalent to

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t}.$$

For example, if the time to failure of a product is exponentially distributed with parameter λ, the pdf is

$$f(t) = \lambda\exp(-\lambda t), \qquad t \geqslant 0.$$

and the cdf is

$$F(t) = \int_0^t f(s)\mathrm{d}s = \int_0^t \lambda\exp(-\lambda t)\mathrm{d}t = 1 - \exp(-\lambda t),\ t \geqslant 0.$$

1.2.3 Reliability Function

Reliability function is usually denoted by $R(t)$, also called the survival function. It is often interpreted as the population fraction survived by time t. $R(t)$ is