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Step-Stress Accelerated Life Testing with Type II Censoring and Exponential Distribution for Solar-Powered Lighting Systems

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Abstract

This study investigates the reliability of solar-powered lighting systems using a partial step-stress accelerated life testing (ALT) model with Type-II censoring. The objective is to estimate the mean failure time and quantify the acceleration effect under elevated stress conditions. Secondary data from a previously reported step-stress accelerated life testing experiment involving 31 lighting devices were analyzed. Initially, the devices were tested at a normal temperature of 293 K until 16 failures occurred. Subsequently, the stress level was increased to 353 K, and testing continued under the accelerated condition until the predetermined number of failures was observed according to a Type-II censoring scheme. Assuming an exponential lifetime distribution and a linear accelerated failure time (AFT) model, the maximum likelihood estimation (MLE) method was employed for parameter inference. The results indicate that the estimated mean failure time under normal conditions is approximately 711.6 hours, which decreases to about 38.7 hours under accelerated stress, yielding an acceleration factor of 18.354. Furthermore, a 95% confidence interval for the mean failure time under normal conditions ranges from 460.2 to 1245 hours. The reliability function and percentile life under different stress levels were also derived. These findings provide a practical statistical framework for evaluating the reliability of solar-powered lighting systems using accelerated life testing methods.

Keywords: Accelerated Life Testing; Exponential Distribution; Solar Lighting Reliability; Step-Stress Model; Type II Censoring

1. Introduction

Solar-powered lighting systems have become an integral component of sustainable infrastructure, particularly in public street lighting, rural electrification, and off-grid environments. The adoption of renewable energy technologies in lighting systems contributes to reduced greenhouse gas emissions, lower operational expenditures, and improved accessibility to reliable lighting services in regions lacking conventional electrical grids [1]. As deployment continues to expand, ensuring long-term system reliability is essential for maintaining operational safety, cost efficiency, and functional sustainability.

A solar-powered lighting system typically consists of photovoltaic panels, rechargeable batteries, charge controllers, and lighting units operating under heterogeneous environmental conditions such as temperature variability, humidity, and prolonged outdoor exposure. These stressors

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may accelerate physical degradation and increase the probability of component failure [1, 2]. From a reliability standpoint, unexpected failures can reduce illumination performance, increase maintenance frequency, and disrupt service continuity. Consequently, rigorous reliability modeling is necessary to support effective system design, deployment, and operational planning.

Classical reliability evaluation relies on lifetime observations collected under normal operating conditions. However, modern lighting devices are engineered for extended service lives, making failure events relatively rare within practical experimental durations. This limitation often results in inefficient statistical inference due to insufficient failure information. Accelerated Life Testing (ALT) addresses this challenge by subjecting experimental units to elevated stress levels while preserving the underlying failure mechanisms, thereby enabling faster reliability assessment and reducing experimental costs [3]. Among various ALT schemes, step-stress accelerated life testing is particularly attractive because stress levels are increased sequentially, allowing earlier observation of failures without continuously exposing units to extreme stress conditions [4].

From a statistical perspective, lifetime data obtained from step-stress experiments are commonly analyzed within a parametric framework. The exponential distribution is frequently employed in reliability and survival analysis due to its constant hazard rate and analytical tractability [5]. Furthermore, it has been shown to provide stable inferential properties in accelerated testing settings, particularly for small to moderate sample sizes [6]. In many practical reliability experiments, tests are terminated after a predetermined number of failures, resulting in Type-II censored samples. This censoring mechanism effectively controls testing time and cost while preserving essential failure information; nevertheless, specialized statistical procedures are required to obtain consistent parameter estimates and reliable measures of uncertainty under censoring [7].

Statistical inference for step-stress accelerated life testing with censored observations has received considerable attention in the reliability literature, especially regarding parameter estimation and confidence interval construction [4, 8]. Prior studies have also demonstrated the suitability of parametric survival models for censored lifetime data in engineering reliability contexts [9, 10]. Nevertheless, empirical investigations utilizing real lifetime data from renewable-energy-based lighting systems remain limited. More specifically, the joint implementation of partial step-stress accelerated life testing, Type-II censoring, and real observational data for solar-powered lighting devices has not been sufficiently explored. Existing studies predominantly emphasize methodological derivations or simulation-based analyses rather than experimentally grounded evaluations of renewable-energy technologies [11, 12].

To address this gap, the present study develops a statistical inference framework for partial step-stress accelerated life testing with Type-II censoring under an exponential accelerated failure-time (AFT) model. Model parameters are estimated using maximum likelihood estimation, and corresponding confidence intervals are constructed to quantify estimation uncertainty. Specifically, this study applies a partial step-stress ALT design to real lifetime data obtained from a solar-powered lighting system while establishing likelihood-based inference within an exponential AFT structure with Type-II censoring. In addition to its methodological relevance, the proposed framework provides practical insights for improving the efficiency of reliability assessment in renewable-energy lighting technologies, thereby supporting the dependable deployment of sustainable lighting infrastructure.

2. Research Methods

This study applies a statistical framework for step-stress accelerated life testing with Type-II censoring to evaluate the reliability of solar-powered lighting systems. The methodological procedure consists of several stages, including the description of the experimental data, the formulation of the exponential lifetime model, and the estimation of model parameters using maximum likelihood estimation. The following subsections describe each methodological component in detail.

2.1. Data Source and Variable

The data analyzed in this study are secondary data obtained from a previously reported step-stress accelerated life testing experiment [13]. The experiment involved 31 units of solar-powered lighting devices tested under two temperature levels. Initially, all devices were operated under a normal temperature of 293 K. The experiment was conducted under this condition until 16 failure events were observed. After the sixteenth failure, the stress level was increased by raising the temperature to 353 K, representing the accelerated testing condition. Following the increase in stress level, the experiment continued under the accelerated condition, and additional failures were observed. The observed data therefore consist of failure times recorded both before and after the stress change.

The variable of interest in this study is the failure time, measured in units of hundreds of operating hours, representing the duration until a lighting device ceases to function properly. The dataset consists of sixteen failure times occurring before the stress change and fifteen failure times observed after the stress level was increased. These second-stage observations correspond to actual failure times under the accelerated stress level, rather than censored observations. The complete dataset is presented in Table 1.

Table 1: Failure Time Data (in Hundreds of Operating Hours) of Solar-Powered Lighting Devices

Stress Level	Failure Times
First stress level (293K)	0.140, 0.783, 1.324, 1.582, 1.716, 1.794, 1.883, 2.293, 2.660, 2.674, 2.725, 3.085, 3.924, 4.396, 4.612, 4.892
Second stress level (353K)	5.002, 5.022, 5.082, 5.112, 5.147, 5.238, 5.244, 5.247, 5.305, 5.337, 5.407, 5.408, 5.445, 5.483, 5.717

2.2. Type II Censoring

Type II censoring is a censoring scheme commonly used in reliability and survival analysis, in which an experiment is terminated after a predetermined number of failures have been observed [5, 6]. Let n denote the total number of test units and r the predetermined number of observed failures, where $r < n$. Under this scheme, the first r ordered failure times are fully observed, while the remaining $n - r$ units are treated as right-censored at the time of the r-th failure [5, 6]. This censoring scheme is widely applied in accelerated life testing because it allows researchers to control the number of observed failures while reducing the duration and cost of the experiment [6, 14]. The censored observations indicate that the corresponding units survive beyond the censoring time, and this partial information must be incorporated into the likelihood function to obtain valid statistical inference [5, 14]. In this study, the Type II censoring scheme is incorporated within a step-stress accelerated life testing framework to analyze the reliability of solar-powered lighting devices.

2.3. Statistical Modeling Using the Exponential Distribution

The exponential distribution is one of the most widely used models in reliability and survival analysis, particularly for systems characterized by a constant failure rate. This distribution is appropriate for modeling failure mechanisms in which the probability of failure does not depend on the age of the system.

Let T denote a non-negative random variable representing the failure time of a device. Under the exponential distribution, the probability density function is defined as.

$$f(t) = \frac{1}{\theta} \exp\left(-\frac{t}{\theta}\right), \quad t \geq 0 \tag{1}$$

where $\theta > 0$ represents the mean failure time.

The corresponding cumulative distribution function and survival function are given by

$$F(t) = 1 - \exp\left(-\frac{t}{\theta}\right), \qquad S(t) = \exp\left(-\frac{t}{\theta}\right). \tag{2}$$

The hazard function associated with the exponential distribution is constant and expressed as

$$h(t) = \frac{f(t)}{S(t)} = \frac{1}{\theta} \tag{3}$$

which reflects the assumption of a time-independent failure rate. This property makes the exponential distribution particularly suitable for modeling electronic and mechanical components operating under stable conditions [3].

2.4. Parameter Estimation Using Maximum Likelihood Method

The parameters of the exponential failure time model are estimated using the Maximum Likelihood Estimation (MLE) method, which is widely applied in reliability and survival analysis, particularly in the presence of censored data [3].

Let $t_1, t_2, \ldots, t_r$ denote the observed failure times, where r represents the number of failures observed from a total of n test units. Under the Type II censoring scheme, the remaining $n - r$ observations are right-censored at the censoring time t_r, as commonly formulated in survival data analysis [4]. The likelihood function for the exponential model under Type II censoring can be expressed as

$$L(\theta) = \prod_{i=1}^{r} f(t_i; \theta) \left[S(t_r; \theta)\right]^{n-r} \tag{4}$$

where $f(t; \theta)$ and $S(t; \theta)$ denote the probability density function and the survival function of the exponential distribution, respectively [4]. Substituting these expressions into the likelihood function yields the maximum likelihood estimator of the mean failure time under Type-II censoring.

$$\widehat{\theta} = \frac{\sum_{i=1}^{r} t_i + (n-r)\, t_r}{r} \tag{5}$$

which represents the estimated mean lifetime of the system under the assumed exponential model.

2.5. Step-Stress Accelerated Failure-Time Model

Accelerated life testing (ALT) is a reliability assessment approach in which test units are subjected to stress levels higher than normal operating conditions in order to induce failures within a shorter testing period while preserving the same underlying failure mechanism as in normal operation [4, 15]. Among various ALT schemes, the step-stress test is widely used, where the applied stress level is increased during the experiment rather than being kept constant [4].

In a step-stress accelerated life testing experiment, test units are initially operated under a normal stress level and, after a predetermined condition is met, the stress level is elevated to accelerate the failure process. Let n denote the total number of test units. Let t_0 represent the failure time of a unit under normal operating conditions, and let t_s denote the corresponding failure time under an accelerated stress level. [3, 4, 16].

Under the accelerated failure-time (AFT) assumption, the effect of increased stress is modeled through a constant acceleration factor $A_F > 1$, such that the failure time under normal conditions is related to the failure time under accelerated conditions by

$$t_0 = A_F\, t_s \tag{6}$$

Since the exponential mean is a scale parameter, the mean lifetimes under the two stress levels satisfy

$$\theta_0 = A_F\, \theta_s$$

Let $F_0(t)$ and $F_s(t)$ denote the cumulative distribution functions (CDFs) of the failure time under normal and accelerated stress levels, respectively. Within the AFT framework, the relationship between these distributions is given by

$$F_o(t) = F_s\left(\frac{t}{A_F}\right) \tag{7}$$

which directly follows from the definition of accelerated failure-time [17]. By differentiating the above expression with respect to t, the corresponding probability density functions satisfy

$$f_o(t) = \left(\frac{1}{A_F}\right) f_s\left(\frac{t}{A_F}\right) \tag{8}$$

where $f_0(t)$ and $f_s(t)$ denote the probability density functions under normal and accelerated conditions [4]. Similarly, the hazard functions under the two stress levels are related by

$$h_o(t) = \frac{f_o(t)}{1 - F_o(t)} = \frac{\left(\frac{1}{A_F}\right) f_s\left(\frac{t}{A_F}\right)}{1 - F_s\left(\frac{t}{A_F}\right)} = \left(\frac{1}{A_F}\right) h_s\left(\frac{t}{A_F}\right) \tag{9}$$

An equivalent expression can be obtained by rearranging the above relationship.

$$h_s(t) = A_F\, h_o(t)\, A_F\, t \tag{10}$$

For the exponential distribution, the hazard function is constant and given by

$$h(t) = \frac{1}{\theta}$$

Therefore, under normal and accelerated stress levels we have

$$h_0(t) = \frac{1}{\theta_0}, \qquad h_s(t) = \frac{1}{\theta_s} \tag{11}$$

Since the accelerated failure-time assumption implies

$$\theta_s = \frac{\theta_0}{A_F}, \tag{12}$$

the hazard function under accelerated stress becomes

$$h_s(t) = A_F\, h_0(t) \tag{13}$$

This result indicates that the hazard rate under accelerated stress is scaled by the acceleration factor [7].

3. Results and Discussion

This section presents the results obtained from the implementation of the proposed partial step-stress accelerated life testing model. The analysis includes parameter estimation, confidence interval construction, and the evaluation of reliability measures such as failure rates and lifetime percentiles. The results are then interpreted in the context of reliability assessment for solar-powered lighting systems.

3.1. Parameter Estimation under Partial Step-Stress Model

This subsection presents the estimation of model parameters for the partial step-stress accelerated life testing scheme under the exponential distribution. The estimation is carried out using the maximum likelihood method based on the likelihood function derived in the previous subsection.

Consider a partial step-stress accelerated life testing experiment in which n units are initially operated under the normal stress level S_0. Let

$$t_1 \leq t_2 \leq \cdots \leq t_r$$

denote the ordered failure times observed under S_0, where only the first $r < n$ failures are observed and the data are subject to Type-II censoring.

After the occurrence of the r-th failure at time t_r, the stress level is increased to a higher level S_1, and the remaining $n - r$ units are observed until failure occurs. Let

$$y_{r+1} \leq y_{r+2} \leq \cdots \leq y_n$$

denote the ordered failure times observed under the accelerated stress level S_1.

Under the accelerated failure-time assumption with linear acceleration factor $A_F > 1$, the failure times observed under S_1 are transformed to the normal stress time scale according to:

$$y_{r+i} = t_r + \frac{1}{A_F}\,(t_{r+i} - t_r) = \frac{1}{A_F}\,t_{r+i} + \left(1 - \frac{1}{A_F}\right) t_r \tag{14}$$

or

$$t_{r+i} = A_F\, y_{r+i} - (A_F - 1)\, t_r, \qquad i = 1,\ 2, \ldots, n - r \tag{15}$$

This transformation expresses the failure times observed under accelerated conditions in terms of the equivalent time scale under the normal stress level.

Consequently, the combined data set

$$t_1 \leq t_2 \leq \cdots \leq t_r \leq y_{r+1} \leq y_{r+2} \leq \cdots \leq y_n$$

can be treated as failure times expressed on a common time scale corresponding to the normal operating condition. Assuming that the failure times follow an exponential distribution with mean parameter θ, the likelihood function for the combined data under the partial step-stress scheme can be expressed as

$$L(\theta,\ A_F) = \prod_{i=1}^{r} f(t_i; \theta) \prod_{i=1}^{n-r} f(A_F\, y_{r+i} - (A_F - 1)\, t_r;\ \theta)\ A_F$$

For the exponential distribution in Eq. (1), substituting this expression into the likelihood function yields

$$L(\theta,\ A_F) = \theta^{-n}\, A_F^{n-r} \exp\left[-\frac{1}{\theta}\left(\sum_{i=1}^{r} t_i + A_F \sum_{i=1}^{n-r} y_{r+i} - (A_F - 1)(n - r)\, t_r\right)\right]$$

Taking the natural logarithm gives the log-likelihood function

$$\ell = -n \ln \theta + (n - r) \ln A_F - \frac{1}{\theta}\left(\sum_{i=1}^{r} t_i + A_F \sum_{i=1}^{n-r} y_{r+i} - (A_F - 1)(n - r)\, t_r\right)$$

The parameter estimates are obtained by maximizing the log-likelihood function with respect to θ and A_F. Differentiating the log-likelihood function with respect to A_F gives

$$\frac{\partial \ell}{\partial A_F} = \frac{n - r}{A_F} - \frac{1}{\theta}\left(\sum_{i=1}^{n-r} y_{r+i} - (n - r)\, t_r\right)$$

Solving this equation yields the estimator of the acceleration factor

$$\widehat{A}_F = \frac{\theta\,(n-r)}{\sum_{i=1}^{n-r} y_{r+i} - (n-r)\,t_r} \tag{16}$$

Under the exponential model, the mean lifetime under accelerated conditions is given by

$$\theta_s = \frac{\sum_{i=1}^{n-r} y_{r+i} - (n-r)\,t_r}{n-r} \tag{17}$$

Since the AFT assumption implies

$$\theta_s = \frac{\theta_0}{A_F} \tag{18}$$

the estimator of the acceleration factor can be obtained as

$$\widehat{A}_F = \frac{\widehat{\theta}_0}{\widehat{\theta}_s} \tag{19}$$

where $\widehat{\theta}$ denotes the estimated mean lifetime under normal operating conditions and $\widehat{\theta}_s$ denotes the estimated mean lifetime under the accelerated stress level.

3.2. Confidence Interval Estimation

To quantify the uncertainty associated with the parameter estimates, confidence intervals are constructed for the mean lifetime under normal operating conditions [18]. Under Type-II censoring, the confidence interval for the parameter θ is constructed using the pivotal quantity

$$V = \frac{2T}{\theta}$$

follows a chi-square distribution with $2r$ degrees of freedom, where

$$T = \sum_{i=1}^{r} t_i + (n-r)\,t_r$$

Based on this property, the $100(1-\alpha)\%$ confidence interval for θ is given by:

$$\frac{2T}{\chi^2_{(2r);\,\alpha/2}} < \widehat{\theta} < \frac{2T}{\chi^2_{(2r);\,1-\alpha/2}} \tag{20}$$

Since the accelerated stress mean lifetime is related to the normal stress mean through the acceleration factor, the confidence interval for θ_s can be obtained by applying the same transformation to the interval bounds [6, 19].

3.3. Lifetime Percentile Estimation

To further evaluate the reliability characteristics of the tested units, lifetime percentiles are estimated based on the cumulative distribution function (CDF) of the exponential distribution. Percentile measures provide practical information regarding the proportion of units expected to fail within a specified time period and are commonly used in reliability assessment and maintenance planning [15, 20]. For an exponential distribution with mean parameter θ, the cumulative distribution function is given by

$$F(t) = 1 - \exp\left(-\frac{t}{\theta}\right)$$

Where p represents the proportion (or percentage) of units that have failed by time t_p.

$$p = 1 - e^{-t_p/\theta}$$

$$e^{-t_p/\theta} = 1 - p$$

$$-\frac{t_p}{\theta} = \ln(1-p)$$

$$t_p = -\theta \ln(1-p)$$

or equivalently

$$t_{p;\,0} = -\widehat{\theta}_0 \ln(1-p) \qquad t_{p;\,s} = -\widehat{\theta}_s \ln(1-p) \tag{21}$$

3.4. Application of Partial Step-Stress Accelerated Life Testing (ALT) on Solar-Powered Lighting Devices

Using the Maximum Likelihood Estimation (MLE) method with a total sample size of $n = 31$, where $r = 16$ failures are observed and the stress change occurs at time $t_r = 4.892$, the mean failure time under normal operating conditions can be estimated. Based on Eq. (5), the estimator of the mean lifetime under normal stress level S_0 (293 K) is given by

$$\widehat{\theta}_0 = \frac{(0.140 + 0.783 + \ldots + 4.892) + ((31-16) \times 4.892)}{16} = \frac{40.483 + 73.38}{16} = 7.116$$

Based on this calculation, the estimated mean failure time under normal conditions is $\widehat{\theta}_0 = 7.116$ (hundreds of hours), equivalent to approximately 711.6 hours.

At the time when the 16th failure occurs, the stress level is changed to $t_r = 4.892$, and the remaining units are treated as Type II censored observations. The experiment is then continued at a higher stress level, where the temperature is increased to 353 K. The mean failure time at the accelerated temperature of 353 K is estimated using the MLE as in Eq. (17):

$$\widehat{\theta}_s = \frac{(5.002 + 5.022 + \ldots + 5.717) - ((31-16) \times 4.892)}{(31-16)} = \frac{79.196 - 73.38}{15} = 0.387$$

Thus, the estimated mean failure time under accelerated conditions is $\widehat{\theta}_s = 0.387$ (hundreds of hours) or approximately 38.7 hours.

A comparison of the estimated mean failure times at both stress levels indicates the presence of linear acceleration between the first and second stress stages. The acceleration factor is estimated as the ratio of the mean failure times under normal and accelerated conditions based in Eq. (19):

$$\widehat{A}_F = \frac{\widehat{\theta}_0}{\widehat{\theta}_s} = \frac{7.116}{0.387} \approx 18.354$$

The acceleration factor is estimated as $\widehat{A}_F = 18.354$ indicating that failure occurs about 18 times faster at 353 K compared to 293 K. The strong temperature dependence observed in this study underscores the importance of thermal management in solar-powered lighting devices. Elevated temperatures accelerate degradation processes such as battery aging, reduced LED efficiency, and increased thermal stress on electronic control components, leading to a substantial reduction in mean failure time under accelerated conditions. Accordingly, the estimated acceleration factor reflects both the statistical scaling effect of temperature and the underlying physical mechanisms governing system degradation.

Accordingly, the failure rate function of solar-powered lighting devices under normal operating conditions based in Eq. (11). Indicates that the failure rate of solar-powered lighting devices operating at the normal temperature level (293 K) is approximately 0.141 failures per hundred operating hours.

$$h_o(t) = \frac{1}{\widehat{\theta}_0} = \frac{1}{7.116} \approx 0.141$$

The failure rate function of solar-powered lighting devices under accelerated stress based in Eq. (13). This result indicates that the failure rate under accelerated temperature (353 K) conditions is approximately 2.579 failures per hundred operating hours.

$$h_s(t) = 18.354 \times 0.363 \approx 2{,}579$$

This significant increase reflects the strong influence of elevated temperature on the degradation process of solar-powered lighting devices. The $(1-\alpha)100\%$ confidence interval for the parameter $\widehat{\theta}$ using Eq. (20) is given by:

$$\Leftrightarrow \frac{2(113.863)}{\chi^2_{(32);\,0.025}} < \widehat{\theta} < \frac{2(113.863)}{\chi^2_{(32);\,0.975}} \quad \Leftrightarrow \quad 4.602 < \widehat{\theta} < 12.45 \quad \text{(hundreds of hours)}$$

This result indicates that, with 95% confidence, the mean time to failure (MTTF) of solar-powered lighting devices under normal operating conditions lies between 460.2 and 1,245 hours. It is constructed using only the first r observed failures occurring under the initial stress level. Therefore the interval estimation relies primarily on the failure-time information obtained prior to the stress increase.

The failure behavior of solar-powered lighting devices as in Eq. (21) is given:

a. 10th Percentile
   Normal condition (293 K): $t_{0.10;\,0} = -7.116 \ln(1-0.10) \approx 0.7498$
   Accelerated condition (353 K): $t_{0.10;\,s} = -0.387 \ln(1-0.10) \approx 0.0408$
   Approximately 10% of the solar-powered lighting devices are expected to fail before 75 hours at 293 K and before 4 hours at 353 K.
b. 50th Percentile
   Normal condition (293 K): $t_{0.50;\,0} = -7.116 \ln(1-0.50) \approx 4.931$
   Accelerated condition (353 K): $t_{0.50;\,s} = -0.387 \ln(1-0.50) \approx 0.268$
   Approximately 50% of the solar-powered lighting devices are expected to fail before 493 hours at 293 K and before 26 hours at 353 K.
c. 95th Percentile
   Normal condition (293 K): $t_{0.95;\,0} = -7.116 \ln(1-0.95) \approx 21.319$
   Accelerated condition (353 K): $t_{0.95;\,s} = -0.387 \ln(1-0.95) \approx 1.160$
   Approximately 95% of the solar-powered lighting devices are expected to fail before 2,132 hours at 293 K and before 116 hours at 353 K.

A comparison of failure times across all percentiles demonstrates that the relationship between normal operating conditions (293 K) and accelerated conditions (353 K) is proportional. This finding indicates that the acceleration factor remains constant across the entire stress range, which is consistent with the assumptions of the exponential distribution-based life–stress model. In this model, increasing the stress level affects the scale parameter without altering the fundamental shape of the lifetime distribution.

These results imply that product design should prioritize thermal management and component selection to withstand temperature-induced degradation. For maintenance, the estimated percentile lives, such as the 50th percentile (493 hours at 293 K), enable proactive scheduling of replacements in field deployments. A key limitation of this study is the assumption of a constant failure rate via the exponential distribution, which may not capture wear-out failure modes. Future work should consider distributions like the Weibull and incorporate additional stress factors for a more comprehensive reliability assessment.

4. Conclusion

This study successfully demonstrates the application of a partial step-stress accelerated life testing (ALT) model to assess the reliability of solar-powered lighting systems. By employing a two-level step-stress scheme with Type-II censoring and assuming an exponential lifetime distribution, the research effectively quantifies the impact of elevated thermal stress on device longevity. The analysis reveals a significant acceleration effect, with the mean failure time reducing from approximately 711.6 hours under normal operating conditions (293 K) to about 38.7 hours under accelerated stress (353 K), corresponding to an acceleration factor of 18.354. The constructed confidence intervals and derived percentile lives provide crucial metrics for predicting failure behavior and planning maintenance schedules. The proposed methodological framework offers a robust, time-efficient, and cost-effective alternative to traditional life testing, particularly for systems where failures are rare under normal use. The findings have direct implications for manufacturers and engineers in the renewable energy sector, enabling more informed reliability predictions, design improvements, and warranty analyses for sustainable lighting infrastructure. For future research, a more comprehensive interval estimation could be obtained by using the Fisher Information matrix for the parameters, which would allow the construction of asymptotic confidence intervals that incorporate information from both the normal-stress and accelerated-stress failure times.

CRediT Authorship Contribution Statement

Ardi Kurniawan: Conceptualization, Methodology, Supervision. **Vanisia Suci:** Resources, Investigation, Writing-original draft, Conceptualization, Validation. **Yovita Karin:** Writing-review & editing, Formal analysis.

Declaration of Generative AI and AI-assisted Technologies

During the preparation of this work, Generative AI tools (specifically ChatGPT) were used solely for language refinement and grammar editing purposes. No part of the analysis, interpretation, or core content was generated by AI. All substantive results and discussions were manually developed by the authors.

Declaration of Competing Interest

The authors declare no competing interest.

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Data Availability

The dataset used in this study was obtained from the journal *Inference on the Triple Modular Redundancy System*, which serves as the primary source of the data analyzed in this research. Further details regarding the data are discussed in Section 2.1 of this paper.

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