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Novel Statistical Techniques for Conducting Accelerated Life Test to Demonstrate Product Reliability

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ABSTRACT

In Reliability Demonstration Testing (RDT), finding the right sample size is very important since the cost of the prototypes is high and difficult to make. If the sample size for the RDT is test is less, the amount of information obtained from the test will be insufficient, and the conclusion will be meaningless; on contrary, if the sample size is big/huge, the amount of information obtained from the test will be in excess of what is required, resulting in unnecessary costs.

Most of the time, the required sample size and test time are decided based on the RDT test design. Resources required for RDT in terms of batch size and long testing-time is practically not feasible, due to limitation of the project schedule and budget. The reliability engineers must have a sound knowledge of type challenge/risk that is allowed for conducting RDT. The research paper with a case study provides the required information about the modern techniques adopted in reducing the sample-size and testing time with the help of accelerated test models such as Arrhenius, Erying etc., for conducting accelerated life test to demonstrate the product reliability.

Keywords: Confidence level; Significance level; Producer risk; Consumer risk; Accelerated life testing; Reliability demonstration testing; Sample size; Mean time to failure

NOMENCLATURE

TTF	Time to Failure
ALT	Accelerated Life Testing
R(t)	System Reliability
θ	Scale Parameter
β	Shape Parameter
RDT	Reliability Demonstration Test
CL	Confidence Level
CI	Confidence Interval
DOF	Degree of Freedom

1. INTRODUCTION

In general, there are multiple ways to determine the right sample size for conducting Accelerated Life Testing of the product. The research paper discusses two main approaches for determining the right sample size for validating product reliability. "The first one is based on Confidence Intervals (CI), which is also referred to in this paper as the estimation approach and the second one is called Type I and Type II errors."

One of the most important questions when designing a RDT is identifying correct batch size. RDT and ALT are well-known concepts however presently industry is using ALT to reduce test time for RDT, while doing RDT the selection of correct sample size and test duration are indiscriminate/focused more on test time alone. The research paper has brought the process of selecting the right sample size for conducting ALT. It also explains a case study of QTRMs which is considered for demonstration of product reliability and is been deliberated in the manuscript.

The manuscripts also highlight the challenges involved in finalizing the correct sample size along with test duration for conducting RDT using the ALT technique and displaying the data points on the various probability plots were brought out carefully along with the test results for different samples sizes. If the sample is too large unnecessary costs will incur, if the sample is too small results will not be accurate.[5]

2. DETERMINATION OF BATCH-SIZE BASED ON THE RISK-CONTROL TECHNIQUE

There are two types of risk that are there in the reliability demonstration test, they are producer risk(α), the probability of incorrectly rejecting the reliability specification and consumer risk (β) is the probability of incorrectly accepting the reliability specification.1-β is known as the power of the test. The aforesaid statements are summarised in the Table 1.

Table1. Summary of Type I and Type II errors

	When H0 is true	When H1 is true
Do not reject H0	Correct Decision (Probability=1-α)	Type II error (Probability=β)
Reject H0	(Probability=α)	Correct decision (Power=1-β)

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Here, H_0 is known as a null-hypothesis, means that unit/product achieved the targeted dependability requirement and H_1 is known as an alternative-hypothesis, means the unit/product does not meet the system dependability requirement. If the batch-size increases both consumer and producer, risk decreases. Batch-size can be calculated depending on producer and consumer risk by using simulation (Trial and Error method using Microsoft Excel).

A one- and two-failure-mode system reliability and survivability model with applications to complete and censored datasets.[1]

Reliability evaluation and analysis of CNC camshaft grinding machine.[2]

Failure Censoring and Demonstration Tests with Log-Location-Scale Distributions: Sample Size and Number of Failure Requirements.[6]

2.1 Non-Parametric Binomial Reliability Demonstration Test

The first stage in RDT is to establish batch-size which is required towards presenting a certain level of dependability-reliability at a certain "C.L" along with test time with an acceptable number of failures. The below-given equation is used when the reliability demonstration time is equal to the test time of the product as a part of the reliability demonstration test.

$$1-CL=\sum_{k=0}^{n}\binom{n}{k}(1-R)^{k}R^{n-k} \tag{1}$$

where,

'CL' stands for confidence level,

'f' stands for the number of failures.

The sample size is denoted by the letter 'n.'

The letter 'R' stands for shown dependability.

1-CL is the significance level or risk level.

In the above equation, four unknowns are there if three parameters are available, then the other unknown can be calculated easily. The outcome of the reliability calculation as per Eqn. (1), the test can be either the producer or consumer risk.

2.2 Parametric Binomial RDT

In the non-parametric Binomial Reliability Demonstration test, the time factor/element is not considered. Non-parametric testing is usually used for one-shot devices where time is-not an issue or where the unit testing schedule/period is same to the needed demonstration test time. In the majority of cases, product testing takes less time than dependability demonstration. In those circumstances, we'll assume some failure distributions as part of the test plan to account for time.

2.3 Exponential Chi-Squared-RDT

The exponential-Chi square models is mostly used for non-repairable systems and the assumption of a same-constant failures over time (memoryless property). The exponential chi-square technique is based to calculate test time at a given sample size, confidence level, acceptable number of failures, and MTTF.

For step-down stress accelerated life experiments, a novel statistical approach has been developed[7]

$$\chi^2_{1-cl,2f+2}=\frac{2Tn}{MTBF} \tag{2}$$

$\chi^2_{1-cl,2f+2}$: The 1-CL significance level and 2f+2 is DOF

where,

f : Acceptable number of failures

n : Sample size

MTTF: Mean time to failure

T : Test duration

Eqn. (2) consists of five variables (CL, *f*, n, T, and MTTF). If we know first-four, then another parameter can be calculated easily. For the case of the exponential distribution, MTTF can be calculated using demonstrated reliability.

Since, MTTF = −t/ln(R).

Not when the beta is equal to 1 Weibull distribution converts to the exponential distribution. For zero failures both will give the same results. This is because

$$\chi^2_{1-cl}=-2\ln(1-CL) \tag{3}$$

The binomial equation becomes

$$1-CL=R^n \rightarrow \chi^2_{1-cl,2f+2}=\frac{2Tn}{MTBF} \tag{4}$$

2.4 WeiBayes Approach

One-parameter Weibull distribution is a one-parameter version. The important benefit of the one-parameter Weibull distribution is its capacity to version merchandise with growing failure charge, regular failure charge and reducing failure charge in lifestyles facts analysis. WEIBAYES distribution is primarily based totally on the Weibull distribution, however it assumes that the form parameter (β), is an acknowledged value. This distribution is called the "WeiBayes" distribution which is a combination of Weibul and Bayes theorem and here β is priory.

The benefit of this distribution over the two-parameter Weibull is that its miles extra strong for small sample size. In this technique, we can assume the β value from a similar failure mechanism. This may be primarily based on preceding similar tests, remarks and engineering knowledge that will allow us to assume β value which is commonly used as 1.3 for the low fatigue failure mechanism. Here in WeiBayes, we will attempt some viable values of β and discover the effect of predictions.

Figure 1 shows one-parameter Weibull opportunity plots with various assigned-values of β = 1.15, β = 1.2 and β = 1.3 and two-sided 90 % self-assurance bounds on reliability.

Reliability Engineering & System Safety, Bayesian framework for subsea processing system reliability prediction accounting for contributing factors uncertainty.[3]

3. CASE STUDY OF X-BAND QTRM

TRMs Modules are the fundamental components of AESA phased array radars. The T/R modules receive Radio Frequency (RF) signals, amplify them, and transfer the boosted energy to antenna components in transmit mode. The T/R Module receives reflected energy from antenna components in Rx mode, down converts, and processes the data to identify targets.

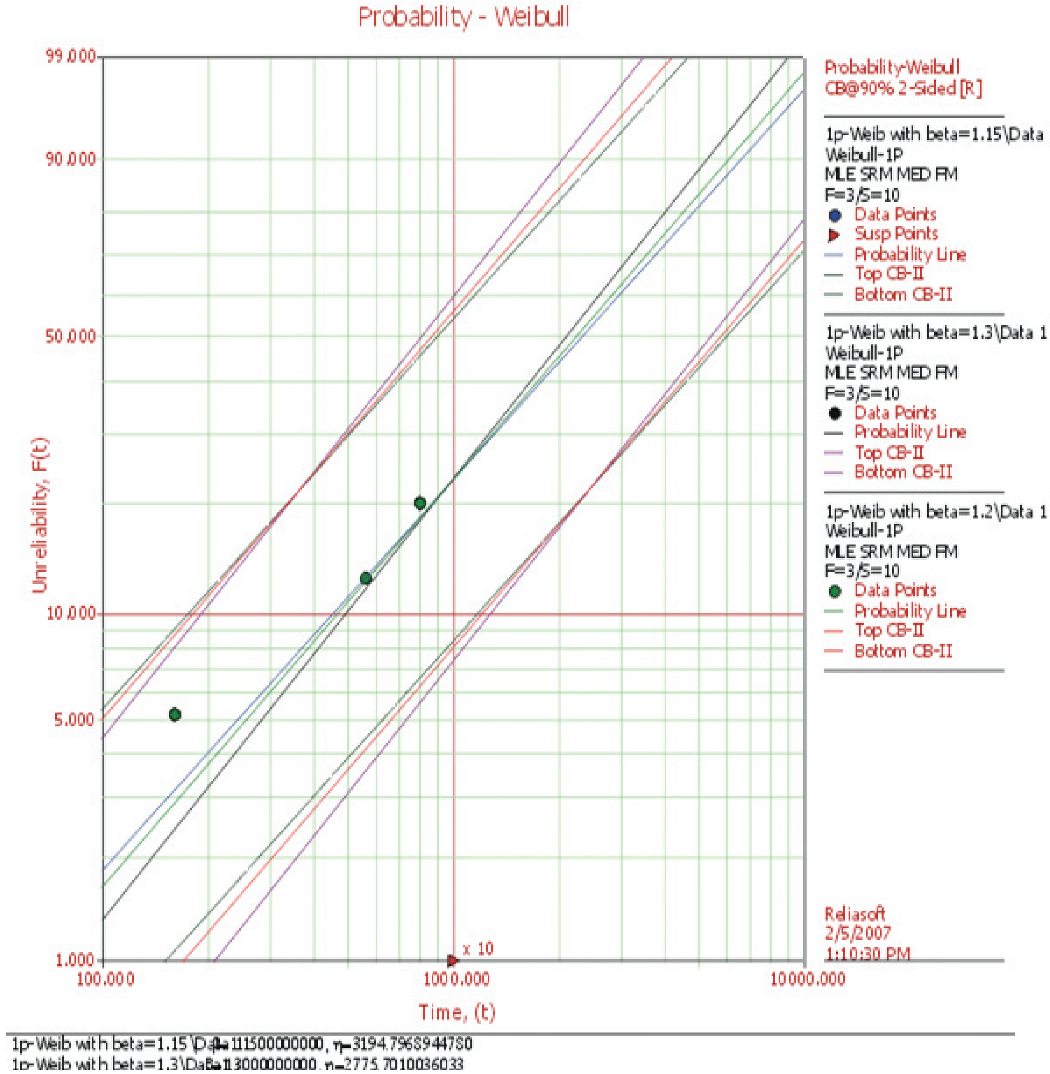
Quad-TRM or QTRM is a package that contains four T/R modules in one package. Figure 2 below shows an RDT of QTRMS using the ALT Technique.

3.1 MTBF Validation Procedure

The Reliability demonstration test, i.e., Acceleration Life Test, should be conducted to validate MTBF.

Accelerated DC-link Capacitor Testing in Photovoltaic Inverters Using Profiles. Methods of Reliability Demonstration Testing and Their Relationships[4].

Methods of Reliability Demonstration Testing and Their Relationships[8]



(Courtesy "Reliability Hotwire e-magazine Issue 72 Feb 2007")

Figure 1. Short- Data analyzed with one-parameter Weibull and different β values.

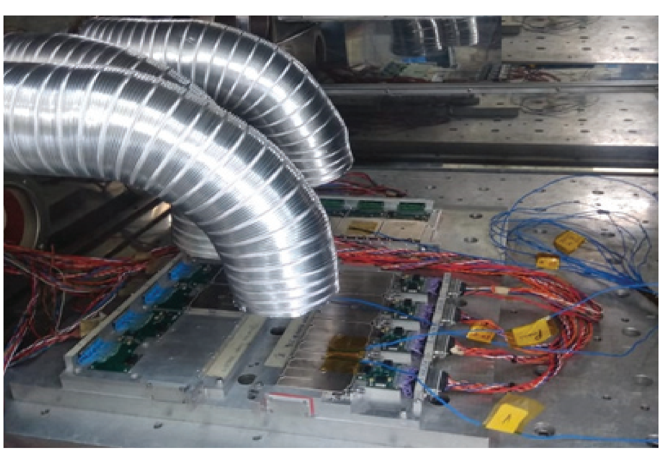


Figure 2. ALT testing of QTRMs.

Acceleration Life Test can be modelled using any one of the stress models (Arrhenius, Eyring, etc.). The test is designed based on the available parameters like MTBF, confidence level, sample size and several failures that can affordable. The test time is calculated using Exponential Chi-Square estimation and the formula is as follows:

$$Test\,Time = \chi^2_{1-cl,2f+2} * \frac{MTBF}{2*n*AF} \quad (5)$$

where,

f = number of failures that can affordable
CL = Confidence Level
AF = Acceleration Factor calculated using stress model

If the system satisfies the designed test case, then it achieves the target MTBF i.e., several failures during the ALT are less than equal to the number of failures specified in the test case.

Using (PSO and MLE), a novel statistical method for step-down stress accelerated life experiments has been developed.[9]

For evaluation of QTRM MTBF, the test case is designed using the Arrhenius model. For calculating the acceleration factor, the activation energy for the system is assumed as 0.4318eV.

The test should be conducted at rated temperature conditions i.e., 90 °C and using an accelerating factor the MTBF for normal operating temperature i.e., 40 °C can be evaluated. The acceleration factor is calculated using the below formula.

$$Acceleration\ Factor\,(AF) = e^{(Ea/k)(1/T1-1/T2)} \tag{6}$$

AF= 20.0

where,

Ea = Activation energy
K = Boltzman constant in eV/Kelvin
T1 = Normal operating temperature in Kelvin
T2 = Rated temperature in Kelvin
Target MTBF = 45555

Table 2. Critical parameters of ALT

1/T1	0.003195
K	8.62E-05
Ea	0.587
Ea/K	6812.116
N	20

3.1.1 Accelerated Test Specification with Number of Failures

Table 3 shows ALT specification with an accelerated temperature towards RDT testing of QTRMs modules and test time.

Table 3. ALT test specification

MTBF T0 (40°C)	Temp (°C)	AF	T(hr) @ f=0	T(hr) @ f=1	T(hr) @ f=2	T(hr) @ f=3	T(hr) @ f=4	T(hr) @ f=5
45555.0	60.0	3.7	1846.4	2923.8	3880.4	4778.9	5641.7	6479.6
45555.0	65.0	5.0	1364.3	2160.4	2867.1	3531.0	4168.5	4787.7
45555.0	70.0	6.7	1017.0	1610.4	2137.2	2632.1	3107.4	3568.9
45555.0	75.0	8.9	764.5	1210.6	1606.7	1978.7	2336.0	2682.9
45555.0	80.0	11.8	579.4	917.5	1217.6	1499.6	1770.3	2033.2
45555.0	85.0	15.4	442.5	700.7	930.0	1145.3	1352.1	1552.9
45555.0	90.0	20.0	340.5	539.2	715.5	881.2	1040.3	1194.8
45555.0	95.0	25.9	263.8	417.8	554.5	682.9	806.2	525.9
45555.0	100.0	33.1	205.9	326.0	432.6	532.8	629.0	722.5
45555.0	105.0	42.2	161.7	256.0	339.8	418.5	494.0	567.4
45555.0	110.0	53.4	127.8	202.4	268.6	330.8	390.5	448.5

Some Practical Guidelines For Planning An Accelerated Life Test.[14]
Accelerated Testing based Models, Test Plans and Data Analysis.[15]
Censored Weibull Regression Data from Accelerated Life Tests Accuracy of Approximate Confidence Bounds.[18]
Overview and Prospected Design of Accelerated Life Test Plans.[19]

From Fig. 3, we can observe that test duration also increases as the number of failures increases. At zero number of failures, the test duration is 340.45 hrs.

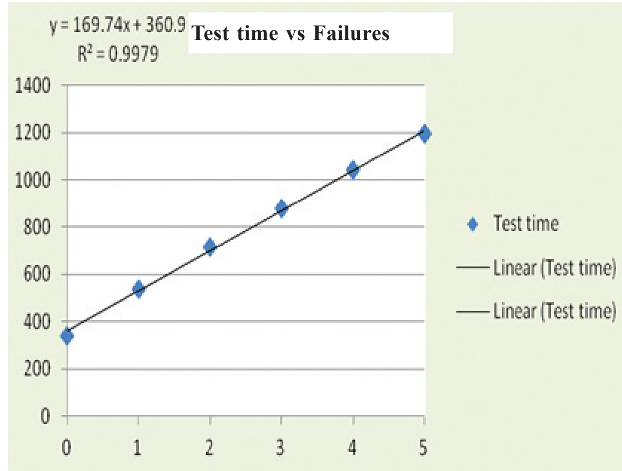


Figure 3. Test time V/s Failures

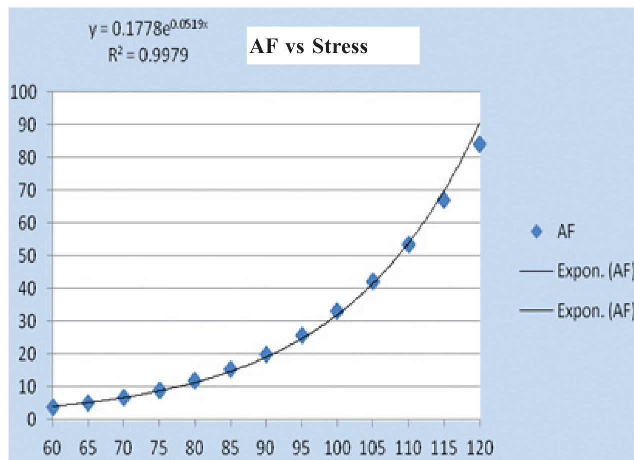


Figure 4. Acceleration Factor V/s Stress.

Figure 4 depicts the Acceleration Factor v/s. Stress which was plotted for a constant use level of 40 °C. Since the value of the AF at 40 °C is equal to 1. The acceleration factor for a temperature of 90 °C is approximately 20.0. This means that the life at the use level of 40°C is twenty times higher than the life at 90 °C.

3.1.2 TTF Data Analysis

- Monte Carlo simulation is used to create the time to failure data. in Microsoft excel by assuming the shape and scale of a Weibull distribution parameters of 1 and 857 hrs. for a sample size of 5.
- The scale parameter is equal to the time. 63.2 % of failures will occur so the scale parameter is considered as 63.2% of test time 1356 hrs. Calculated using chi-square distribution.
- This time to failure data is right-censored data.

Table 4. TTF Data using MS excel for random 5 samples

Θ	B	
857	1	
R(t)	TTF	Censor
0.49667	599.754	1
0.859152	130.100	1
0.601842	435.151	1
0.922885	68.774	1
0.533167	538.986	1

- Using Minitab software life data is done to find the best fit distribution and corresponding distribution parameter by taking the least square as the parameter estimation method.

A Comparison of Approximate Confidence Interval Procedures for Type I Censored Data and a Review of Accelerated Test Models.[10-11]

A Comparison of Type I Censoring and Accelerated Life Test Plans for Weibull and Lognormal Distributions.[12]

Weibull and Extreme Value Distributions: Optimized Accelerated Life Tests.[13]

For Normal and Lognormal Life Distributions, Theory for Optimized Censored Accelerated Tests.[16]

For Weibull and Extreme Value Distributions, Theory for Optimized Censored Accelerated Life Tests.[17]

- Goodness-of-Fit

Table 5. Goodness-of-Fit for various types of Distribution- Five samples

Distribution	Anderson-Darling(adj)	Correlation Coefficient
Weibull	2.474	0.957
Lognormal	2.533	0.932
Exponential	2.706	*
Log logistic	2.562	0.929
3-Parametric Weibull	2.481	0.958
3-Parametric Lognormal	2.442	0.951
2-Parametric Exponential	4.617	*
3-Parameter Log logistic	2.467	0.947
Smallest Extreme Value	2.413	0.954
Normal	2.442	0.951
Logistic	2.467	0.947

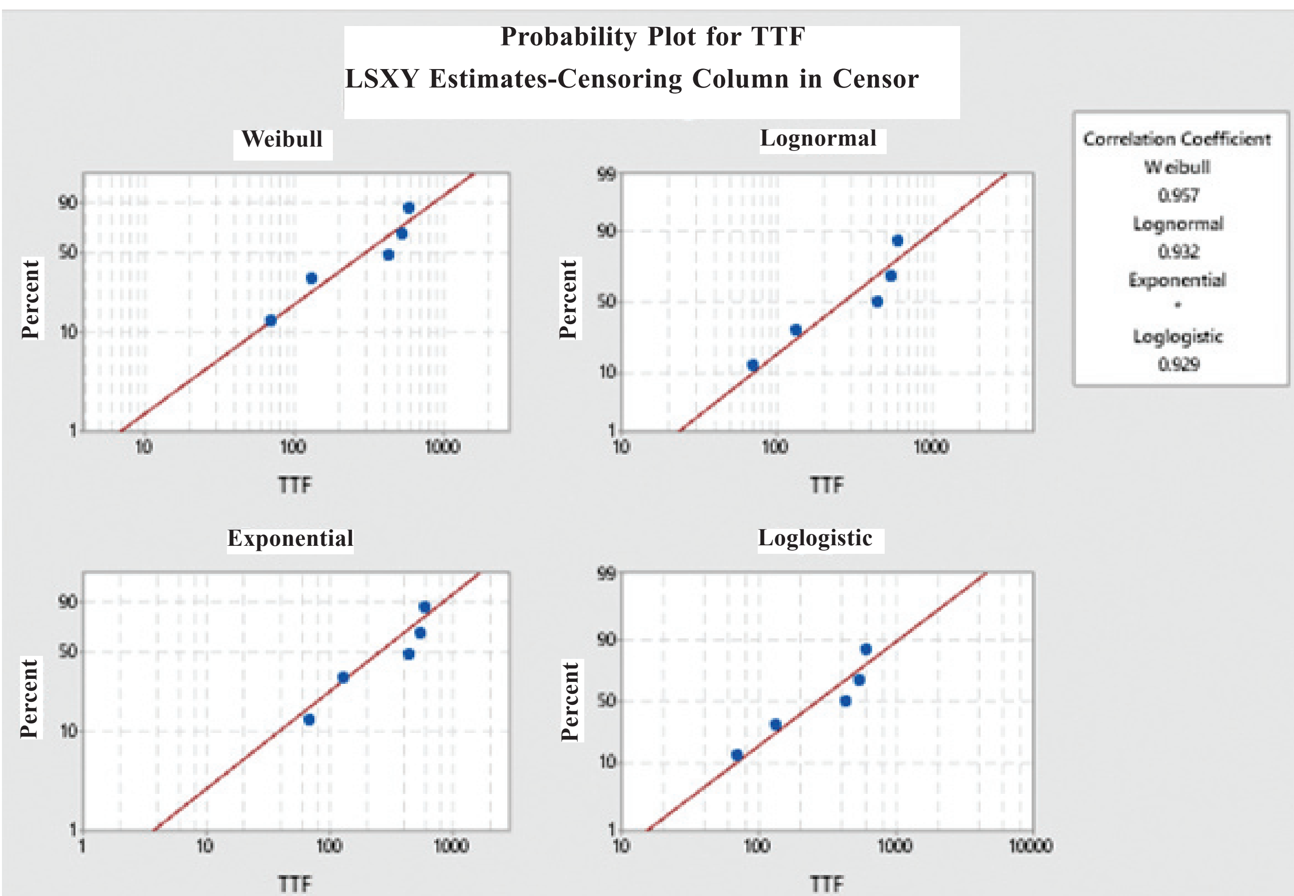


Figure 5. Probability plot of Time to Failure (TTF) for five samples.

Figure 5 depicts the probability plot of TTF for five samples fitted on various distributions showing corresponding correlation coefficient, the plots indicate Weibull has correlation coefficient close to one.

- Goodness-of-Fit

Distribution	Anderson-Darling(adj)	Correlation Coefficient
Weibull	2.474	0.957

4.1 Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution: Weibull

Parameters Estimates

Parameter	Estimate
Shape	1.12080
Scale	407.559

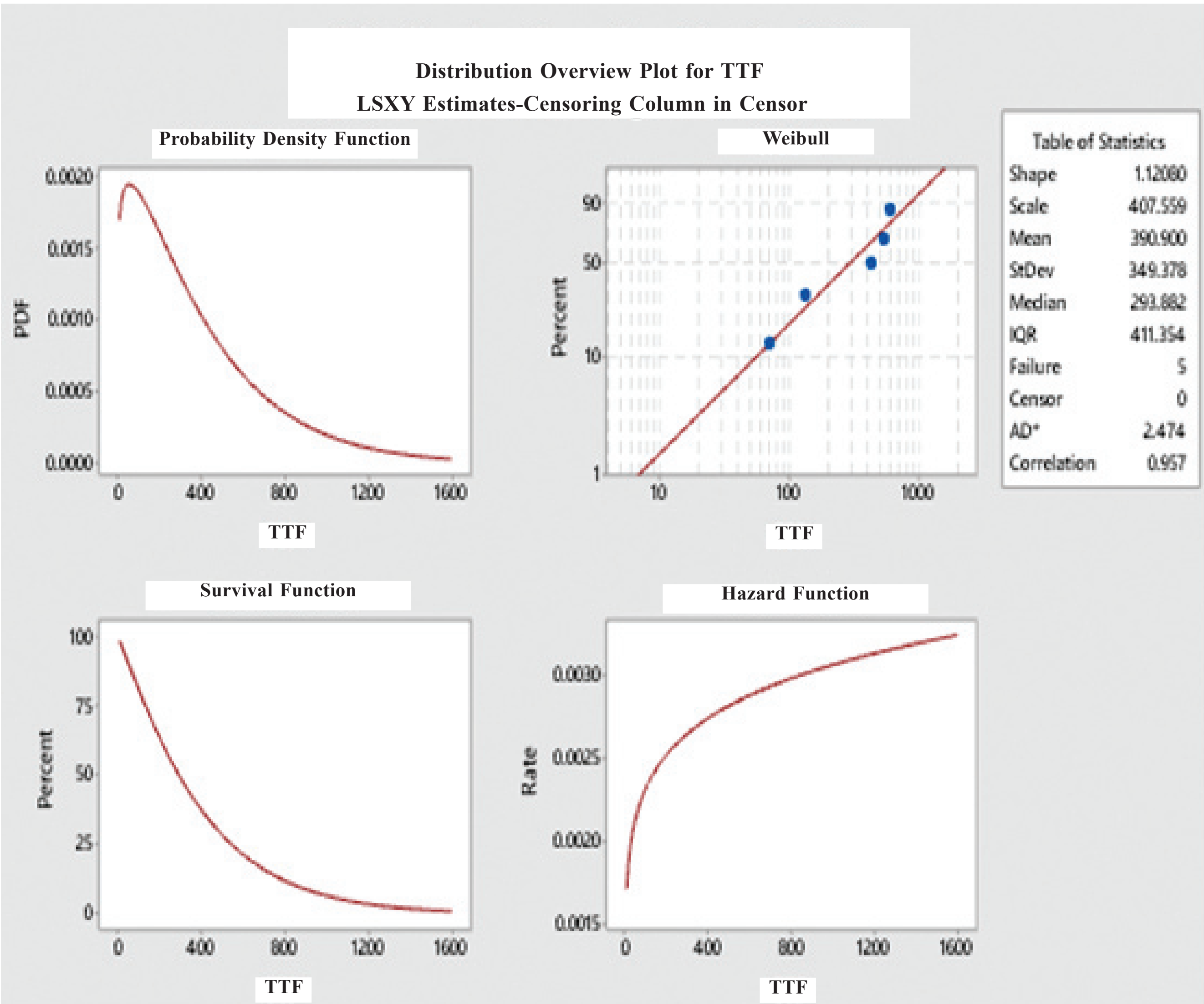


Figure 6. Distribution overview plot for TTF-5 samples.

Figure 6 shows distribution overview plot for Weibull and its parameters Viz., Shape, Scale, Mean, Std Deviation, median, IQR etc., for TTF of five samples.

4. OBSERVATIONS

- From the above figure we can observe the correlation coefficient of various distributions and we can say that the better fit is the Weibull distribution for data plotted.
- The time to failure "data-points" is right-censored data.

Censoring

Censoring Information	Count
Uncensored Value	5
Censoring Value	0

Log-likelihood = -34.145

Characteristics of Distribution

Table 6. MTTF and characteristics of distribution of five samples

	Estimate
Mean (MTTF)	390.900
Standard Deviation	349.378
Median	293.882
First Quartile (Q1)	134.098
Third Quartile (Q3)	545.452
Interquartile Range (IQR)	411.354

Table of survival probabilities

Time	Probability
1357	0.0212732

Case 2

- Time to failure data were created in this scenario using Monte Carlo simulation in Microsoft Excel, assuming a Weibull distribution with shape and scale parameters.of 1 and 214 hrs. for a sample size of 20.
- The scale parameter is equal to the time, 63.2 % of failures will occur so the scale parameter is considered as 63.2 % of test time 340 hrs. Calculated using chi-square distribution.
- This time to failure data is right-censored data.

Table 7. TTF Data using MS Excel for random 20 samples

Θ	β	
214	1	
R(t)	TTF	Censor
0.554019	126.8988	1
0.988008	2.5925	1
0.72825	68.14066	1
0.641691	95.33126	1
0.81083	45.05976	1
0.524559	138.6401	1
0.486268	154.9273	1
0.215728	329.5692	1
0.474099	160.3734	1
0.829438	40.18404	1
0.398483	197.7088	1
0.905458	21.34068	1
0.794047	49.55393	1
0.342079	230.5044	1
0.981508	4.01066	1
0.419645	186.59	1
0.039101	696.556	0
0.950108	10.9974	1
0.466252	163.9599	1
0.634761	97.66442	1
0.524559	138.6401	1

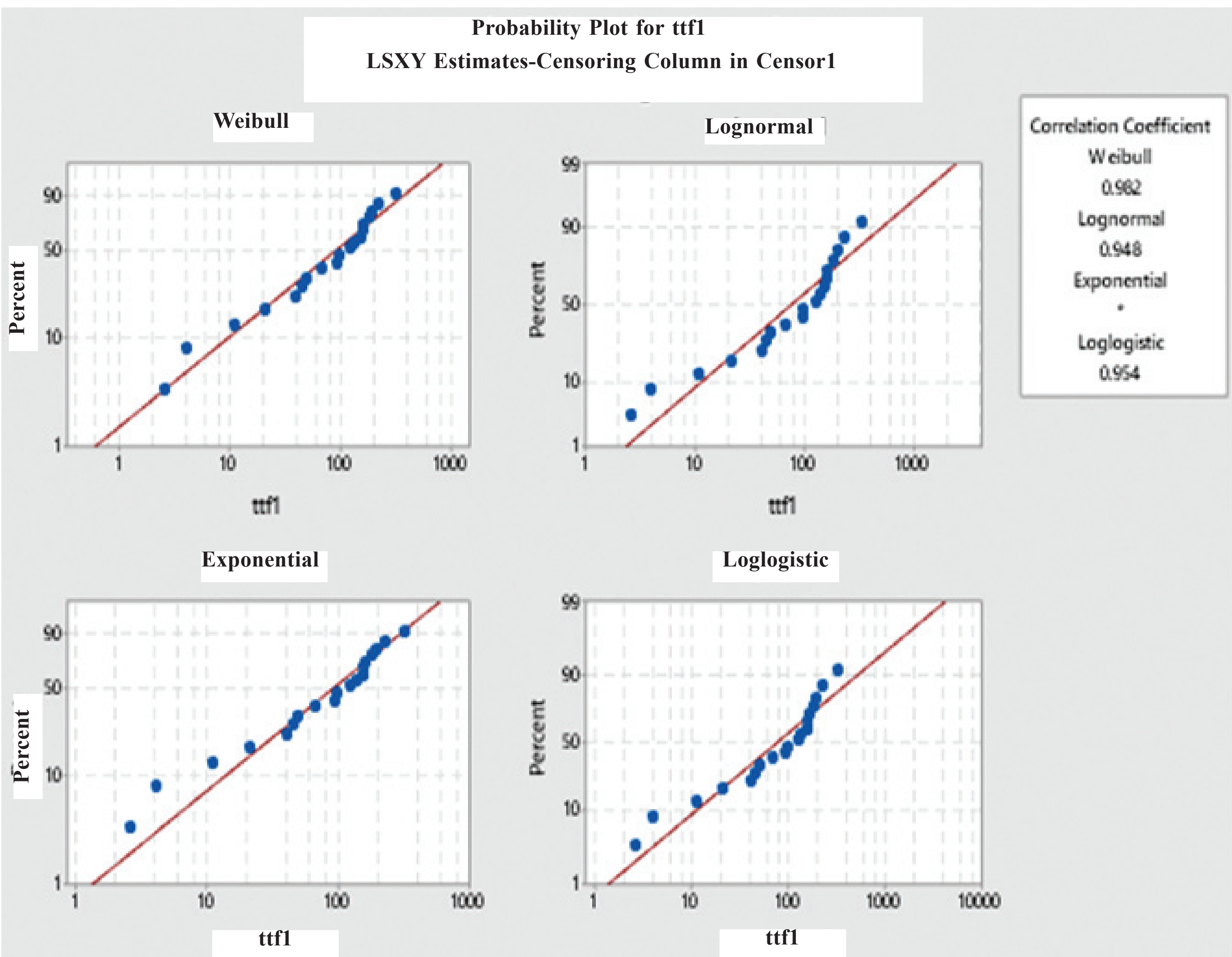


Figure 7. Probability plot for TTF-20 samples

Figure 7 depicts the probability plot of TTF for twenty samples fitted on various distributions showing corresponding correlation coefficients, the plots indicate Weibull has a correlation coefficient close to one.

- Goodness-of-Fit

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	3.454	0.982

- Goodness-of-Fit

Table 8. Goodness-of-Fit for various types of distribution-twenty samples

Distribution	Anderson-Darling (adj)	Correlation Coefficient
Weibull	3.454	0.982
Lognormal	3.795	0.948
Exponential	3.454	*
Log logistic	3.754	0.954
3-Parametric Weibull	3.359	0.986
3-Parametric Lognormal	3.358	0.986
2-Parametric Exponential	4.034	*
3-Parameter Log logistic	3.400	0.982
Smallest Extreme Value	5.282	0.902
Normal	3.571	0.957
Logistic	3.533	0.950

Figure 8 shows a distribution overview plot for Weibull and its parameters viz., Shape, Scale, Mean, Std Deviation, median, IQR etc., for TTF of five samples.

Censoring

Censoring Information	Count
Uncensored Value	19
Right Censoring Value	1

Censoring value Censor=0

4.2 Estimation Method: Least Squares (failure time(X) on rank(Y))

Distribution: Weibull

Parameters Estimates

Parameter	Estimate
Shape	0.842912
Scale	138.412

Log-likelihood = -113.736

Characteristics of Distribution

Table 9. MTTF and characteristics of distribution-twenty samples

	Estimate
Mean(MTTF)	151.383
Standard Deviation	180.449
Median	89.6055
First Quartile(Q1)	31.5681
Third Quartile(Q3)	203.923
Interquartile Range(IQR)	172.355

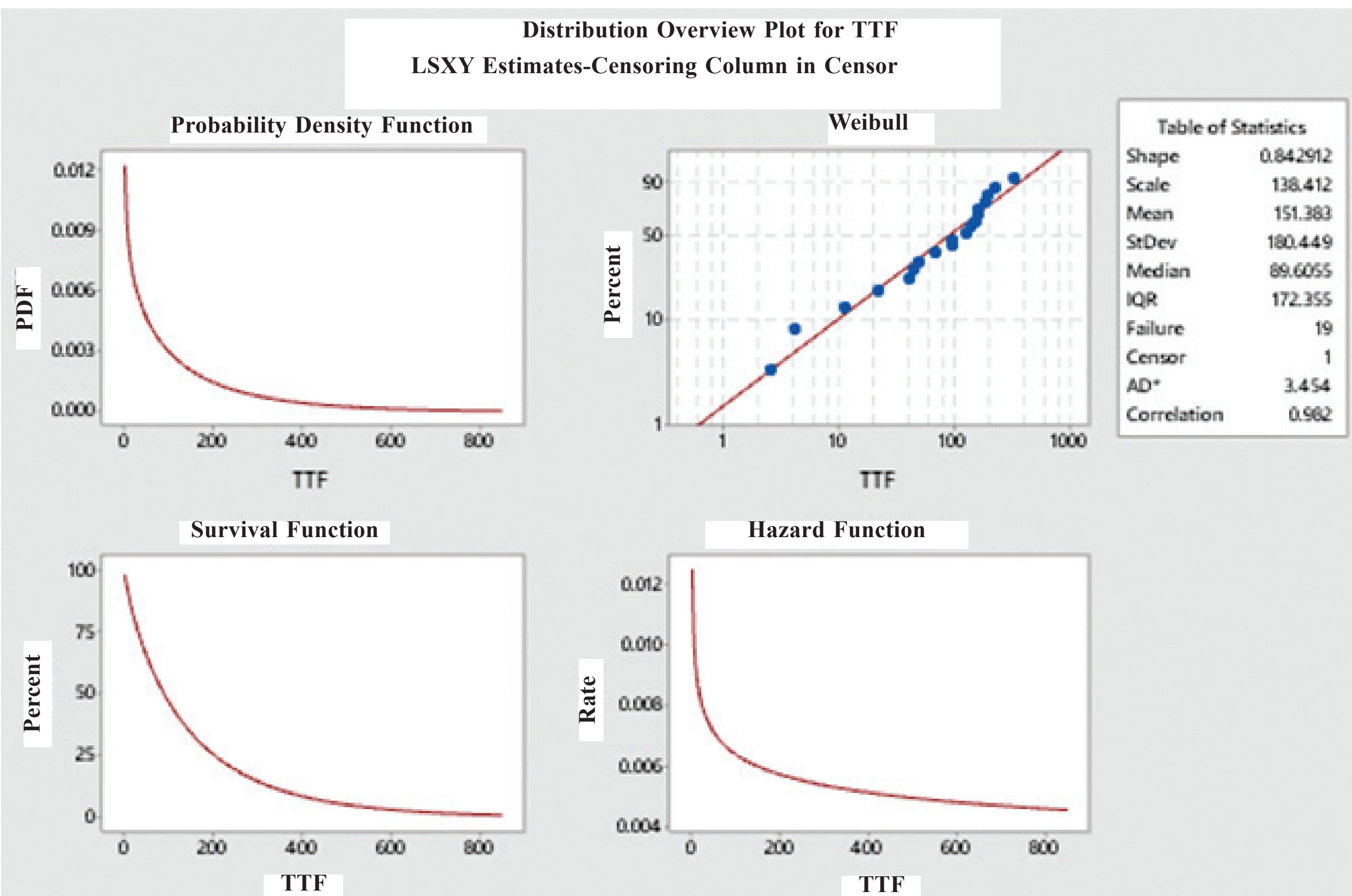


Figure 8. Distribution overview plot for TTF for twenty samples.

Table of Survival Probabilities

Time	Probability
340	0.118480

5. RESULTS AND INFERENCE

- From the above two cases we can observe that as the sample size increases test duration decreases.
- By taking five sample coefficients of correlation is 0.957 and for 20 sample sizes 0.982.

Table 10. Reference and conclusion of RDT for five and twenty samples

Parameters (Weibull)	N=5 samples	N=20 samples
MTTF	391 hrs.	151 hrs.
Correlation coefficient	0.957	0.982
Shape	1.12	0.843
Scale	408 hrs.	138hrs.

- From Table 10, we can conclude that 20 samples time to failure data is better fitting than 5 samples by comparing the coefficient of correlation values.
- From the above table, we can conclude that log-likelihood is more for 20 sample data as compared to five sample data, therefore twenty samples are recommended for conducting ALT test for demonstration of QTRMs reliability.

Note: From the above observations, we can conclude that the higher the samples better the fitting and failure analysis.

6. CONCLUSIONS

In this paper, different methods where used to calculate the right sample size for reliability demonstration testing. The paper mainly focuses on the risk control approach for finding the correct sample size. The Novelty in Research work is if the objective of the reliability test is to evaluate and define product/system reliability measures, then the estimation approach is advisable. On the other hand, If the objective of the test is to demonstrate a specific product/system reliability, then the risk control approach can be used. The outcome of the research has helped in developing a process for the selection of the right sample size and test duration for conducting ALT on QTRMs for product reliability demonstration.

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