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A STUDY ON THE BEHAVIOUR OF OPERATING CHARACTERISTIC CURVES AND DETERMINATION OF RELIABILITY SINGLE SAMPLING PLANS BASED ON EXPONENTIATED RAYLEIGH DISTRIBUTION

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Abstract

This paper attempts to construct reliability single sampling plans under hybrid censoring scheme assuming that the life time of the product follows exponentiated Rayleigh distribution. The nature of the operating characteristic curves of sampling plan is also analysed for various sets of plan parameters based on the exponentiated Rayleigh distribution. Plan parameters are obtained corresponding to two specified points on the operating characteristic curve. Selection of the plan parameters is illustrated with a numerical example.

1. Introduction

Lifetime is a quality characteristic for some products and sampling inspection for such products is carried out by conducting suitable life test. An acceptance sampling plan under which sampling inspection is performed by conducting the life test upon the sampled products may be termed as reliability sampling plan. Implementation of reliability sampling plans may require higher amount of cost and more inspection time. Type-I censoring,

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Type-II censoring, hybrid censoring and progressive censoring are some of the censoring schemes frequently employed in life testing in order to save time and cost of inspection.

Reliability sampling plan is developed based on the probability distribution of the lifetime of the product. One can find several scholarly works written so far by eminent statisticians on designing of reliability sampling plans for various lifetime distributions. Epstein [5], Balasooriya and Saw [4] developed reliability sampling plans by attributes under hybrid and progressive censoring schemes respectively, assuming that the lifetime distribution is exponential. Kantam et al., [9] designed reliability sampling plans by attributes under hybrid censoring scheme assuming that the lifetime distribution is a log logistic distribution. Aslam and Shahbaz [2], Aslam et al., [3] and Srinivasa Rao [17] determined sampling plans based on generalized exponential distribution. Some special probability distributions like Birnbaum-Saunders distribution, Marshall-Olkin extended exponential distribution and Maxwell distribution have also been considered for constructing sampling plans (Aslam and Kantam [1], Srinivasa Rao et al., [18] and Lu [13]).

New statistical distributions have been developed from some of the existing distributions, introducing a parameter in the exponent of the respective cumulative distribution function (Al-Hussaini and Ahsanullah [6]). They are named as "Exponentiated distributions". Exponentiated Rayleigh distribution is introduced from the Rayleigh distribution, which has been receiving much attention among researchers for its wider applicability in modelling for lifetime data. The Exponentiated Rayleigh distribution has several interesting properties which are also common to two-parameter Gamma, Weibull and generalized exponential distributions. Surles and Padgett [19] introduced two-parameter Burr Type X distribution and named it as Exponentiated Rayleigh (ER) distribution. Recently, Kundu and Raqab [10] studied estimation of parameters of this distribution using different estimation procedures. Rosaiah et al., [15] and Sriramachandran and Palanivel [20] determined sampling plans based on exponentiated log-logistic and exponentiated inverse Rayleigh distributions. Hence, we come to know that life testing is done under the hybrid censoring scheme and sampling plans were designed considering consumer's risk only. But, the risk of producer due to rejection of the lots of good quality products is also an important factor, which should also be considered while designing sampling plans.

The performance of the acceptance sampling procedures can be assessed through the operating characteristic curves. Vijayaraghavan et al., [21] and Loganathan et al., [12] studied the behaviours of the operating characteristic curves for Gamma-Poisson and Polya distribution based single sampling plans respectively.

This work attempts to determine reliability sampling plans based on Exponentiated Rayleigh distribution under hybrid censoring scheme considering both producer's risk and consumer's risk. Operating Characteristic (OC) function of the Reliability Single Sampling Plan (RSSP) under the conditions of ER distribution is derived in Section 2. Behaviour of the OC curves of the determined sampling plan is analyzed using different sets of values of the parameters under the assumptions that the number of defects per unit to follow a binomial distribution is studied in Section 3. Procedure of designing the sampling plans is described in Section 4. In Section 5, construction of tables providing optimum sampling plans is discussed and tables are presented for some cases. Selection of sampling plan from the tables for the given requirements is illustrated with an example. Results are summarized in Section 6.

2. Operating Characteristic Function

A RSSP is a procedure, which can be used for taking decision about the submitted lots by conducting a suitable life test to the items selected randomly from the lot. The sampling plan can be defined by a set of four parameters (N, n, c, t), where N is the lot size, n is the sample size, c is the acceptance number and t is the test termination time. The sampling plan can be implemented as follows.

1. Select a set of n products randomly from the submitted lot of size N.
2. Conduct life test to the selected items considering t as the test termination time. Observe the number of failed items, $X = x$.
3. Terminate the life test either at time t or $x > c$ before reaching time t,

whichever is earlier.

4. Accept the lot, if $x \leq c$ at time t. Reject the lot, if $x > c$ either at time t or earlier.

Let T be the lifetime of the product, which is distributed according to an Exponentiated Rayleigh distribution having the probability density function

$$f(t;\ \theta,\ \lambda) = \theta\left(\frac{t}{\lambda^2}e^{-\frac{1}{2}\left(\frac{t}{\lambda}\right)^2}\right)\left(1 - e^{-\frac{1}{2}\left(\frac{t}{\lambda}\right)^2}\right)^{\theta - 1};\ t > 0,\ \theta > 0 \text{ and } \lambda > 0$$

Here, θ and λ are respectively the shape and scale parameters. The Exponentiated Rayleigh distribution having the above probability density function may be acronymed as $ER(\theta, \lambda)$. The cumulative distribution function of $ER(\theta, \lambda)$ can be derived as

$$F_T(t;\ \theta,\ \lambda) = \left(1 - e^{-\frac{1}{2}\left(\frac{t}{\lambda}\right)^2}\right)^{\theta},\ t > 0,\ \theta > 0 \text{ and } \lambda > 0. \tag{1}$$

It is a positively skewed distribution, whose moments do not have simple forms (Raqab and Kundu [14]). According to Gupta [8], for a skewed distribution, the population median can describe the population relatively better than the population mean. Median of the $ER(\theta, \lambda)$ distribution is given by

$$\text{Median } (m) = \lambda\sqrt{-2\log\left(1 - \left(\frac{1}{2}\right)^{\frac{1}{\theta}}\right)}. \tag{2}$$

The value of λ can be computed for given values of m and θ using

$$\lambda = \frac{m}{\sqrt{-2\log\left(1 - \left(\frac{1}{2}\right)^{\frac{1}{\theta}}\right)}}.$$

The lot fraction nonconforming, p can be calculated corresponding to each value of t/m from

$$F_T(t/m;\ \theta,\ \lambda) = p.$$

In general, performance of a sampling plan may be studied or analyzed or compared with other sampling plans using its OC function. The OC function of a sampling plan by attributes is given by

$$P_a(p) = P(X \le c) = \sum_{x=0}^{c} P(X = x).$$

The probability distribution of X can be assumed appropriately as Hypergeometric distribution. Schilling and Neubauer [16] pointed out that, when the sample size, n, is less than 10% of the lot size, N, that is $n/N \le 0.10$, the sampling distribution of X can be approximated by the Binomial (n, p) distribution. Under these conditions, the OC function can be defined as

$$P_a(p) = \sum_{x=0}^{c} \binom{n}{x} p^x (1-p)^{n-x}.$$

3. Properties of Operating Characteristic Function

In general, the OC function of the RSSP under the conditions of $ER(\theta, \lambda)$ distribution may be defined as

$$P_a(p) = P(p \mid N,\ n,\ c,\ \lambda,\ \theta) = \sum_{x=0}^{c} P(X = x \mid N,\ n,\ p).$$

Thus, the lot fraction failure of the products under the conditions of $ER(\theta, \lambda)$ distribution can be defined as

$$p = P(T \le t).$$

The cumulative distribution function (1) can be expressed, using m (2) as

$$p = \left(1 - e^{-\left(\frac{t}{m}\right)^2 \left(-\log\left(1-\left(\frac{1}{2}\right)^{\frac{1}{\theta}}\right)\right)}\right)^{\theta},\ t > 0.$$

Differentiating on both sides with respect to t/m, it follows that

$$\frac{dp}{d(t/m)} = \frac{2r\theta\left(\frac{t}{m}\right)\left(1 - e^{-r\left(\frac{t}{m}\right)^2}\right)^{\theta-1}}{e^{r\left(\frac{t}{m}\right)^2}} > 0.$$

Here,

$$r = -\log\left(1 - \left(\frac{1}{2}\right)^{\frac{1}{\theta}}\right).$$

This shows that the lot fraction failure, p, is a monotonically increasing function of t/m for fixed values of θ. The lot quality depends upon the test termination time (t), median lifetime (m) and the model parameter (θ). Due to the monotonicity property of 'p' with respect to 't/m' when 'θ' is fixed, the value of $P_a(p)$ may be calculated corresponding to the values of 't/m' for each given θ. Hence, the OC curves may be drawn considering 't/m' instead of 'p'.

Since the lot fraction failure, 'p', is an increasing function of 't/m', the OC curve of the RSSP may be drawn by plotting the values of the pair $(t/m, P_a(p))$.

The empirical analysis may be carried out to study the properties of the OC function. Behavior of the OC curve may be analyzed with respect to p, n, c, t, m and θ fixing the values of others.

Firstly, the influence of p upon the values of $P_a(p)$ is considered. A set of four OC curves are drawn and are presented in Figure 1. The four curves are drawn corresponding to the plans $(n = 55, c = 1, \theta = 2), (n = 75, c = 2, \theta = 2)$, $(n = 100, c = 3, \theta = 2)$ and $(n = 125, c = 2, \theta = 2)$. Shapes of the OC curves for each given set of values of (n, c, θ) reveal a declining tendency for increasing values of t/m. From the monotonic relationship between p and t/m discussed in beginning of this section, it can be inferred that $P_a(p)$ is a decreasing function of p. For instance, for the sampling plan $(n = 125, c = 2,$

$\theta = 2)$, the lot fraction failure, p, can be calculated corresponding to $t/m = 0.06, 0.12, 0.18$ and 0.24 as 0.005045, 0.018772, 0.039326 and 0.065153. The probability of lot acceptance at these values of p are $P_a(0.005045) = 0.974118$, $P_a(0.018772) = 0.582882$, $P_a(0.039326) = 0.126803$ and $P_a(0.065153) = 0.010422$. Thus, under the conditions of the $ER(\theta, \lambda)$ distribution, the RSSPs will provide larger chance for accepting the good quality lots and smaller chance for acceptance of the lot having poor quality products. It is a preferable property that every sampling plan should possess.

Since, p is a monotonically increasing function of t/m, it can also be inferred that $P_a(p)$ decreases as t increases when m is fixed. It is a common fact that if the life test is prolonged, more number of failures will be observed and ultimately it will reduce acceptance probability of such lots.

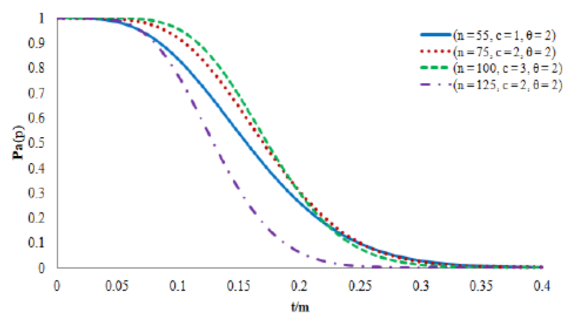

Figure 1. Exponentiated Rayleigh OC Curves for fixed "θ".

Similarly, when t is fixed, p is monotonically decreasing function of m. Thus, $P_a(p)$ will be a monotonically increasing function of m. it is again another common fact that if m increases, the median lifetime of the products will be high. Hence, the lot will be a good lot with smaller lot fraction failure. Thus, the lot acceptance probability will also be large. (Figure 2).

Influence of the sample size, n, upon the values of the OC function is studied. Four OC curves are drawn for four different values of n such as $n = 40, 65, 90$ and 115, fixing the values of remaining characteristics as $c = 2$ and $\theta = 2$. The OC curves are presented in Figure 3. A perusal of the curves indicates a general fact that position of the curves is shifted according to the changes in the values of n displaying the same declining tendency. The swell in the upper portion of the curves at smaller values of p indicates that the RSSPs product the producer against rejecting good quality lots. The level of protection declines when n increases.

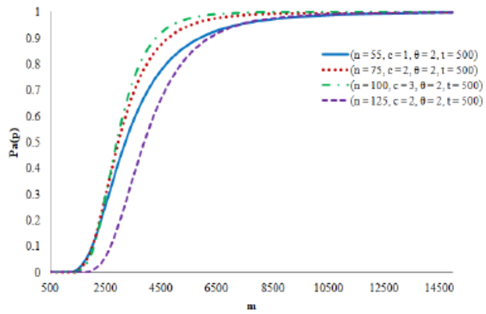

Figure 2. Exponentiated Rayleigh OC curves for fixed "θ" and "t".

For instance, the lot acceptance probability at $t/m = 0.14$, $p = 0.024947$ corresponding to the sample size $n = 40, 65, 90$ and 115 are respectively 0.922434, 0.779034, 0.609785 and 0.450618, similar kind of observation can be made observing the lower portion of the curves also. Thus, the RSSPs with smaller sample size n provide more protection to the producer and the plans with large n are consumer oriented plans.

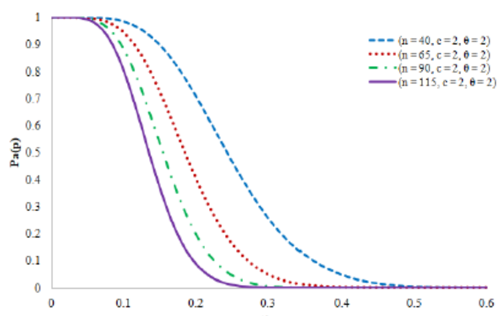

Figure 3. Exponentiated Rayleigh OC curves for fixed "c" and "θ".

Next, effect of the acceptance number, c, upon the values of $P_a(p)$ is analyzed. A set of four OC curves are drawn and are presented in Figure 4. The OC curves displayed in Figure 4 are drawn for the acceptance numbers,

$c = 1, 3, 5$ and 7 when $n = 75$ and $\theta = 2$. The lot fraction failure, *p*, can be calculated as 0.031818. When $n = 75$, the probability of lot acceptance can be noted from Figure 4 as 0.306528, 0.783680, 0.967630 and 0.997340 corresponding to $c = 1, 3, 5$ and 7. Thus, it may be concluded that the sampling plan having large acceptance number will protect the producer by giving more chance for accepting the lot.

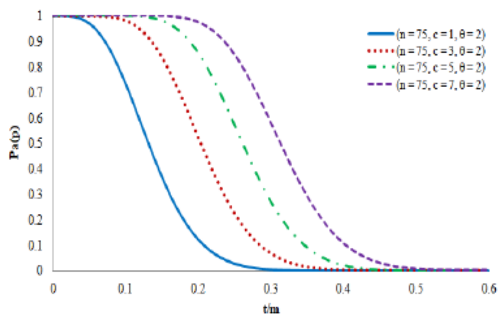

Figure 4. Exponentiated Rayleigh OC curves for fixed "*n*" and "θ".

Finally, effect of the parameter θ upon $P_a(p)$ is studied. In this respect, a set of four OC curves are drawn fixing the values of *n* and *c* as 750 and 0 respectively and taking four different values of θ as 1.5, 2.0, 2.5 and 3.0. The OC curves are displayed in Figure 5. These curves reveal that the probability of lot acceptance increases as θ increases for fixed values of *n* and *c*. For instance, the values of $P_a(p)$ corresponding to $\theta = 1.5, 2.0, 2.5$ and 3.0 at $t/m = 0.3$ can be obtained as $P_a(0.003348) = 0.080867$, $P_a(0.000330) = 0.780920$, $P_a(0.000031) = 0.976959$ and $P_a(0.000003) = 0.997876$. Shapes of the curves indicate a general fact that the good quality lots have large probability of acceptance and poor quality lots have smaller probability of acceptance.

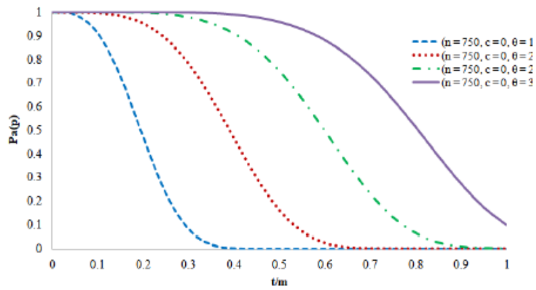

Figure 5. Exponentiated Rayleigh OC curves for fixed "*n*" and "*c*".

4. Determination of Plan Parameters

The Optimum RSSPs can be determined under the conditions of the $ER\ (\theta, \lambda)$ distribution using two points on the OC curve, viz., $(p_1, 1-\alpha)$ and (p_2, β). Here, p_1 represents the acceptable quality level, α denotes the producer's risk, p_2 represents the limiting quality level and β denotes the consumer's risk. Such plans will protect the interests of the producer and the consumer simultaneously. An optimum RSSP can be determined corresponding to the points satisfying the following conditions

$$P_a(p_1) \geq 1 - \alpha$$

and

$$P_a(p_2) \leq \beta.$$

These conditions may be expressed using the Binomial (n, p) distribution as

$$\sum_{x=0}^{c} \binom{n}{x} p_1^x (1 - p_1)^{n-x} \geq 1 - \alpha \tag{3}$$

and

$$\sum_{x=0}^{c} \binom{n}{x} p_2^x (1 - p_2)^{n-x} \leq \beta. \tag{4}$$

If m_1 and m_2 denote median lifetime of the products as expected by the producer and the consumer respectively, values of p_1 and p_2 can be calculated from

$$F_T(t/m_1;\ \theta,\ \lambda_1) = p_1 \tag{5}$$

and

$$F_T(t/m_2;\ \theta,\ \lambda_2) = p_2 \tag{6}$$

Different methods may be followed to determine the optimum values of n and c using binomial probabilities subject to (3) and (4). The iterative procedure discussed in Guenther [7], Vijayaraghavan et al., [22] and Loganathan et al., [11] may be used to determine the plan parameters n and c for the given requirements. Thus, for given $\theta, t, m_1, m_2, \alpha$ and β, the optimum values of n and c can be determined as follows.

Step-1. For specified values of m_1 and m_2 with $m_1 > m_2$, calculate λ_1 and λ_2 using (2).

Step-2. Corresponding to t, λ_1 and λ_2, determine p_1 and p_2 using (5) and (6).

Step-3. Set $c = 0$.

Step-4. Find the largest n, say n_L, such that $P_a(p_1) \geq 1 - \alpha$.

Step-5. Find the smallest n, say n_S, such that $P_a(p_1) \leq \beta$.

Step-6. If $n_S \leq n_L$, then the optimum plan is (n_S, c); otherwise increase c by 1.

Step-7. Repeat the Steps 4 through 6 until optimum values of n and c are obtained.

After determining n and c, the sampling inspection may be carried out for a submitted lot under hybrid censoring scheme as described in Section 2.

5. Construction of Tables

Values of n and c of the optimum RSSPs are determined using binomial for certain combinations of $\theta,\ t,\ m_1, m_2, \alpha$ and β. The producer's risk and consumer's risk are considered at two different levels, such as $\alpha = 0.025, 0.05$ and $\beta = 0.05, 0.10$. Various levels of median lifetime of the products as expected by the producer and the consumer are taken respectively as $m_1 = 200, 210, 230, 240, 250$ hours and $m_2 = 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120$ hours. The values assumed for test termination time and the shape parameter are respectively $t = 50$ hours and $\theta = 2$.

Parameters of the optimum RSSPs are presented in Table 1 and Table 2. Each cell entry in these tables represents the optimum value of the pair (n, c) determined corresponding to the specified values of $\theta, t, m_1, m_2, \alpha$ and β. Selection of plans from these tables for the given requirements is illustrated as below.

Illustration

Let the lifetime of the products considered for inspection be distributed according to the $ER(2, \lambda)$ distribution. Median lifetime of the products meeting the expectation of the producer and consumer are respectively $m_1 = 210$ hours and $m_2 = 90$ hours. Suppose that the quality inspector prescribes test termination time as $t = 50$ hours. Then, the values of acceptable quality level and limiting quality level can be computed as $p_1 = 0.0045$ and $p_2 = 0.0995$. If the producer's risk and the consumer's risk are specified as $\alpha = 0.025$ and $\beta = 0.05$, then the plan parameters determined using binomial probabilities can be selected from Table 1 as $n = 46$ and $c = 1$.

Now, the life test based on lot-by-lot sampling inspection can be carried out as follows: a sample of 46 products may be selected randomly from the submitted lot. Life test may be conducted on all the sampled products for 50 hours. At 50 hours, if the number of failures exceeds one, the life test may be terminated. The lot may be accepted. If a second failure occurs even before 50 hours, the life test should be terminated immediately. The lot may be rejected.

Table 1. Parameters of Reliability Single Sampling Plans using Binomial Probabilities when $t = 50$ hours, and $\theta = 2$.

		m_1	200	210	220	230	240	250
		t/m_1	0.2500	0.2381	0.2273	0.2174	0.2083	0.2000
m_2	t/m_2	p_1 \ p_2	0.0055	0.0045	0.0038	0.0032	0.0027	0.0023
70	0.7143	0.2167	(20,1) (20,1)	(20,1) (20,1)	(20,1) (13,0)	(20,1) (13,0)	(20,1) (13,0)	(20,1) (13,0)
75	0.6667	0.1769	(25,1) (25,1)	(25,1) (25,1)	(25,1) (25,1)	(25,1) (16,0)	(25,1) (16,0)	(25,1) (16,0)
80	0.6250	0.1452	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)	(31,1) (20,1)
85	0.5882	0.1198	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)
90	0.5556	0.0995	(62,2) (46,1)	(46,1) (46,1)	(46,1) (46,1)	(46,1) (46,1)	(46,1) (46,1)	(46,1) (46,1)
95	0.5263	0.0831	(74,2) (56,1)	(74,2) (56,1)	(56,1) (56,1)	(56,1) (56,1)	(56,1) (56,1)	(56,1) (56,1)
100	0.5000	0.0699	(88,2) (88,2)	(88,2) (66,1)	(88,2) (66,1)	(66,1) (66,1)	(66,1) (66,1)	(66,1) (66,1)
105	0.4762	0.0591	(105,2) (105,2)	(105,2) (105,2)	(105,2) (79,1)	(105,2) (79,1)	(79,1) (79,1)	(79,1) (79,1)
110	0.4545	0.0502	(153,3) (124,2)	(124,2) (124,2)	(124,2) (93,1)	(124,2) (93,1)	(124,2) (93,1)	(93,1) (93,1)
115	0.4348	0.0429	(179,3) (145,2)	(179,3) (145,2)	(145,2) (145,2)	(145,2) (109,1)	(145,2) (109,1)	(145,2) (109,1)
120	0.4167	0.0369	(246,4) (208,3)	(208,3) (169,2)	(208,3) (169,2)	(169,2) (169,2)	(169,2) (127,1)	(169,2) (127,1)

In each cell, the first pair is the value of (n, c) corresponding to $(\alpha = 0.025, \beta = 0.05)$ and the second pair is corresponding to $(\alpha = 0.05, \beta = 0.05)$.

Table 2. Parameters of Reliability Single Sampling Plans using Binomial Probabilities when $t = 50$ hours, and $\theta = 2$.

		m_1	200	210	220	230	240	250
		t/m_1	0.2500	0.2381	0.2273	0.2174	0.2083	0.2000
m_2	t/m_2	p_2 \ p_1	0.0055	0.0045	0.0038	0.0032	0.0027	0.0023
70	0.7143	0.2167	(17,1) (17,1)	(17,1) (10,0)	(17,1) (10,0)	(17,1) (10,0)	(17,1) (10,0)	(10,0) (10,0)
75	0.6667	0.1769	(21,1) (21,1)	(21,1) (21,1)	(21,1) (21,1)	(21,1) (12,0)	(21,1) (12,0)	(21,1) (12,0)
80	0.6250	0.1452	(26,1) (26,1)	(26,1) (26,1)	(26,1) (26,1)	(26,1) (15,0)	(26,1) (15,0)	(26,1) (15,0)
85	0.5882	0.1198	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)	(31,1) (31,1)
90	0.5556	0.0995	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)	(38,1) (38,1)
95	0.5263	0.0831	(63,2) (46,1)	(46,1) (46,1)	(46,1) (46,1)	(46,1) (46,1)	(46,1) (46,1)	(46,1) (46,1)
100	0.5000	0.0699	(75,2) (55,1)	(75,2) (55,1)	(55,1) (55,1)	(55,1) (55,1)	(55,1) (55,1)	(55,1) (55,1)
105	0.4762	0.0591	(89,2) (65,1)	(89,2) (65,1)	(89,2) (65,1)	(65,1) (65,1)	(65,1) (65,1)	(65,1) (65,1)
110	0.4545	0.0502	(105,2) (105,2)	(105,2) (77,1)	(105,2) (77,1)	(105,2) (77,1)	(77,1) (77,1)	(77,1) (77,1)
115	0.4348	0.0429	(154,3) (123,2)	(123,2) (123,2)	(123,2) (90,1)	(123,2) (90,1)	(123,2) (90,1)	(123,2) (90,1)
120	0.4167	0.0369	(180,3) (143,2)	(180,3) (143,2)	(143,2) (143,2)	(143,2) (105,1)	(143,2) (105,1)	(143,2) (105,1)

In each cell, the first pair is the value of (n, c) corresponding to $(\alpha = 0.025, \beta = 0.10)$ and the second pair is corresponding to $(\alpha = 0.05, \beta = 0.10)$.

6. Conclusion

The researcher has designed the Reliability Single Sampling Plans for carrying out life test based sampling inspection under the hybrid censoring scheme when the lifetime of the product is distributed according to the Exponentiated Rayleigh distribution. These plan parameters will safeguard the interests of both producer and consumer. Since the hybrid censoring scheme is employed to carry out the life test, implementation of the sampling plans will reduce the time and cost for conducting the life test. Behavior of the OC curves also studied to assess the performance of the determined sampling plans.

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