American Journal of Electrical Power and Energy Systems
2018; 7(6): 68-78
http://www.sciencepublishinggroup.com/j/epes
doi: 10.11648/j.epes.20180706.11
ISSN: 2326-912X (Print); ISSN: 2326-9200 (Online)

Heat Power Equipment Sample Tests Using Time-Series Techniques

Trukhanov Vladimir Mihailovich[1, 2], Sultanov Makhsud Mansurovich[1], Gorban' Yuliya Anatolyevna[1], Kukhtik Mikhail Petrovich[2]

[1]Department of Heat Power and Heat Engineering, the Moscow Power Engineering Institute, Volzhsky, Russia

[2]Department of Automation of Manufacturing Processes, Volgograd State Technical University, Volgograd, Russia

Email address:
sultanov_mm@mail.ru (S. M. Mansurovich)

To cite this article:
Trukhanov Vladimir Mihailovich, Sultanov Makhsud Mansurovich, Gorban' Yuliya Anatolyevna, Kukhtik Mikhail Petrovich. Heat Power Equipment Sample Tests Using Time-Series Techniques. *American Journal of Electrical Power and Energy Systems*. Vol. 7, No. 6, 2018, pp. 68-78. doi: 10.11648/j.epes.20180706.11

Received: November 4, 2018; **Accepted**: December 17, 2018; **Published**: January 23, 2019

Abstract: The article is concerned with the problem of planning of the amount of sample tests of heat power equipment components using time-series techniques. In the operation process of thermoelectric power stations (TPS) their expensive components (turbines, bearings, oil systems, generators, transformers, pipelines etc.) require securing of preset level of reliability and safety. For achievement of this aim it is necessary to develop corresponding plan of sample tests. Peculiarity of heat power equipment components is that they are devices consisting of elements' totality of mechanical, hydraulic, pneumatic, electronic and other types. The basis of the proposed sample tests amount planning technique is the condition of test sample restorability after failure through improvements. In this case, the risk of developer (supplier) is assumed to be close to zero (α = 0). Improvement will be considered effective if carried out tests are successful in the same amount after improvement. Novelty of the proposed test amount planning technique for one preset level of reliability allows getting required output characteristics of heat power equipment in shorter period.

Keywords: Test Amount Planning, Components, Reliability, Distribution Law

1. Introduction

The known techniques of test amount planning are applicable to large-scale and mass production, when a large number of elements can be put to the test, for example, diodes, capacitors, chips, switches, seals, valves, bushings, components of heat power equipment are complex expensive objects consisting of mechanical, hydraulic, pneumatic and electronic elements. As the components of heat power equipment is a turbine, which includes components such as: generator, oil system, shut-off valve, control valve, steam distributor, hydrogen seal, shaft bearings, steam lines. Device component developers are specific businesses that need to carry tests to confirm a high level of operating safety.

The basis of the proposed sample test amount planning technique is the condition of test sample restorability after failure through improvements. In this case, the risk of developer (supplier) is assumed to be close to zero $\alpha \approx 0$ (for example, $\alpha = 0.00001$).

The results of analysis and research indicate that the proposed technique allows achieving the required level of reliability for one or two samples through directional improvement.

The main difference between the time-series and the fixed amount methods is that the number of tests to confirm the estimated parameter of the reliability function is a random value and is not determined in advance. The essence of the time-series techniques is that the hypothesis confirmation (H_0 or H_1) depends on the ratio of density functions of the estimated parameter. This ratio is called a likelihood ratio, which is described below (1):

$$\frac{P_1}{P_0} = \prod_{i=1}^{n} \frac{f(m_i,\ \theta_1)}{f(m_i,\ \theta_0)}, \tag{1}$$

where P_1 – acceptable level of failure free operation;

P_0 – required level of failure free operation;
$F\,(m_i, \Theta_i)$ – density function of random value;
m_i – failure amount in the i-th aggregate;
Θ_1 – acceptable level of reliability;
Θ_0 – the required level of reliability;
n – scope of testing.

At development and manufacturing of expensive nondiscardable products like TPS [1] heat power equipment it is possible to preset only line of acceptance assuming that in the process of design and experimental try-out and batch manufacturing product achieves preset level of reliability and will be accepted in operation.

In the test process it is possible to observe how reliability varies from product to product (from batch to batch, from cycle to cycle) and how various improvements impact on it – increase or decrease it.

2. Test amount Planning Technique

2.1. Test Amount Planning Technique at One Level of Reliability

Control of reliability level of expensive repairable products using time-series techniques with one-sided border of one preset level of reliability has been stated in [15].

It is possible to use time-series techniques with one-sided border for control of various reliability indicators: probabilities of nonfailure operation, intensity of failures, mean time between failures, time between failures and others. At this controlled products can be both repairable and nonrepairable, mean time between failures can be discrete (e.g. number or operation cycles) or continuous (e.g. operation time in hours, haul in km etc.) and its distribution can be binomial, normal, exponential etc.

There are various techniques of control of probability R of nonfailure operation for executing of one work cycle by complex repairable product. Selection of reliability indicator as probability of nonfailure operation is connected with that probability of nonfailure operation during one work cycle is preset more often then other indicators in technical requirements on product.

Consider time-series techniques with one-sided border for binomial sampling plan. Research of binomial sampling plan is connected with that binomial distribution law of random variable (e.g. appearing of failures) is acceptable for majority of products working in cycling mode. It is assumed that variable R can vary under influence of some reasons, in particular, – under causes contributed in construction of product.

Content of technique consists in the following. Straight line – line of acceptance (figure 1) is plotted in coordinates $N0m$ (N – number of work cycles of product, m – number of failures).

Parameters h and h/S determine location of line of acceptance.

Task consists in achievement of required reliability level, test plan is composed without rejection boundary, i.e. with only one line of acceptance as shown on figure 1.

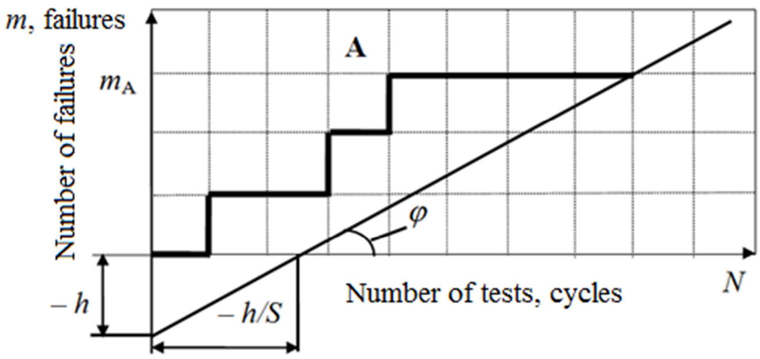

Figure 1. *Graph of time-series analysis with one-sided border.*

At $P < S$ function $L\,(P) = 1$, and at $P > S$ function $L\,(P)$ is connected with P by following relation (2).

$$P = \frac{L(P)^{-\frac{S}{h}} - 1}{L(P)^{-\frac{1}{h}} - 1}, \tag{2}$$

where P – failure probability; h – intersection coordinate of acceptance line and failure axis; $L\,(P)$ – operative characteristic.

So, probability of decision making (only acceptance) equals to one at $P \leq S$. However at $P > S$ there is certain probability of non-decision making at all. In this case, probability of decision making is determined by operative characteristic $L\,(P)$. As during tests supplier risk is assumed equal to zero then operative characteristic will be equal to customer risk (3).

$$L(P) = \beta. \tag{3}$$

It is possible to obtain relation for determination of two parameters S and h (4) for acknowledgement of preset reliability $R = 1 - P$ with confident probability $\gamma = 1 - \beta$ from expression (2).

$$P = \frac{\beta^{-\frac{S}{h}} - 1}{\beta^{-\frac{1}{h}} - 1}. \tag{4}$$

It is necessary to find one more relation between parameters S and h in order to determine them uniquely. There are various ways to obtain this relation. This technique has been proposed in the works [6, 15]. Its essence consists in the following. It is necessary to determine that at preset value of P customer must take certain risk Δβ consisting in that product is considered as satisfying the requirements of reliability after carrying out of series of consecutive successful tests, i.e. (5).

$$\Delta\beta = (1 - P)^{-\frac{h}{S}}, \tag{5}$$

where h/S – number of failures to first moment of decision making about acceptance.

Thus, system of two equations (6) is composed for determination of acceptance bound.

$$\begin{cases} P = \dfrac{\beta^{-\frac{S}{h}} - 1}{\beta^{-\frac{1}{h}} - 1}, \\ \Delta\beta = (1 - P)^{-\frac{h}{S}}, \end{cases} \tag{6}$$

where P – probability of failure at executing of one work cycle;

β – customer risk, i.e. probability of that product which reliability doesn't satisfy the preset requirements will be accepted;

Δβ – initial customer risk, i.e. probability of making a mistake that product satisfies the preset requirements of reliability after carrying out of series of consecutive successful cycles from the beginning of tests.

Preseting values of P, β and Δβ in system of equations, location of the acceptance line in the plane $N0m$ is determined (ref. figure 1). Test results are marked on prepared in that way coordinate grid: horizontal segment of unit length is laid off at successful cycle; vertical segment of unit length is laid off at failure in cycle. The obtained broken line reflecting test results is called trajectory of test process. If trajectory crosses acceptance line plotted at preset values of P, β and Δβ, it means that preset probability of nonfailure operation of one cycle is verified with confidence probability $\gamma = 1 - \beta$. It is clear that the higher reliability of product is, the less failures are observed during the tests and the flatter trajectory of process is.

At design and experimental try-out and batch manufacturing improvement or substitution of failed units for new ones are realized for increase of reliability. Trajectory of test process of one product at which improvements have been realized or several products tested consecutively is represented at figure 2.

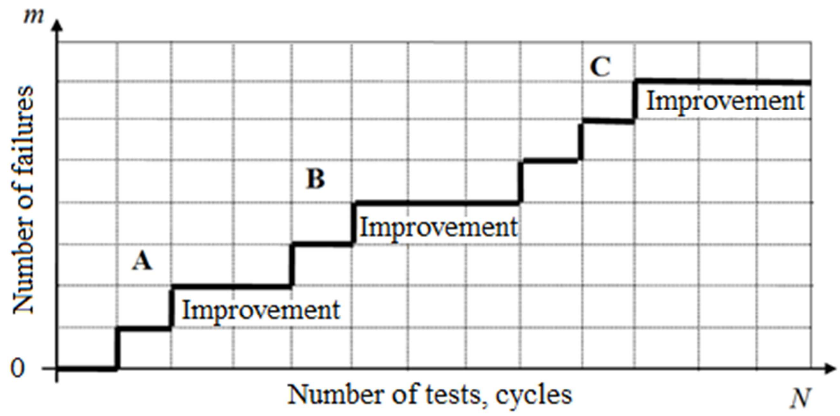

Figure 2. *Trajectory of test process with improvements.*

Analysis of figure shows that change (increase) of reliability has been occurred in points (*A*–*C*). However it is not always obvious that there are good causes to consider such change as statistically significant and what guarantees that actual increase of reliability has been achieved. Special statistical significance tests are used for check of significance of reliability change.

Coordinate grid can be prepared at transparent material (celluloid, tracing paper etc.) with the aim of control of product reliability during the try-out. This grid has acceptance lines for several intermediate values $R = 1 - p$ (for example, $R = 0.8; 0.9; 0.95;...$). This pattern (plane-table) is laid on graph of time-series analysis in such a way in order that coordinate origin of plane-table would coincides with point of last considerable (significant) change of trajectory of test process (for example, point C at figure 2) and coordinate axes of plane-table would be parallel to general coordinate axes. Intersection point of trajectory with acceptance line shows that level of reliability respondent to this acceptance line has been achieved (figure 3).

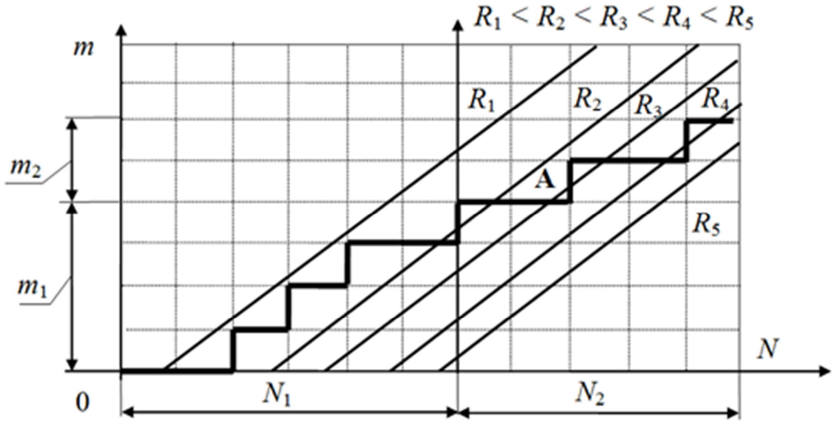

Figure 3. *Trajectory of test process for time-series analysis with assemblage of acceptance lines.*

Notation conventions: straight lines – lines of plane-table; m – number of failures; N – number of tests.

In this way, if plane-table is laid on graph of time-series analysis in such a way in order that coordinate origin of plane-table would coincides with point 0 then it will be seen that trajectory crosses acceptance line $R3$. Point A is point of significant change of reliability (effective improvement has been realized here).

If coordinate origin of plane-table is transferred in point A then it will be seen that trajectory crosses acceptance line $R4$, i.e. higher level of reliability has been achieved.

Graphic representation of time-series technique with one-sided bound as assemblage of acceptance lines can be used at preset low indicators of reliability. It is possible to keep control of reliability level directly during tests using such graphs.

As graph is filled up by trajectory of actual control depending on at which level trying-out product is at given instant, it is possible to stop tests and realize corresponding improvements with the aim of reliability increase of this product. Such visual control during the tests is exactly that essential difference from classical approach, according to which they judge about indicators of reliability only after realization of full assigned test amount. Graphic representation of assemblage of acceptance lines is not quite convenient for test products which, as a rule, are subjected to a large number of tests and many design improvements and also for products with high indicators of reliability in consequence of their unhandiness.

In is necessary to create multitude of graphs at control of high indicators of reliability by graph technique what results in additional difficulties at their using. In this connection coordinates of boundary points belonging to acceptance lines are marked on graph instead of plotting of these lines. Such solution is more convenient as it eliminates plotting of a large number of graphs and their constant filling up during the tests and also increases test amount (number of tests) and number of failures practically without limit keeping high accuracy of results at this [6].

Consider derivation of equation for acceptance line. The system will solve system of equations (6) for that. Finding the logarithm of the second equation of this system, will obtain (7).

$$\ln \Delta\beta = -\frac{h}{S}\ln(1-P), \tag{7}$$

Whence obtain (8)

$$-\frac{S}{h} = \frac{\ln(1-P)}{\ln \Delta\beta}. \tag{8}$$

From the first equation of the system (6) have (9).

$$\beta^{-\frac{1}{h}} - 1 = \frac{\beta^{-\frac{S}{h}} - 1}{P} \tag{9}$$

or (10)

$$\beta^{-\frac{1}{h}} = 1 + \frac{\beta^{-\frac{S}{h}} - 1}{P}. \tag{10}$$

Finding the logarithm of the equation (10), will obtain (11)

$$-\frac{1}{h}\ln\beta = \ln\left[1 + \frac{\beta^{-\frac{S}{h}} - 1}{P}\right] \tag{11}$$

Whence obtain (12).

$$-\frac{1}{h} = \frac{\ln\left[1 + \frac{\beta^{-\frac{S}{h}} - 1}{P}\right]}{\ln\beta}. \tag{12}$$

From the equation (8) will find (13)

$$S = -\frac{h\ln(1-P)}{\ln\Delta\beta}. \tag{13}$$

From the equation (12) will find (14)

$$h = \frac{-\ln\beta}{\ln\left[1 + \frac{\beta^{-\frac{S}{h}} - 1}{P}\right]}. \tag{14}$$

After solving the system of equations relatively unknowns h and S, will obtain the equation of acceptance line [6] as (15).

$$m = SN + h, \tag{15}$$

where m – number of failures (ordinate axis); N – number of test cycles (abscissa axis).

From the equation (15) will obtain (16).

$$N = \frac{m-h}{S} = \frac{m}{S} - \frac{h}{S} = \frac{m}{\frac{-h\ln(1-P)}{\ln\Delta\beta}} + \frac{\ln\Delta\beta}{\ln(1-P)} = \frac{\ln\Delta\beta}{\ln(1-P)} - \frac{m\ln\Delta\beta}{h\ln(1-P)} \tag{16}$$

Substitute in the expression (16) value of h from formula (14) and will obtain (17).

$$N = \frac{\ln\Delta\beta\left[m\ln\left(1 + \frac{\beta^{-\frac{S}{h}} - 1}{P}\right) + \ln\beta\right]}{\ln\beta\ln(1-P)}. \tag{17}$$

Further, substituting value of S/h from the expression, will obtain functional dependence of number of test on number of failures at preset values of magnitudes P, β and Δβ finally (18).

$$N = \frac{\ln\Delta\beta\left[m\ln\left(1 + \frac{\beta^{\frac{\ln(1-P)}{\ln\Delta\beta}} - 1}{P}\right) + \ln\beta\right]}{\ln\beta\ln(1-P)}. \tag{18}$$

As indicator of reliability is more often preseted as probability of nonfailure operation in technical requirements then will substitute value $R = 1 - p$ instead of p in formula (17) and will obtain expression (19) [6].

$$N = \frac{\ln\Delta\beta\left[m\ln\left(1 + \frac{\beta^{\frac{\ln R}{\ln\Delta\beta}} - 1}{1-R}\right) + \ln\beta\right]}{\ln\beta\ln R}. \tag{19}$$

Equation (19) is analytic form of expression of consecutive binomial sampling plan. Preseting value of failure number m, probability R of nonfailure operation of one cycle, customer risk β and initial customer risk Δβ, test amount N is determined. Test amounts N (in cycles) for some values of m, R, β and Δβ = 0.25β for time-series analysis with one-sided bound have been calculated and represented in table 1 borrowed from the work [1].

Example of table using. It is required to determine test amount N of control systems of turbine T-100-130 TMZ (number of cycles), which is necessary for acknowledgement of probability R = 0.9 of nonfailure operation during one cycle at confidence probability γ = 1 – β = 0.9, if 5 failures have been fixed during the tests. We find N = 112 on table 1.

It is possible to control reliability level of control systems in the process of test carrying out with the help of this table. Thus, for example, N = 655 of test cycles have been carried out during the tests and 1 failure has been fixed at this. It is inquired what probability R has been verified by these tests and with what confidence probability γ. Found that R = 0.992 and γ = 0.95 on table 1.

It is possible to compose tables of test planning and control of reliability level by time-series technique with one-sided bound for binomial distribution law with the help of computer. The obtained tables are convenient at test planning and control of reliability level when one level of reliability indicator is presented in the technical requirements.

Using of time-series technique with one-sided bound at binomial distribution law is explained by that product between improvements doesn't subjected to design, technological and other changes, i.e. probability of failure occurrence in each interval between improvements is considered as constant magnitude. Starting from this assumption it is possible to keep binomial sampling plan and at introduction of improvements. Achievement of preset reliability level as a result of carrying out of the last improvement is realized with some constant probability P (probability of failure occurrence in one cycle). Reliability R of product grows from one improvement to another in general test pattern, i.e. takes values of R_1, R_2,..., R_n consecutively to required level $R_{\text{тр}}$, after that tests are stopped, and product is accepted to operation.

Table 1. *Calculated values of test amounts N for some preset magnitudes R, m, γ at Δβ = 0.25β.*

Probability *R* of nonfailure operation at one cycle	**Number of failures *m***	**Test amount *N*, cycles, at confidence probability γ = 1 – β, equal to**						
		0.5	**0.6**	**0.7**	**0.8**	**0.9**	**0.95**	**0.99**
0.500	1	5	6	6	7	8	9	12
	5	15	15	16	17	19	21	25
	10	26	27	29	30	33	36	41
	20	49	51	53	57	61	66	74

Probability R of nonfailure operation at one cycle	Number of failures m	Test amount N, cycles, at confidence probability $\gamma = 1 - \beta$, equal to						
		0.5	0.6	0.7	0.8	0.9	0.95	0.99
	50	118	123	128	135	145	155	173
	100	223	242	252	267	285	303	337
0.900	1	32	34	38	43	50	58	75
	5	80	85	91	99	112	124	160
	10	140	148	157	170	189	206	243
	20	261	274	290	311	343	371	428
	50	622	652	688	734	804	866	986
	100	1225	1283	1352	1440	1574	1690	1915
0.992	1	411	446	490	552	655	756	984
	5	1019	1083	1162	1268	1438	1596	1934
	10	1778	1879	2002	2164	2416	2646	3122
	20	3298	3472	3681	3954	4373	4747	5498
	50	7256	8249	8720	9326	10245	11050	1265
	100	15453	16211	17117	18280	20030	21555	2460
0.999	1	32951	35770	39345	44290	52558	60643	7893
	5	81614	86787	93160	101675	11531	128012	1550
	10	14242	150558	160429	173407	19379	212223	2503
	20	26408	278101	294967	316869	350686	380644	440984
	50	629068	660728	698580	747256	821156	885909	1012628
	100	1273350	1298440	1371208	1464567	1605438	1728018	1965367

2.2. Test Planning with Time-Series Techniques at Two Preset Levels of Reliability Indicator for the Poisson Distribution Law

Let consider the time-series techniques with two-sided confidence bound and two preset reliability levels for the Poisson distribution law in order to reduce the test amount.

In this case, the logarithm of the likelihood ratio is written as:

$$\ln\left(\frac{P_1}{P_0}\right) = \ln\left[\prod_{i=1}^{n}\frac{q_1^{m_i}e^{-q_1}m_i!}{q_0^{m_i}e^{-q_0}m_i!}\right] = \ln\left[\prod_{i=1}^{n}\frac{q_1^{m_i}e^{-q_1}}{q_0^{m_i}e^{-q_0}}\right].$$

After taking the logarithm of the right part of the equation we obtain:

$$\ln\left(\frac{P_1}{P_0}\right) = \sum_{i=1}^{n} m_i \ln\left(\frac{q_1}{q_0}\right) - n(q_1 - q_0),$$

where q_1 – acceptable failure rate, $q_1 = \lambda_1 t$;

q_0 – required failure rate, $q_0 = \lambda_0 t$; $q_1 > q_0$.

Then the test stop condition is the fulfillment of inequalities (20), (21):

$$\left(\sum_{i=1}^{n} m_i\right)_{rej} \cdot \ln\left(\frac{q_1}{q_0}\right) - n(q_1 - q_0) \geq \ln\left(\frac{1-\beta}{\alpha}\right); \quad (20)$$

$$\left(\sum_{i=1}^{n} m_i\right)_{ac} \cdot \ln\left(\frac{q_1}{q_0}\right) - n(q_1 - q_0) \leq \ln\left(\frac{\beta}{1-\alpha}\right), \quad (21)$$

where α – supplier risk;

β – customer risk.

If the inequality (20) is satisfied after n number of tests, then the hypothesis H_0 is discarded, i.e. the failure rate is greater than the permissible value λ_0. If the inequality (21) is satisfied after n number of tests, then the hypothesis H_0 is accepted, i.e. the failure rate is less than or equal to the permissible value λ_0.

Transformation of equations (20) and (21) by pre-marking $\left(\sum_{i=1}^{n} m_i\right)_{rej} = m_{rej}$ and $\left(\sum_{i=1}^{n} m_i\right)_{ac} = m_{ac}$:

$$m_{rej} = \frac{\ln\left(\frac{1-\beta}{\alpha}\right) + n\,(q_1 - q_0)}{\ln\left(\frac{q_1}{q_0}\right)}, \quad (22)$$

$$m_{ac} = \frac{\ln\left(\frac{\beta}{1-\alpha}\right) + n\,(q_1 - q_0)}{\ln\left(\frac{q_1}{q_0}\right)}. \quad (23)$$

To determine the average amount of tests at first approximation, could take the binomial distribution with the parameter $q = \lambda t$ instead of the Poisson distribution law. Then the average number of product operational periods to confirm the failure rate λ_0 is determined by the formula (24):

$$n_0 = \frac{\alpha \ln\left(\frac{1-\beta}{\alpha}\right) + (1-\alpha)\ln\left(\frac{\beta}{1-\alpha}\right)}{\lambda_0 t \ln\left(\frac{\lambda_1}{\lambda_0}\right) + (1-\lambda_0 t)\ln\left(\frac{1-\lambda_1 t}{1-\lambda_0 t}\right)}. \quad (24)$$

Each period of operation of the product corresponds to the duration t, and the total test time will be equal to:

$$S_0 = n_0 t.$$

Similarly, the average number of product operational periods to confirm the failure rate λ_1 is from the ratio:

$$n_1 = \frac{\beta \ln\left(\frac{\beta}{1-\alpha}\right) + (1-\beta)\ln\left(\frac{1-\beta}{\alpha}\right)}{\lambda_1 t \ln\left(\frac{\lambda_1}{\lambda_0}\right) + (1-\lambda_1 t)\ln\left(\frac{1-\lambda_1 t}{1-\lambda_0 t}\right)},$$

a total testing time, respectively, is:

$$S_1 = n_1 t.$$

Sample. For construction of lines of acceptance m_{ac} and refusal m_{rej}, considering that the probability of failure-free operation obeys the Poisson's law at the following initial data: duration of operation of the device during one cycle $t = 10\ h$; $\alpha = 0.00001$, $\beta = 0.1$; $\lambda_1 = 12 \cdot 10^{-3}\ 1/h$; $\lambda_0 = 10 \cdot 10^{-3}\ 1/h$.

Determine the average duration of the test to confirm the failure rate λ_0.

Decision. To construct rejection and acceptance lines (Figure 4), use the formulas (22) and (23), where $q_1 = \lambda_1 t$, $q_0 = \lambda_0 t$:

$$m_{rej} = \frac{\ln\left(\frac{1-0.1}{0.00001}\right) + n\left(12 \cdot 10^{-3} \cdot 10 - 10 \cdot 10^{-3} \cdot 10\right)}{\ln\left(\frac{12 \cdot 10^{-3} \cdot 10}{10 \cdot 10^{-3} \cdot 10}\right)} = 0.11n + 62.57;$$

$$m_{ac} = \frac{\ln\left(\frac{0.1}{0.99999}\right) + n\left(12 \cdot 10^{-3} \cdot 10 - 10 \cdot 10^{-3} \cdot 10\right)}{\ln\left(\frac{12 \cdot 10^{-3} \cdot 10}{10 \cdot 10^{-3} \cdot 10}\right)} = 0.11n - 12.63.$$

The average number of periods of work is determined by the formula (6):

$$n_0 = \frac{0.00001 \ln\left(\frac{1-0.1}{0.00001}\right) + 0.99999 \ln\left(\frac{0.1}{0.99999}\right)}{10 \cdot 10^{-3} \cdot 10 \ln 1.2 + \left(1 - 10 \cdot 10^{-3} \cdot 10t\right)\ln\left(\frac{1 - 12 \cdot 10^{-3} \cdot 10}{1 - 10 \cdot 10^{-3} \cdot 10}\right)} = 1155.$$

The total time of the test:

$$S_0 = n_0 t = 11550\ \text{h}.$$

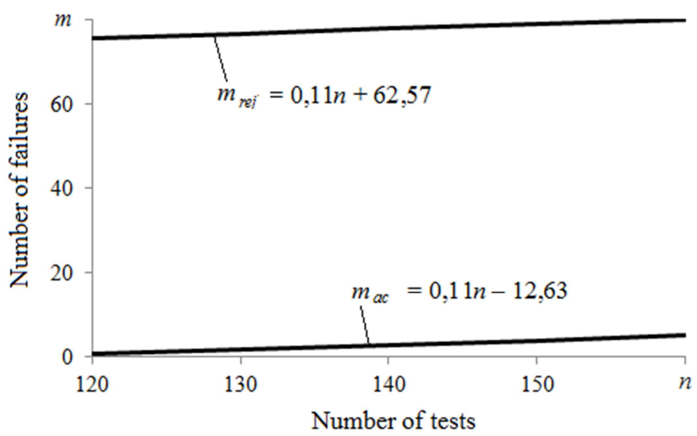

Figure 4. *Line of acceptance and rejection* m_{ac} *and* m_{rej}.

2.3. Test Planning with Time-Series Techniques at Two Preset Levels of Reliability Indicator for the Normal Distribution law of Mean time Between Failures

To confirm the specified failure time T_0 in the interval ($T_1 \le T \le T_0$) is determined by the average amount of tests by sequential analysis with a two-sided confidence bound on the expression of the form (25):

$$n_0 = \frac{(1-\alpha)\ln\left(\frac{\beta}{1-\alpha}\right) + \alpha \ln\left(\frac{1-\beta}{\alpha}\right)}{M\left[\ln\left(\frac{f(t_i, T_0, \sigma_0)}{f(t_i, T_1, \sigma_1)}\right)\right]}. \quad (25)$$

Accordingly, to confirm the failure time T_1, the average test volume is according to the formula:

$$n_1 = \frac{\beta \ln\left(\frac{\beta}{1-\alpha}\right) + (1-\beta)\ln\left(\frac{1-\beta}{\alpha}\right)}{\mathbf{M}\left[\ln\left(\frac{f(t_i, T_0, \sigma_0)}{f(t_i, T_1, \sigma_1)}\right)\right]},$$

where $\mathbf{M}\left[\ln\left(\frac{f(t_i, T_0, \sigma_0)}{f(t_i, T_1, \sigma_1)}\right)\right]$ – the mathematical expectation of a random variable from a sequence of observations, M takes the value T_0 or T_1.

Denote:

$$\mathbf{M}[z] = \mathbf{M}_{T_0}\left[\ln\left(\frac{f(t_i, T_0, \sigma_0)}{f(t_i, T_1, \sigma_1)}\right)\right]$$

or (26)

$$\mathbf{M}[z] = \int_{-\infty}^{\infty} \ln\left(\frac{f(t_i, T_0, \sigma_0)}{f(t_i, T_1, \sigma_1)}\right) f(t_i, T_0, \sigma_0)\, dt, \tag{26}$$

where $f(t, T_0, \sigma_0) = \frac{1}{\sigma_0\sqrt{2\pi}} \exp\left[-\frac{1}{2\sigma_0^2}(t - T_0)^2\right]$.

Taking $\sigma_1 = \sigma_0 = \sigma$, we find the likelihood ratio (27):

$$\ln\frac{f(t_i, T_0, \sigma)}{f(t_i, T_1, \sigma)} = \ln\frac{\exp\left[-\frac{1}{2\sigma_0^2}(t_i - T_0)^2\right]}{\exp\left[-\frac{1}{2\sigma_0^2}(t_i - T_1)^2\right]}. \tag{27}$$

Logarithm the expression (28):

$$\frac{1}{2\sigma^2}\sum_{i=1}^{n}(t_i - T_1)^2 - \frac{1}{2\sigma^2}\sum_{i=1}^{n}(t_i - T_0)^2 = \frac{1}{2\sigma^2}\left[T_1^2 - T_0^2 + 2\sum_{i=1}^{n} t_i(T_0 - T_1)\right]. \tag{28}$$

Assume the following assumption: all test periods are the same in time, i.e.. $t_i = t$. In this case, the expression (28) can be written as follows (29):

$$\ln\frac{f(t_i, T_0, \sigma)}{f(t_i, T_1, \sigma)} = \frac{1}{2\sigma^2}\left[T_1^2 - T_0^2 + 2nt(T_0 - T_1)\right]. \tag{29}$$

Next, substituting the expression (29) into formula (26) and integrating (30):

$$\mathbf{M}[z] = \int_{-\infty}^{\infty} \frac{1}{2\sigma^2}\left[T_1^2 - T_0^2 + 2\sum_{i=1}^{n} t_i(T_0 - T_1)\right]\frac{1}{\sigma_0\sqrt{2\pi}}\, e^{-\frac{(t_i - T_0)^2}{2\sigma^2}}\, dt$$

$$= \frac{(T_0 - T_1)}{\sigma^2}\left(T_1 - \frac{T_0 - T_1}{2}\right) = -\frac{(T_0 - T_1)^2}{2\sigma^2}. \tag{30}$$

Then, to confirm the mean time between failures T_0, substitute the expression (30) in (25) and we obtain (31):

$$n_0 = \left|\frac{\left[(1-\alpha)\ln\left(\frac{\beta}{1-\alpha}\right) + \alpha\ln\left(\frac{1-\beta}{\alpha}\right)\right]2\sigma^2}{-(T_0 - T_1)^2}\right|, \tag{31}$$

where n_0 – the number of periods of operation of duration T_0 each or the number of failures per time S.

In this case, the total test volume is (32):

$$S = n_0 T_0. \tag{32}$$

Based on the expression (29) for the logarithm of the likelihood ratio, was write the conditions for acceptance and rejection of the hypothesis H_0, consisting in the fact that $T = T_0$: the rejection of hypothesis H_0:

$$\frac{1}{2\sigma^2}\left[T_1^2 - T_0^2 + 2nt(T_0 - T_1)\right] \geq \ln\left(\frac{1-\beta}{\alpha}\right):$$

the adoption of the hypothesis H_0:

$$\frac{1}{2\sigma^2}\left[T_1^2 - T_0^2 + 2nt(T_0 - T_1)\right] \leq \ln\left(\frac{\beta}{1-\alpha}\right).$$

Since the number of m failures is fixed in the process of testing, the conditions of acceptance and rejection of the H_0 hypothesis can be represented as inequalities (33), (34):

$$\frac{nt}{T_1} = m_{rej} = \frac{1}{2}\left(\frac{T_0}{T_1} + 1\right) + \frac{\sigma^2 \ln\left(\frac{1-\beta}{\alpha}\right)}{T_0(T_0 - T_1)}, \tag{33}$$

$$\frac{nt}{T_1} = m_{ac} = \frac{1}{2}\left(\frac{T_0}{T_1} + 1\right) + \frac{\sigma^2 \ln\left(\frac{\beta}{1-\alpha}\right)}{T_0\left(T_0 - T_1\right)}. \quad (34)$$

Example. To construct lines of acceptance of MPR and rejection of MBR, for the normal law of distribution of operating time for failure at the following initial data: T_0 = 100 *h*; T_1 = 80 *h*; σ = 10 *h*; α = 0.00001, β = 0.1.

Determine the number of periods of work duration *T*0 each and the total amount of testing.

Decision. To construct rejection and acceptance lines (Figure 5), use the formulas (33) and (34) for some values of T_0/T_1:

$$m_{rej} = \frac{1}{2}\left(\frac{T_0}{T_1} + 1\right) + \frac{\left(-230.26\right)\cdot T_0 / T_1}{100^2\left(T_0 / T_1 - 1\right)},$$

$$m_{ac} = \frac{1}{2}\left(\frac{T_0}{T_1} + 1\right) + \frac{1140.76 \cdot T_0 / T_1}{100^2\left(T_0 / T_1\right)}.$$

We define by the formula (31) the number of periods of work with duration T_0 each:

$$n_0 = \left|\frac{\left[0.9999 \ln\frac{0.1}{0.9999} + 0.9999 \ln\frac{0.9}{000001}\right]\cdot 2\cdot 10^2}{-\left(100-80\right)^2}\right| = 1.15.$$

Calculate the total volume of tests according to the formula (14):

$$S = 1.15 \cdot 100 = 115\,\text{h}.$$

To confirm the time between failures within T_0 = 100 *h* and T_1 = 80 *h*, it is necessary to conduct a test volume of 115 *h*.

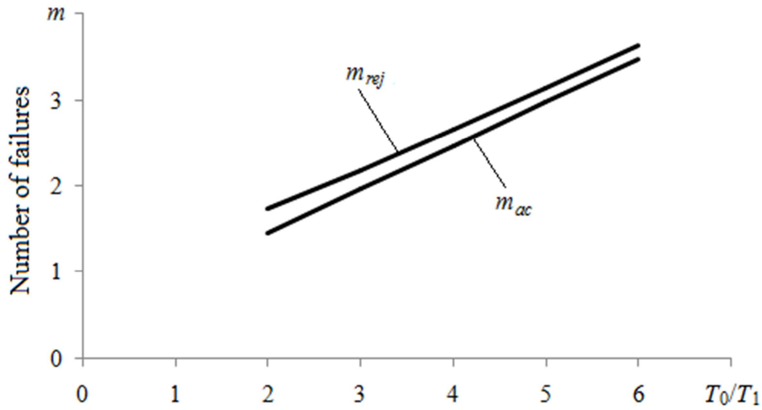

Figure 5. *Line of acceptance and rejection* m_{ac} *and* m_{rej} .

2.4. Test Planning of Expensive Discardable Products Using Time-Series Techniques for Various Distribution Laws at Supplier Risk α = 0

From practical experiences was know that during the tests samples are not rejected, but being improved and retested till the desired parameters are reached. Under such conditions the supplier risk is considered to be zero α = 0 for the product anyways is delivered to customer after failure restoration.

According to the accepted condition the math expression for the acceptance lines and average amount of tests at respective distribution laws are described in table 2.

Mathematical expressions for the lines of acceptance and average number of tests with various distributions and α = 0.

Table 2. *The mathematical expressions for the acceptance lines and the average volume of tests at various distribution laws and α = 0.*

Distribution law	The condition of acceptance of hypotheses H_0	The average number of trials (cycles, hours)
Binomial	$m_{ac} = \frac{\ln\beta - n\ln\left(\frac{1-q_1}{1-q_0}\right)}{\ln\left(\frac{q_1}{q_0}\right) - \ln\left(\frac{1-q_1}{1-q_0}\right)}$	$n_0 = \frac{\ln\beta}{q_0\ln\left(\frac{q_1}{q_0}\right) + \left(1-q_0\right)\ln\left(\frac{1-q_1}{1-q_0}\right)}$, (c.)
Exponential	$\frac{S}{T_0} = \frac{T_1}{T_0 - T_1}\left[m_{ac}\ln\left(\frac{T_0}{T_1}\right) - \ln\beta\right]$	$S_0 = T_0\left[m_0\frac{T_1}{T_0-T_1}\ln\left(\frac{T_0}{T_1}\right) - \frac{T_1}{T_0-T_1}\ln\beta\right]$, (h), where $m_0 = \frac{\ln\beta}{\ln\left(\frac{T_0}{T_1}\right) - \frac{T_0}{T_1} + 1}$

Distribution law	The condition of acceptance of hypotheses H_0	The average number of trials (cycles, hours)
Poisson's	$m_{ac} = \frac{\ln\beta + n(q_1 - q_0)}{\ln\left(\frac{q_0}{q_1}\right)}$, where $q_1 = \lambda_1 t$, $q_0 = \lambda_0 t$	$S_0 = n_0 t, (h)$, where $n_0 = \frac{\ln\beta}{\lambda_0 t \ln\left(\frac{\lambda_0}{\lambda_1}\right) + (1 - \lambda_0 t)\ln\left(\frac{1-\lambda_1 t}{1-\lambda_0 t}\right)}$, t – duration of each test period
Normal	$m_{ac} = \frac{1}{2}\left(\frac{T_0}{T_1} + 1\right) + \frac{\sigma^2 \ln\beta}{T_0(T_0 - T_1)}$	$S_0 = n_0 T_0, (ч)$, where $n_0 = -\frac{2\sigma^2 \ln\beta}{(T_0 - T_1)^2}$

3. Discussion

During the sample test heat power equipment components [1, 2] are not rejected due to their high cost. Once the failure origin is identified the failed components are being improved and then the test is continued [3-6]. To confirm the improvement efficiency the tests are carried out again with the same amount. Improvement is efficient if no failure occurs during the retest. There are various methods for planning test amount, including ones using fixed amount [7-11].

4. Results

The test amount planning technique for binomial distribution law of products at one preset level of reliability indicator has been considered. The formulas of test amounts for one level and the table of calculated values of test amounts for some preset magnitudes (probabilities of nonfailure operation, number of failures, confidence probability) have been represented. The test amount planning technique for normal distribution law of mean time between failures and Poisson distribution law for probability of failure at two preset levels of reliability indicator has been considered.

Also, foreign authors are engaged in the issues of reliability of power equipment. The works of such authors as Suleimenov B. A., Agrawal V., Salomon D. [12-14].

5. Conclusions

1. The proposed mathematical model of planning the amount of testing at given reliability level at binomial distribution law of faultness probability and producer's risk (α=0) can be of research and practical interest for expensive CHP power equipment usage, including prototype models.
2. In order to improve CHP powe equipment reliability the suggested techniques can be used to determine the amount of testing at the given values of faultness probability, failure number and confidence level.
3. In the solution of planning the amount of testing of expensive power equipment optimization problem, precisely to reduce its amount, the equipment reliability model at Poisson and normal distribution laws of time between failures at two given reliability levels and at minimal (α = 0.00001) and zero producer's risk (α = 0).
4. In the process of power equipment reliability evaluation techniques development the mean amount of testing calculation at different distribution laws and α = 0 is suggested to prevent computation errors.

References

[1] Sultanov M. M. Assessment of reliability, extension of service life and optimization of repair of thermal power plant equipment and power systems. –Volzhsky: Volzhsky branch of MPEI , 2016.–100 p.

[2] Lloyd D., Lipov M. Reliability. –M.: Soviet radio, 1964. – 687 p.

[3] Reliability and efficiency in engineering. T. 1. Methodology. Organization. Terminology/ Under edition A. I. Rembezy. – M.: Engineering, 1986. – 224 p.

[4] Reliability and efficiency in engineering. T. 6. Experimental testing/ Under edition R. S. Sudakova, O. I. Teskina. – M.: Engineering, 1989. – 376 p.

[5] Sultanov M. M., Truhanov V. M. Mathematical model of change of output operational characteristics of steam turbines of TPP // The reliability and security of energy. –2017. – T. 10, №1. – p. 42-47.

[6] TruhanovV. M. Reliability of engineering products. Theory and practice: textbook. – 2nd edition, revised and supplemented/ V. M. Truhanov.–M.: Edition «Spektr», 2013. – 334 p.

[7] RD50-650-87. Methodical instructions. Reliability in technology. Composition and general rules for setting reliability requirements. – M.: Edition of standards, 1988. – 23 p.

[8] RD 50-109-89. Recommendations. Reliability in technology. Ensuring product reliability. Ensuring requirements. –M.: Edition of standards, 1989. – 16 p.

[9] Truhanov V. M. Reliability in technology. M.: Edition «Spektr», 2017. – 634 p.

[10] Sultanov M. M., Truhanov V. M., Arakelyan E. K., Kulikova M. A. Methods of achieving and ensuring a high level of reliability and safety of power equipment of TPP, HPP, NPP at all stages of the life cycle, ISSN: 2312-055X, 2018. – 6-14 p.

[11] Truhanov V. N., Sultanov M. M. Estimation technique of corrective effects for forecasting of reliability of the designed and operated objects of the generating systems, ISSN: 1742-6596, 2017.–1-13 p.

[12] Truhanov V. M., Sultanov M. M., Kukhtik M. P., Gorban Yu. A. Mathematical model of predicting of failures by statistical method at testing of prototypes of heat-power equipment of power supply systems of TEHS// The reliability and security of energy. – 2018. – T. 11, № 3. – p. 235-240.

[13] Suleimenov B. A., Sugurova L. A., Suleimenov A. B., Suleimenov A. B., Zhirnova O. V. Synthesis of the equipment health management system of the turbine units' of thermal powerstations.–MECHANICS & INDUSTRY, 2018.

[14] Agrawal V., Panigrahi B. K., Subbarao P. M. V. Increasing Reliability of Fault Detection Systems for Industrial Applications.–IEEE INTELLIGENT SYSTEMS, 2018.

[15] Salomon D., Motta G. Handbook of data compression.– Springer Science & Business Media, 2010.