ACCELERATED LIFE TESTING OF ONE-SHOT DEVICES

DATA COLLECTION AND ANALYSIS

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With great love and affection, we dedicate this book to

Sarah and Julia Balakrishnan, and Colleen Cutler	*NB*
Grace Chu, Sophia Ling, and Sheldon Ling	*MHL*
Tian Feng and Victoria So	*HYS*

Contents

Preface

Lifetime information obtained from one-shot devices is very limited as the entire data are either left- or right-censored. For this reason, the analysis of one-shot device testing data poses a special challenge. This book provides several statistical inferential methods for analyzing one-shot device lifetime data obtained from accelerated life-tests and also develops optimal designs for two mainstream accelerated life-tests – constant-stress and step-stress accelerated life-tests – that are commonly used in reliability practice. The discussions provided in the book would enable reliability practitioners to better design their experiments for data collection from efficient accelerated life-tests when there are budget constraints in place. This is important from estimation and prediction point of view as such optimal designs would result in as accurate an inference as possible under the constraints imposed on the reliability experiment. Moreover, R codes are presented within each chapter so that users can try out performing their own analysis on one-shot device testing data.

In addition, the inferential methods and the procedures for planning accelerated life-tests discussed in this book are not only limited to one-shot devices alone but also can be extended naturally to accelerated life-tests with periodic inspections (interval-censoring) and those with continuous monitoring and censoring (right-censoring). The book finally concludes by highlighting some important issues and problems that are worth considering for further research. This may be especially useful for research scholars and new researchers interested in taking on this interesting and challenging area of research in reliability theory and practice.

It is possible that some pertinent results or references got omitted in this book, and we assure you that it is due to inadvertency on our part and not due to scientific antipathy. We will appreciate greatly if the readers inform us of any corrections/omissions, or any comments pertinent to any of the discussions in the book!

Our sincere thanks go to the entire Wiley team, Ms. Mindy Okura-Marszycki, Ms. Kathleen Santoloci, and Mr. Brett Kurzman, for taking great interest in this project from day one, for all their help and encouragement during the whole course, and for their fine assistance during the final production stage of the book. Our thanks also go to our research collaborators and graduate students for their incisive comments and queries, which always benefited us greatly and helped clarify some of our own ideas! We express our sincere appreciation to Ms. Elena Maria Castilla Gonzalez, a doctoral student of Professor Leandro Pardo in the Department of Statistics and Operations Research at Complutense University of Madrid, Spain, for her careful reading of Chapter 5 and also for sharing with us some R codes that she had developed concerning robust inferential methods for one-shot device test analyses. Last but not least, our special thanks go to our families for their patience and understanding, and for providing constant support and encouragement during our work on this book!

Finally, the first author (NB) wishes to state to his older daughter, Ms. Sarah Balakrishnan, that though she lost out on getting his Volvo car due to a major car accident, she should be heartened by the fact that the accident resulted in the germination of his interest and ideas on one-shot devices (airbags), and ultimately this book solely dedicated to the topic!

July, 2020

Narayanaswamy Balakrishnan
Man Ho Ling
Hon Yiu So

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/Balakrishnan/Accelerated_Life_Testing

The Student companion site will contain the codes and case studies.

1

One-Shot Device Testing Data

1.1 Brief Overview

One-shot device testing data analyses have recently received great attention in reliability studies. The aim of this chapter is to provide an overview on one-shot device testing data collected from accelerated life-tests (ALTs). Section 1.2 surveys typical examples of one-shot devices and associated tests in practical situations. Section 1.3 describes several popular ALTs, while Section 1.4 provides some examples of one-shot device testing data that are typically encountered in reliability and survival studies. Finally, Section 1.5 details some recent developments on one-shot device testing data analyses and associated issues of interest.

1.2 One-Shot Devices

Valis et al. (2008) defined one-shot devices as units that are accompanied by an irreversible chemical reaction or physical destruction and could no longer function properly after its use. Many military weapons are examples of one-shot devices. For instance, the mission of an automatic weapon gets completed successfully only if it could fire all the rounds placed in a magazine or in ammunition feed belt without any external intervention. Such devices will usually get destroyed during usual operating conditions and can therefore perform their intended function only once.

Shaked and Singpurwalla (1990) discussed the submarine pressure hull damage problem from a Bayesian perspective and assessed the effect of various strengths of underwater shock waves caused by either a nuclear device or a chemical device on the probability of damage to a submarine pressure hull. A record is made of whether a copy of a diminutive model of a submarine pressure hull is damaged or not, and a specific strength of the shock wave on the model. Fan et al. (2009)

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considered electro-explosive devices in military applications, which induct a current to excite inner powder and make them explode. Naturally, we cannot adjudge the functioning condition of the electro-explosive device from its exterior, but can only observe it by detonating it directly. After a successful detonation, the device cannot be used anymore; if the detonation becomes a failure, we will also not know when exactly it failed. Nelson (2003) described a study of crack initiation for turbine wheels. Each of the 432 wheels was inspected once to determine whether it had started to crack or not. Newby (2008) provided some other examples of one-shot devices, such as fire extinguishers or munitions. A full test would require the use of the considered devices and, therefore, their subsequent destruction. The test carried out would show whether a device is still in a satisfactory state, or has failed by that inspection time.

One-shot device testing data also arise in destructive inspection procedures, wherein each device is allowed for only a single inspection because the test itself results in its destruction. Morris (1987) presented a study of 52 Li/SO_2 storage batteries under destructive discharge. Each battery was tested at one of three inspection times and then classified as acceptable or unacceptable according to a critical capacity value.

Ideally, reliability data would contain actual failure times of all devices placed on test (assuming, of course, the experimenter could wait until all devices fail), so that the observed failure times can reveal the failure pattern over time, and we could then estimate the reliability of the device reasonably. But, in practice, many life-tests would get terminated before all the units fail. Such an early stoppage of the life-test by the experimenter may be due to cost or time constraints or both. This would result in what is called as “right-censored data” because the exact failure times of the unfailed devices are unknown, but all we know is that the failure times of those devices are larger than the termination time. Considerable literature exists on statistical inference for reliability data under right-censoring; for example one may refer to the books by Cohen (1991), Balakrishnan and Cohen (1991), and Nelson (2003).

Moreover, when nondestructive and periodic inspections are carried on devices, their exact failure times will not be observed, but the intervals wherein the failures occurred will only be available. If a failure is observed by the first inspection, then it is known that the failure time of the device is less than the first inspection time, resulting in “left-censoring.” Similarly, if a failure is observed between two consecutive inspection times, then it is known that the failure time is between these two corresponding inspection times, resulting in “interval-censoring.” Finally, the failure times of all surviving units at the final inspection time are right-censored as their exact failure times will not be observed. Exact failure times can only be observed from a life-testing experiment with continuous surveillance. The periodic inspection process with nondestructive evaluation would actually provide a reasonable approximation to failure times of devices under test, especially when the inspection time intervals are short, even though the precision of inference will be less in this case.

It is useful to note that in all the preceding examples of one-shot devices, we will not observe the actual lifetimes of the devices. Instead, we would only observe either a success or a failure at the inspection times, and so only the corresponding binary data would be observed, consequently resulting in less precise inference. In this manner, one-shot device testing data differ from typical data obtained by measuring lifetimes in standard life-tests and, therefore, poses a unique challenge in the development of reliability analysis, due to the lack of lifetime information being collected from reliability experiments on such one-shot devices. If successful tests occur, it implies that the lifetimes are beyond the inspection times, leading to right-censoring. On the other hand, the lifetimes are before the inspection times, leading to left-censoring, if tests result in failures. Consequently, all lifetimes are either left- or right-censored. In such a setting of the lifetime data, Hwang and Ke (1993) developed an iterative procedure to improve the precision of the maximum likelihood estimates for the three-parameter Weibull distribution and to evaluate the storage life and reliability of one-shot devices. Some more examples of one-shot devices in the literature include missiles, rockets, and vehicle airbags; see, for example, Bain and Engelhardt (1991), Guo et al. (2010), and Yun et al. (2014).

1.3 Accelerated Life-Tests

As one-shot devices (such as ammunition or automobile airbags) are usually kept for a long time in storage and required to perform its function only once, the reliability required from such devices during their normal operating conditions would naturally be high. So, it would be highly unlikely to observe many failures on tests under normal operating conditions within a short period of time. This renders the estimation of reliability of devices to be a challenging problem from a statistical point of view. In this regard, ALTs could be utilized to mitigate this problem. In ALTs, devices are subject to higher-than-normal stress levels to induce early failures. In this process, more failures could likely be obtained within a limited test time. As the primary goal of the analysis is to estimate the reliability of devices under normal operating conditions, ALT models would then typically extrapolate (from the data obtained at elevated stress levels) to estimate the reliability under normal operating conditions. ALTs are known to be efficient in capturing valuable lifetime information, especially when there is a need to shorten the life-testing experiment. For this reason, ALTs have become popular and are commonly adopted in many reliability experiments in practice. One may refer to the detailed reviews presented by Nelson (1980), Cramer and Kamps (2001), Pham (2006), and Meeker and Escobar (2014), and the excellent booklength account provided by Nelson (2009).

Constant-stress accelerated life-tests (CSALTs) and step-stress accelerated life-tests (SSALTs) are two popular ALT plans that have received great attention in the literature. Under a CSALT, each device gets tested at only one prespecified stress level. To mention a few recent works, for example, Wang et al. (2014) considered CSALTs with progressively Type-II right censored samples under Weibull lifetime distribution; for pertinent details on progressive censoring, see Balakrishnan (2007) and Balakrishnan and Cramer (2014). Wang (2017) discussed CSALTs with progressive Type-II censoring under a lower truncated distribution. Lin et al. (2019) studied CSALTs terminated by a hybrid Type-I censoring scheme under general log-location-scale lifetime distributions. SSALTs are an alternative to apply stress to devices in a way that stress levels will increase at prespecified times step-by-step. For SSALTs, there are three fundamental models for the effect of increased stress levels on the lifetime distribution of a device: The tampered random variable model proposed by DeGroot and Goel (1979), the cumulative exposure model of Sedyakin (1966) and Nelson (1980); see also (Nikulin and Tahir, 2013), and the tampered failure rate model proposed by Bhattacharyya and Soejoeti (1989). All these models of SSALTs have been discussed extensively by many authors. Gouno (2001) analyzed data collected from SSALTs and presented an optimal design for SSALTs; see also Gouno (2007). Zhao and Elsayed (2005) analyzed data on the light intensity of light emitting diodes collected from SSALTs with four stress levels under Weibull and log-normal distributions. For the case of exponential lifetime distribution, by considering a simple SSALT under Type-II censoring, Balakrishnan et al. (2007) developed exact likelihood inferential methods for the model parameters; see also Balakrishnan (2008) for details, while Xiong et al. (2006) considered the situation when the stress changes from a low-level stress to a high-level stress at a random time.

1.4 Examples in Reliability and Survival Studies

1.4.1 Electro-Explosive Devices Data

Fan et al. (2009) considered data, presented in Table 1.1, on 90 electro-explosive devices under various levels of temperature at different inspection times. Ten devices under test at each condition were inspected to see whether there were any

Table 1.1 Failure records on electro-explosive devices under CSALTs with temperature (K).

Test group	Inspection time	Temperature	Number of samples	Number of failures
1	10	308	10	3
2	10	318	10	1
3	10	328	10	6
4	20	308	10	3
5	20	318	10	5
6	20	328	10	7
7	30	308	10	7
8	30	318	10	7
9	30	328	10	9

Source: Fan et al. (2009).

failures or not at each inspection time for each temperature setting. These data were then used to estimate the reliability of electro-explosive devices at different mission times under the normal operating temperature.

1.4.2 Glass Capacitors Data

Zelen (1959) presented data from a life-test of glass capacitors at four higher-than-usual levels of temperature and two levels of voltage. At each of the eight combinations of temperature and voltage, eight items were tested. We adopt these data to form one-shot device testing data by taking the inspection times (hours) as $\tau \in \{300, 350, 400, 450\}$, which are summarized in Table 1.2. These data were then used to estimate the mean lifetime of glass capacitors for 250 V and 443 K temperature.

1.4.3 Solder Joints Data

Lau et al. (1988) considered data on 90 solder joints under three types of printed circuit boards (PCBs) at different temperatures. The lifetime was measured as the number of cycles until the solder joint failed, while the failure of a solder joint is defined as a 10% increase in measured resistance. A simplified dataset is derived from the original one and presented in Table 1.3, where two stress factors considered are temperature and a dichotomous variable indicating if the PCB type is "copper-nickel-tin" or not.

Table 1.2 Failure records on glass capacitors under CSALTs with two stress factors: temperature (K) and voltage (V).

Test group	Inspection time	Temperature	Voltage	Number of samples	Number of failures
1	450	443	200	8	1
2	400	453	200	8	0
3	350	443	250	8	0
4	300	453	250	8	1
5	450	443	300	8	3
6	400	453	300	8	4
7	350	443	350	8	3
8	300	453	350	8	2

Source: Zelen (1959).

Table 1.3 Failure records on solder joints under CSALTs with temperature (K) and a dichotomous variable indicating if the PCB type is "copper-nickel-tin (CNT)" or not.

Test group	Inspection time	Temperature	CNT	Number of samples	Number of failures
1	300	293	Yes	10	4
2	300	333	Yes	10	4
3	100	373	Yes	10	6
4	1300	293	No	20	10
5	800	333	No	20	3
6	200	373	No	20	4

Source: Lau et al. (1988).

1.4.4 Grease-Based Magnetorheological Fluids Data

Zheng et al. (2018) studied grease-based magnetorheological fluids under SSALTs with four levels of temperature and observed whether their viscosities or shear stresses decreased by more than 10% after tests. Twenty samples of grease-based magnetorheological fluids were subject to higher-than-normal operating temperature. Then, each sample was inspected only once and only whether it had failed or not at the inspection time was observed, and not the actual failure time. The data collected in this manner, presented in Table 1.4, were then used to estimate the mean lifetime of grease-based magnetorheological fluids under the normal operating temperature.

1.4.5 Mice Tumor Toxicological Data

It is important to point out that one-shot device testing data arise from diverse fields beyond reliability engineering, such as in mice tumor studies from tumorigenicity experiments; see Kodell and Nelson (1980). In such a study, each mouse received a particular dosage of benzidine dihydrochloride in its drinking water and was later sacrificed to detect whether some tumors had developed by then or not. Tumor presence can be detected only at the time of mouse's sacrifice or natural death. These data are summarized in Table 1.5. The data collected in this form were then used to measure the impact of the chemical dosage on the risk of tumor development.

1.4.6 ED01 Experiment Data

Lindsey and Ryan (1993) described experimental results conducted by National Center for Toxicological Research in 1974. 3355 out of 24 000 female mice were randomized to a control group or groups that were injected with a high dose (150 ppm) of a known carcinogen, called 2-AAF, to different parts of the bodies. The inspection times on the mice were 12, 18, and 33 months and the outcomes of mice were death without tumor (DNT) and death with tumor (DWT), and sacrificed without tumor (SNT) and sacrificed with tumor (SWT). Balakrishnan et al. (2016a), in their analysis, ignored the information about parts of mouse bodies where the drugs were injected and combined SNT and SWT into one sacrificed group, and denoted the cause of DNT as natural death and the cause of DWT as death due to cancer. These data are summarized in Table 1.6. They then estimated the chance of death without tumor.

1.4.7 Serial Sacrifice Data

Ling et al. (2020) were primarily concerned with the data (Berlin et al., 1979), presented in Table 1.7, on the presence or absence of two disease categories – (a)

Table 1.4 Failure records on grease-based magnetorheological fluids under SSALTs with temperature (K).

Stage	Inspection time (h)	Temperature	Number of samples	Number of failures
1	864	333	5	1
2	1512	339	5	1
3	1944	345	5	2
4	2160	351	5	2

Source: Zheng et al. (2018).

Table 1.5 The number of mice sacrificed, with tumor from tumorigenecity experiments data.

Test group	Inspection time (mo)	Sex	Dosage (ppm)	Number of mice sacrificed	Number of mice with tumor
1	9.33	F	60	72	1
2	14.00	F	60	48	3
3	18.67	F	60	36	18
4	9.33	F	120	48	0
5	14.00	F	120	47	14
6	18.67	F	120	26	25
7	9.33	F	200	47	4
8	14.00	F	200	45	38
9	9.33	F	400	24	16
10	14.00	F	400	10	9
11	9.33	M	120	48	0
12	14.00	M	120	44	7
13	18.67	M	120	42	11
14	9.33	M	200	47	3
15	14.00	M	200	32	5
16	18.67	M	200	19	8
17	9.33	M	400	24	0
18	14.00	M	400	22	11
19	18.67	M	400	15	11

Source: Kodell and Nelson (1980).

thymic lymphoma and/or glomerulosclerosis and (b) all other diseases – for an irradiated group of 343 female mice given γ-radiation and a control group of 361 radiation-free female mice to study the onset time and the rate of development of radiation-induced disease. All of the mice in both groups were sacrificed at various times, with the presence of a disease indicating that the disease onset occurred before sacrifice, while the absence of a disease indicating that the disease onset would occur after sacrifice.

Table 1.6 The number of mice sacrificed, died without tumor, and died with tumor from the ED01 experiment data.

Test group	Inspection time (mo)	High dose of 2-AAF	Number of mice		
			Sacrificed	Died without tumor	Died with tumor
1	12	No	115	22	8
2	12	Yes	110	49	16
3	18	No	780	42	8
4	18	Yes	540	54	26
5	33	No	675	200	85
6	33	Yes	510	64	51

Source: Lindsey and Ryan (1993).

Table 1.7 Serial sacrifice data on the presence or absence of two disease categories: (a) thymic lymphoma and/or glomerulosclerosis and (b) all other diseases.

Test group	Sacrifice time (d)	γ-radiation	Number of mice			
			Healthy	With (a) only	With (b) only	With (a) and (b)
1	100	No	58	13	0	1
2	200	No	40	23	1	1
3	300	No	18	41	1	3
4	400	No	8	25	1	6
5	500	No	1	21	1	16
6	600	No	1	11	0	21
7	700	No	0	9	1	39
8	100	Yes	54	12	1	0
9	200	Yes	36	24	3	5
10	300	Yes	13	35	1	17
11	400	Yes	0	13	2	28
12	500	Yes	0	3	1	35
13	600	Yes	0	0	1	30
14	700	Yes	0	0	1	28

Source: Berlin et al. (1979).