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Evaluation of Sampling Inspection Plans for Life-tests Based on Generalized Gamma Distribution

R. Vijayaraghavan[1*], K. Sathya Narayana Sharma[2] and C. R. Saranya[3]

Department of Statistics, Bharathiar University, Coimbatore 641046, INDIA

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***Abstract*:** Acceptance sampling is concerned with rules for deciding about the acceptance or rejection of a lot of products submitted for inspection based on the quality of the products assessed through the testing of items drawn randomly from the lot. Sampling inspection plans which are used for taking decisions about the acceptability of the product with respect to life time are called life-test sampling plans. Lifetime of the product is considered as a continuous random variable, which is modelled by a probability distribution. The literature of sampling inspection for lifetime data provides applications of various types of continuous distributions in the studies relating to the design and evaluation of life-test sampling plans. This paper presents the procedures and tables for the selection of life-test sampling plans under the conditions for application of the generalized gamma distribution. The criteria for designing life-test plans when lot quality is evaluated in terms of mean life and hazard rate are proposed.

Keywords: *Acceptable mean life, Hazard rate, Generalized Gamma Distribution, Mean life, Reliability sampling.*

I. INTRODUCTION

Statistical product control is the methodology that consists of procedures with which acceptability or non-acceptability of a lot of finished items can be determined by the inspection of one or more samples of items drawn randomly from the lot. Most often, the perception of producers as well as consumers about the quality of the items is greatly influenced by the efficacy of items for a certain length of time, and hence, the lifetime of an item becomes an important quality characteristic and its assessment turns into an imperative aspect in product control. The process of assessing the lifetime of the product or item through experiments is called a life-test. Sampling inspection procedures that are adopted for taking decisions on the disposition of the lot(s) of items based on the assessment of quality using lifetimes of the items as the quality variables are known as the life-test or reliability sampling plans.

Under a life-test sampling plan, the test units, which are subjected to a set of test procedures, are randomly selected from the lot, and the lot is either accepted or rejected based on the information provided by the test results. A specific life-test sampling plan can be developed considering the lifetime of the products as the quality characteristic, which is modelled by an appropriate continuous-type probability distribution. Life-test sampling plans usually focus on the objective of determining whether the lifetimes of items reach the specified standard or not based on the observations made from the sampled lifetime data. A central feature of a life-test plan is that it involves the lifetime characteristic as the random variable which can be more adequately described by the exponential, Weibull, lognormal, or gamma distribution rather than the normal distribution.

The material in this research paper is presented in four sections. Section I provides the conceptual framework of acceptance sampling and reliability sampling. Varied references on reliability sampling are cited in Section II. Sampling inspection plans for life tests based on generalized gamma distribution are introduced in Section III. The notion of the generalized gamma distribution and its application in life testing are also presented in this section. Section IV presents concluding remarks on the contents of this paper.

II. LITERATURE IN SAMPLING INSPECTION PLANS FOR LIFE TESTS

The literature of sampling inspection for life-time data provides application of many continuous distributions in the studies concerned with the design and evaluation of life-test sampling plans. In the past several years, significant contributions have been made in the development of life-test sampling plans based on the above distributions and several compound distributions for modelling lifetime data. Epstein [9, 10], Handbook H-108 [20], and Goode and Kao [12, 13, 14] present the theory and development of life test sampling plans based on exponential and Weibull distributions. Gupta and Groll [19] discussed life-test sampling plans using gamma distribution. Life-test sampling plans using normal and lognormal distribution have been discussed by Gupta [18]. A detailed account of such plans was provided by Schilling and Neubauer [31]. The recent literature in reliability sampling plans include the works of Wu and Tsai [42], Wu, *et al*., [43], Kantam, *et al*., [24], Jun, *et al*., [23], Tsai and Wu [33], Balakrishnan, *et al*., [3], Aslam and Jun [1,2], Kalaiselvi and Vijayaraghavan [25], Kalaiselvi, *et al*., [26], Loganathan, *et al*., [27], Hong, *et al*., [21], Vijayaraghavan, *et al*., [39] and Vijayaraghavan and Uma [40,41].

Gamma distribution, defined by Karl Pearson [30], is a skewed distribution and is a Pearsonian type III distribution. It is considered as a lifetime distribution and is frequently used as a model for survival-type data. The literature in reliability theory provides some works relating to gamma distribution and its applications. For instance, one may refer to Birnbaum and Saunders [4], Drenick [8], Greenwood and Durand [15], Gupta [17], Choi and Wette [6], Gross and Clark [16], Cohen and Norgaard [7], and Johnson, *et al*., [22]. Erlangian distribution and exponential distribution are the particular cases of gamma distribution. According to Marshall and Olkin [28], the gamma distribution describes three kinds of failure rates, namely, increasing failure rate, decreasing failure rate and constant failure rate.

The family of gamma distribution has been considered as very important in the literature of analysing skewed data. Stacy [32] introduced the generalized gamma distribution and special sub-models as the exponential, gamma, Weibull and Rayleigh distribution. The generalized distribution is suitable for modelling data in different forms of hazard rate function such as increasing, decreasing and unimodal. According to Glaser [11], McDonald and Richards [29] and Marshall and Olkin [28], the generalized gamma distribution has the increasing failure rate, decreasing failure rate, bathtub shaped failure rate and inverted bathtub shaped failure rate depending the values of the shape parameters.

Considering the importance of the generalized gamma distribution in life testing and reliability, a specific life test sampling plan is developed in this paper. With the condition that the lifetime quality characteristic is adequately modelled by the generalized gamma distribution, the criteria for designing life-test plans when lot quality is evaluated in terms of mean life and hazard rate are proposed. Factors for adapting MIL-STD-105D [34] to life and reliability testing indexed by acceptable quality level under the assumption of generalized gamma distribution are also illustrated.

III. LIFE TEST SAMPLING INSPECTION PLANS BASED ON GENERALIZED GAMMA DISTRIBUTION

Life-test sampling plans consist of various procedures and rules for either accepting or rejecting a batch of items based on the sampled lifetime information. Under such plans, samples are tested for a specified length of time. When all units are tested to failure, the standard plans can be utilized to assess the results against specified requirements, and the results can be used in a variable sampling plan when the lifetimes are measured and the distributional assumption of the quality characteristics is satisfied. Further, the number of failures which occur before a required time can be used with standard attributes plans in determining the disposition of the material. (See, Schilling and Neubauer [31]).

A typical lifetest sampling plan can be formulated in the following manner: Suppose, n items are placed for a life-test and the experiment is stopped at a predetermined time, T. The number of failures occurred until the time point T is observed, and let it be m. The lot is accepted if m is less than or equal to the acceptance number, say, c; otherwise, it is rejected. Thus, the life-test sampling plan is represented by n, the number of units on test, and c, the allowable number of failures, called the acceptance number.

Life-tests, terminated before all units have failed, may be classified into two types, namely, failure terminated and time terminated. In a failure terminated life-test, a given sample of n items is tested until the r^{th} failure occurs and then the test is terminated.

In time terminated life-test, a given sample of n items is tested until a pre-assigned termination time, T, is reached and then the test is terminated. Generally, these tests may be defined with reference to the specifications given in terms of one of the characteristics such as (a) mean life, that is, the expected life of the product, (b) hazard rate, that is, the instantaneous failure rate at some specified time, t, and (c) reliable life, that is, the life beyond which some specified proportion of items in the lot will survive. (See, Schilling and Neubauer [31]).

One of the significant features of a life-test plan is that it involves a random characteristic, that is, lifetime or time to failure, which can be more adequately described most often by skewed distributions. Application of continuous-type of distributions such as normal, exponential, Weibull, gamma and lognormal for lifetime variables in the studies concerned with the design and evaluation of lifetest sampling plans has been provided in the literature of sampling inspection. Accordingly, important contributions have been made in the development of lifetest sampling plans based on the above distributions. Application of generalized gamma distribution, which is one of the lifetime distributions, is now considered under life-test sampling plan.

Generalized Gamma Distribution

Let T be a random variable representing the lifetime of the components. Assume that T follows a generalized gamma distribution. The probability density function and the cumulative distribution function of T are, respectively, defined by

$$f(t;\theta,\eta,\lambda)=\frac{\eta}{\theta\,\Gamma(\lambda)}\left(\frac{t}{\theta}\right)^{\lambda\eta-1}e^{-\left(\frac{t}{\theta}\right)^{\eta}},\; t,\theta,\eta,\lambda>0 \qquad (1)$$

and

$$F(t;\theta,\eta,\lambda)=\frac{\gamma\left(\lambda,\left(\frac{t}{\theta}\right)^{\eta}\right)}{\Gamma(\lambda)},\; t,\theta,\eta,\lambda>0, \qquad (2)$$

where θ is the scale parameter, λ and η are the shape parameters and γ is the lower incomplete gamma function and Γ is the gamma function.

It can be noted that if $\lambda=1,$ the generalized gamma distribution becomes a Weibull distribution with scale parameter, θ , and shape parameter, $\eta.$ Further, if $\eta=1,$ it becomes a gamma distribution. The proportion, $p,$ of product failing before time t, is defined by the cumulative probability distribution of T and is expressed by

$$p=P(T\le t)=F\left(t;\theta,\eta,\lambda\right) \qquad (3)$$

The mean lifetime and the hazard rate function for specified time t under the generalized gamma distribution are the functions of θ,λ and η , and are, respectively, given by

$$\mu=E(T)=\theta\frac{\Gamma\left(\lambda+\frac{1}{\eta}\right)}{\Gamma(\lambda)} \qquad (4)$$

and

$$Z(t;\theta,\eta,\lambda)=\frac{\frac{\eta}{\theta\,\Gamma(\lambda)}\left(\frac{t}{\theta}\right)^{\lambda\eta-1}e^{-\left(\frac{t}{\theta}\right)^{\eta}}}{1-\frac{\gamma\left(\lambda,\left(\frac{t}{\theta}\right)^{\eta}\right)}{\Gamma(\lambda)}} \qquad (5)$$

Application of Generalized Gamma Distribution

The procedures for determining life-test sampling plans based on Weibull distribution were provided in Technical Reports TR 3 [35], TR 4 [36] and TR 6 [37] utilizing mean life and hazard rate as the criteria for acceptance of the lots. Analogous approaches are considered here to develop sampling plans using the generalized gamma distribution as the lifetime distribution. The mean life criterion consists in the determination of the ratio $t/E(t),$ which corresponds to the proportion, $p,$ of product failing before time t.

In practice, when a life-test sampling plan is dealt with, acceptable mean life and unacceptable mean life, which are associated with the producer's risk and consumer's risk are generally specified. With the specification of these values, a desired sampling plan can be determined. A specific requirement on the mean of the generalized gamma distribution can be stated in terms of the proportion, p, of the population failing by a specified time, t. By definition, p is given by the relation (3).

Corresponding to the specifications for the acceptable and unacceptable mean life, the quality levels are defined by p_1 and p_2 with associated risks, α and β , where p_1 is the acceptable proportion of the lot failing before specified time, t, and p_2 is the unacceptable proportion of the lot failing before specified time, t. A set of conversion factors has been constructed based on reliability criteria, such as mean life and hazard rate for life-test plans under the conditions of generalized gamma distribution and presented in tables, which can be used for determining the plans for specified requirements.

It can be observed that the dimensionless ratio, t/μ , and the hazard rate function, $Z(t)$, depend on the parameters of the generalized gamma distribution. As per the Technical Report TR 7 [38], the quantities $t/\mu\times100,$ and $tZ(t)\times100$ can be used to determine the life-test sampling plans under the two reliability criteria, respectively. The values of the ratio $t/\mu\times100$ can be computed from the expressions (2) and (4) corresponding to the selected proportion, p, of product failing before time t for specified values of λ and $\eta.$ In a similar manner, the values of $tZ(t)\times100$ can be determined utilizing expressions (5).

Tables 1 and 2 provide the conversion factors $t/\mu\times100$ and $tZ(t)\times100$ corresponding to the mean life and hazard rate criteria for specified sets of values of λ and η , and the values of p. These tables can be used, respectively, to determine life-test plans and their operating characteristics based on mean life and hazard rate. The conversion factors can also be used to obtain the mean life and hazard rate when the test termination time is specified, and *vice versa*. The following illustrations based on mean life and hazard rate criteria are provided to demonstrate the use of Tables 1 and 2 in determining operating characteristics of a given plan and in finding a sampling plan satisfying the requirements in terms of acceptable quality level (acceptable mean life) and limiting quality level (unacceptable mean life).

Numerical Illustration 1

It is desired to use a single sampling plan by attributes with the parameters specified by $n = 130$ and $c = 5$ for fulfilling the requirements such as $(p_0 = 0.02, \alpha = 0.05)$ and $(p_1 = 0.07, \beta = 0.10)$ when the lifetime of the item follows GGD with the shape parameters fixed as $\lambda = 2$ and $\eta = 0.75$.

Assume that a test termination time of 750 hours is employed and the number of failures is counted at that time. Then, the operating characteristics of this plan in terms of mean life along with the values of $k = \frac{t}{\mu} \times 100$ and $\mu = \frac{t}{k} \times 100$, where *t* = 750 hours, are obtained and are tabulated in Table 3 using the operating characteristics of the attributes plan and Table 1.

Numerical Illustration 2

Suppose that a single sampling plan by attributes with parameters *n* and *c* is to be defined when the requirements are specified in terms of acceptable mean life of 16150 hours and unacceptable mean life of 6400 hours with associated risks of 5 percent and 10 percent, respectively. Assume that the individual items are to be tested for 750 hours and that the lifetime of the items are distributed as generalized gamma distribution with the shape parameters fixed as $\lambda = 2$ and $\eta = 0.75$. At the specified levels, the values of *k* are determined as

$$k_0 = t/\mu \times 100 = (750/16150) \times 100 = 4.64$$

and

$$k_1 = t/\mu \times 100 = (750/6400) \times 100 = 11.71.$$

Entering Table 1 with these values, the proportions of product failing corresponding to acceptable and unacceptable mean life are determined as $p_0 = 0.02$ and $p_1 = 0.07$, respectively. The operating ratio, which is the measure of discriminating good and bad lots, is defined by $OR = 0.07/0.02 = 3.5$, corresponding to which a single sampling plan can be chosen from Schilling and Neubauer [31] as $(n = 130, c = 5)$ or from Cameron [5] as $(n = 131, c = 5)$.

In a similar manner, Table 2 can be used to determine conversion factors so as to obtain the life-test plans and the corresponding hazard rates.

Numerical Illustration 3

The acceptable mean life under the life test sampling plans based on the generalized gamma distribution can be determined using the ratio $k = t/\mu \times 100$ for any specified value of acceptable quality level, *AQL*, shown in MIL-STD-105D [38]. If *AQL* is 3% at $P_a(AQL) = 0.95$, the test termination time is fixed as *t* = 450 hours and the shape parameters are specified as $\lambda = 3$ and $\eta = 0.5$, then the expected mean life, μ, is determined as $\mu = t/k \times 100 = 12217$ hours, which can be considered as the acceptable mean life. Accordingly, if a lot consisting of items that have the acceptable mean life specified at 12217 hours is considered, the probability of acceptance of the lot would be 95%.

Corresponding to the fixed value of *AQL* = 3% with 95% acceptance probability, the conversion factors for mean life and hazard rate criteria for the case in which the shape parameters are fixed as $\lambda = 3$ and $\eta = 0.5$ under the generalized distribution are as given below:

Criterion	Conversion Factor	Value of the Factor	AQL
Percent Nonconforming as per MIL-STD-105D	$p \times 100$	3	0.03
Expected Mean Life	$k = (t/\mu) \times 100$	3.683	12217
Hazard Rate	$tZ(t) \times 100$	3.895	0.000086

IV. CONCLUDING REMARKS

Sampling inspection plans for life-tests are proposed when the lifetime quality characteristic is modelled by a generalized gamma distribution. Procedures for the selection of such life-test sampling plans are developed when lot quality is evaluated in terms of two different criteria viz., mean life and hazard rate. The tables presented for the selection of parameters of the life test sampling plans are restricted for the values of shape parameters fixed as $\lambda = 1, 2, 3$ and $\eta = 0.5, 0.75$.

The users or practitioners can generate the required sampling plans for other choices of λ and η adopting the procedure described in this paper. Conversion factors are provided which would help to determine the mean life and hazard rate for a specified test termination time and *vice versa*. The factors for adapting MIL-STD-105D to life and reliability testing indexed by acceptable quality level are provided.

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Authors' Profile

Dr. R. Vijayaraghavan, the principal author of the paper, is an academician with an illustrious career in teaching and research for about three decades. Presently, he is a Professor and Head of the Department of Statistics in Bharathiar University, Coimbatore – 641 046. His field of specialization is Statistical Quality Control and Reliability. His other fields of interest include Statistical Modelling, Time Series Analysis and Regression Analysis. He has about 70 research papers to his credit published in some of the leading international journals of repute, which include Journal of Quality Technology, Communications in Statistics – Theory and Methods, Communications in Statistics – Simulation and Computation, Journal of Applied Statistics and Journal of Testing and Evaluation.

K. Sathya Narayana Sharma and **C. R. Saranya** are Research Fellows pursuing the course at the Department of Statistics, Bharathiar University, Coimbatore for the award of Ph. D., Degree in Statistics. Their field of specialization is Statistical Quality Control and Reliability.

Table 1

Values of $(t/\mu)\times 100$ Based on Generalized Gamma Distribution for Specified Values of λ and η

$p\%$	$\eta = 0.5$			$\eta = 0.75$		
	$\lambda = 1$	$\lambda = 2$	$\lambda = 3$	$\lambda = 1$	$\lambda = 2$	$\lambda = 3$
1	0.0500	0.3833	1.5917	0.2520	2.8436	7.1486
2	0.0500	0.7833	2.6833	0.5039	4.6434	10.1506
3	0.0500	1.2000	3.6833	0.8399	6.2272	12.5478
4	0.1000	1.6500	4.6416	1.2598	7.7030	14.6211
5	0.1500	2.1167	5.5750	1.6798	9.0708	16.5216
6	0.2000	2.6000	6.4916	2.0997	10.4386	18.2925
7	0.3000	3.1000	7.3999	2.6036	11.7344	19.9555
8	0.3500	3.6167	8.3083	3.1076	13.0302	21.5536
9	0.4500	4.1667	9.2166	3.6115	14.2900	23.1087
10	0.6000	4.7167	10.1250	4.1994	15.5138	24.5990
11	0.7000	5.3000	11.0417	4.7873	16.7736	26.0460
12	0.8500	5.9000	11.9584	5.4592	17.9974	27.4715
13	1.0000	6.5000	12.8835	6.1312	19.2212	28.8754
14	1.1500	7.1333	13.8168	6.8031	20.4451	30.2577
15	1.3500	7.7833	14.7586	7.4750	21.6689	31.6183
16	1.5500	8.4666	15.7086	8.2309	22.8927	32.9574
17	1.7500	9.1499	16.6753	8.9868	24.1165	34.2965
18	2.0000	9.8499	17.6502	9.7427	25.3763	35.6356
19	2.2500	10.5833	18.6418	10.5826	26.6001	36.9531
20	2.5000	11.3332	19.6418	11.4224	27.8240	38.2489
21	2.8000	12.0999	20.6584	12.2623	29.0838	39.5664
22	3.1000	12.8999	21.6833	13.1862	30.3436	40.8623
23	3.4500	13.7166	22.7332	14.1101	31.6034	42.1582
24	3.8000	14.5499	23.7915	15.0340	32.8992	43.4756
25	4.1500	15.4165	24.8664	15.9578	34.1590	44.7714
50	24.0499	46.9496	59.5889	51.5686	71.8115	80.1663
60	41.9996	68.1648	80.3689	74.7491	92.0753	97.8530
70	72.5006	99.1792	83.3368	107.5896	118.2058	119.8588
80	129.5497	149.4332	83.3368	158.4890	155.3500	150.0493
90	265.1399	166.6735	83.3368	255.4058	220.2084	200.7040

Table 2

Values of $tZ(t)\times 100$ Based on Generalized Gamma Distribution for Specified Values of λ and η

$p\%$	$\eta = 0.5$			$\eta = 0.75$		
	$\lambda = 1$	$\lambda = 2$	$\lambda = 3$	$\lambda = 1$	$\lambda = 2$	$\lambda = 3$
1	1.5474	0.9982	1.3616	0.9587	1.4493	2.0346
2	1.5632	1.9306	2.6428	1.6147	2.8592	3.9673
3	1.5793	2.8379	3.8955	2.3690	4.2546	5.8565
4	2.2274	3.7643	5.1324	3.2081	5.6463	7.6992
5	2.7291	4.6804	6.3552	3.9812	6.9980	9.5344
6	3.1579	5.5903	7.5649	4.7107	8.3927	11.3552
7	3.8541	6.4968	8.7664	5.5337	9.7507	13.1525
8	4.1821	7.4017	9.9666	6.3210	11.1340	14.9499
9	4.7408	8.3315	11.1634	7.0813	12.5024	16.7571
10	5.4544	9.2359	12.3553	7.9273	13.8521	18.5413
11	5.9055	10.1649	13.5508	8.7481	15.2511	20.3177
12	6.5026	11.0941	14.7398	9.6462	16.6264	22.1040
13	7.0558	12.0032	15.9311	10.5206	18.0118	23.8959
14	7.5766	12.9357	17.1242	11.3759	19.4059	25.6900
15	8.2011	13.8701	18.3189	12.2157	20.8076	27.4832
16	8.7883	14.8256	19.5150	13.1260	22.2160	29.2735
17	9.3471	15.7643	20.7205	14.0208	23.6306	31.0823
18	9.9845	16.7060	21.9268	14.9028	25.0836	32.9079
19	10.5916	17.6677	23.1419	15.8492	26.5086	34.7258
20	11.1752	18.6320	24.3579	16.7828	27.9388	36.5353
21	11.8213	19.5990	25.5822	17.7061	29.4054	38.3810
22	12.4432	20.5842	26.8076	18.6884	30.8762	40.2169
23	13.1167	21.5719	28.0482	19.6603	32.3513	42.0651
24	13.7669	22.5625	29.2898	20.6240	33.8605	43.9463
25	14.3989	23.5699	30.5395	21.5816	35.3445	45.8170
50	34.6634	52.5860	65.9409	51.9970	78.8831	98.9132
60	45.8155	67.6593	83.8635	68.7219	101.4885	125.7952
70	60.1967	86.4959	105.4998	90.2960	129.7424	158.9277
80	80.4652	112.2326	168.0305	120.6807	168.3480	203.5327
90	115.1165	265.0880	305.2198	172.6718	232.0421	275.9514

Table 3

Operating Characteristics for a Specific Life Test Sampling Plan

$$\left(n=130, c=5, \lambda=2, \eta=0.75\right)$$

p	P_a	$\lambda=2$, $\eta=0.75$		p	P_a	$\lambda=2$, $\eta=0.75$	
		k	μ			k	μ
0.010	0.99792	2.844	26374.925	0.045	0.46684	8.387	8942.559
0.015	0.98593	3.779	19843.984	0.050	0.363431	9.071	8268.320
0.020	0.95274	4.643	16152.076	0.055	0.274527	9.755	7688.629
0.025	0.89142	5.435	13798.788	0.060	0.20175	10.439	7184.897
0.030	0.80313	6.227	12044.027	0.070	0.101285	11.734	6391.482
0.035	0.69577	6.983	10740.291	0.080	0.046734	13.030	5755.871
0.040	0.58021	7.703	9736.526	0.090	0.020067	14.290	5248.431
0.045	0.46684	8.387	8942.559	0.100	0.008094	15.514	4834.405

