ISSN 0040-6015, Thermal Engineering, 2013, Vol. 60, No. 8, pp. 567–572. © Pleiades Publishing, Inc., 2013.
Original Russian Text © K.E. Aronson, A.Yu. Ryabchikov, Yu.M. Brodov, M.I. Loginov , 2013, published in Teploenergetika.

Development of a Procedure for Substantiating Replacement Terms for the Condenser Tubes of Steam Turbine Installations

K. E. Aronson, A. Yu. Ryabchikov, Yu. M. Brodov, and M. I. Loginov
Ural Federal University, ul. Mira 19, Yekaterinburg, 620002 Russia

Abstract—Results obtained from elaboration of a procedure for estimating replacement terms for the condenser tube systems of steam turbine installations are presented. Censored data processing methods are used in performing statistical assessment of replacement terms. The service life of condenser tubes blanked off in the course of turbine operation is assumed to be known (complete operation time), and that for tubes blanked off during the turbine repair process is assumed to be undetermined (censored operation time). The criterion for estimating the replacement term for a condenser tube system is defined as the ratio between the number of tubes blanked off during a repair and in the course of turbine operation. The procedure is validated by the results from a study on analyzing the damageability of tubes made of different materials for the condensers of 11 turbines with capacities ranging from 25 to 500 MW.

Keywords: steam turbine unit condenser, condenser tube replacement terms, statistical methods, censored data

DOI: 10.1134/S0040601513080016

The problem of substantiating replacement terms for the condenser tube systems of steam turbine installations(STIs) does not have a clear-cut solution as yet. An explanation to this is as follows. The failure criterion of a single tube is fairly obvious (degraded quality of the main condensate determined during operational monitoring or the occurrence of leaks in subjecting the condenser to hydraulic pressurization tests during the turbine repair), whereas a failure criterion for the condenser as a whole has not been formulated as yet. In some publications [1, 2], the replacement term is determined as the time by which 10% of tubes in the apparatus have been blanked off or as the apparatus service life (equal to 30 years for condensers). Such recommendations cannot be regarded as a reliable substantiation for replacing condenser tubes.

One characteristic feature relating to condenser tube failures (especially for tubes made of brass) is as follows. After a long period of normal operation characterized by a constant failure rate, there comes a moment when a large number of tubes fail abruptly in the condenser, so that the apparatus becomes in fact unable to perform its intended functions and does not allow further operation of the turbine unit. A need arises to make significant expenditures of money and take the STI out from operation for repair, which may take as long as a few months if the thermal power station is insufficiently prepared for condenser repair. The aim of this work is to determine the moment of time at which work on planning the financial and time resources for restoring (overhauling) the condenser should be started.

Economic models [3, 4], models representing the kinetics of corrosion damage inflicted to tubes [5, 6], and statistical models [6–8] using an approximation of the probability or other statistical indicators characterizing failures of individual tubes in apparatuses were applied for substantiating the replacement terms of the condenser tube systems.

In [3, 4], an economic approach to the problem of substantiating replacement terms for the tube systems of STI heat-transfer apparatuses was presented. Both of these works use an objective function defined proceeding from the equality between the specific operational costs for an apparatus with some of its tubes blanked off (increased consumption of heat by the turbine) and the specific operational and capital costs in the case of installing a new tube system or overhauling the old one.

Calculations of the optimal replacement terms for the tubes of different STI heat-transfer apparatuses performed out using modern procedures for carrying out technical-economic substantiation of measures taken in power engineering have shown that the cost of fuel at thermal power stations, the cost of tubes, and the STI operating mode have an essential effect on the replacement terms of the tube systems of heat-transfer apparatuses [1, 3]. According to the results of the performed calculations, the fraction of damaged heat-transfer surface at which it is advisable to replace condenser tube systems varies from 10–13% for condensing turbines to 12–25% for cogeneration turbines.

In [5], a model representing the kinetics of metal corrosion process was proposed for estimating the damageability of condenser tubes, according to which the extent of corrosion damage inflicted to the tubes is proportional to the square root of the condenser operation time. Such a model does not take into account the extent of damage inflicted to the tubes due to other factors during normal operation, nor does it take into account changes in the tube failure rate in the course of exhausting the condenser service life. According to [8], the largest number of condenser failures that led to turbine shutdown (up to 39.3%) was connected with vibration of tubes. Erosion–corrosion damages to tubes lead to failures in 37.5% of cases; up to 12.5% of failures are due to poor quality of tube manufacture or their rolling in tube sheets; 7.1% of failures are due to general thinning of tube walls, and 3.6% of tube damages are inflicted by fragments of blades entering into the condenser steam space from the turbine low-pressure flow path. These data were obtained on 150 steam-turbine installations with capacities ranging from 12 to 800 MW installed at 60 thermal power stations in Russia for the period from 1994 to 1999.

In [6], failures of tubes made of CuNi5Fe1 alloy used in K-33160 and K-45600 condensers are approximated by a linear function. The remaining service life of tube systems is determined by extrapolating the values of this function to the point at which the fraction of failed tubes reaches 10%. In [7], the corrosion rate of tubes made of Grade CuZn4 brass is determined, and the condenser service life is estimated to the point at which the residual tube wall thickness reaches 0.6 mm (the initial tube wall thickness is equal to 1 mm).

In [8], a statistical distribution function for the operation time of tubes used in K-15240 condensers (made of CuNi5Fe1 alloy) is constructed, and the moment of time is estimated (with a preset confidence probability) at which the number of blanked off tubes exceeds 10% of the total number of tubes in the condenser. The state of tube metal in a number of turbine condensers at the Reftinsk district power station (DPS) was analyzed, and the following was shown from that analysis. If a tube sample (made of Grade CuZn32 brass) randomly selected for analysis has a mean residual wall thickness $\delta_w \leq 0.46$ mm, the extent to which the condenser tubes are damaged is 90% or more with a probability of 99.7%, due to which the tube bundle has to be replaced.

The above-described approaches to processing statistical information about damageability of condenser tubes can be used during normal operation of a condenser. However, when a growth occurs in the tube failure rate, and when a change occurs in the law describing the damage inflicted to them, application of the methods described in [6–8] may result in that the remaining life of the condenser will be estimated with a significant error.

One else difficulty is that a statistical analysis of condenser tube damageability is in many cases carried out under the conditions of incomplete and partially inadequate initial information. In our opinion, methods for processing censored data [9] can be used for analyzing such information.

METHODS FOR SUBSTANTIATING REPLACEMENT TERMS FOR THE CONDENSER TUBE SYSTEMS OF STEAM TURBINE INSTALLATIONS

In substantiating the time when condenser tube systems are to be replaced, it is necessary to be sure that the damaged tubes are uniformly distributed in a bundle (in this case, tube failures are predominantly due to exhaustion of their service life) [10]. The results of such investigation must also be corroborated by the data from an analysis of the material of tube samples cut out from the condenser.

The following initial data are required for estimating the time at which condenser tubes are to be replaced: the total number of tubes in the apparatus; the total number of tubes that have failed (have been blanked off) by the time at which estimation is carried out; and an array of data containing information about the number of failed tubes and the total periods of time for which they have been in operation (n_i, τ_i), where $i = 1, ..., m$; n_i is the number of tubes failed by the ith moment of time; and τ_i is the period of time for which the tubes have been in operation at the ith moment of time. In addition, the schedule of turbine repairs has to be known.

As an example, the table contains selected data on the blanked-off tubes in the K-15240 condenser of the K-300-23.5 turbine produced by KhTZ that is installed at the Reftinsk DPS. The first column of the table contains data on the tubes blanked off as they become damaged; the first line of the second column indicates the difference between the total number of blanked off tubes and the number of tubes for which the time of their blanking off is known; and the fourth column contains the sign by which the data on tube failures are either censored (0), i.e., with unknown time to failure, or complete (1), i.e., with the known time to failure.

Figure 1 presents data on the relative number of blanked off tubes $\Sigma n_i/N$ as a function of operating time for a number of condensers. The condensers denoted in Fig. 1 by digits *1–3* are assembled from brass tubes, and those denoted by *4–6* are assembled from tubes made of CuNi5Fe1 alloy. Two damageability periods are characteristic of condensers with brass tubes: the first one is a period of normal operation characterized by a low failure rate, and the second one is a period in which the service life becomes exhausted, and which is characterized by a rapidly growing tube failure rate. From a few tens to a few hundreds of tubes can be blanked off at once. Obviously, further operation of the condenser under such conditions is impossible.

Data on blanked-off tubes

Number of failed tubes $k_i(r_i)$	Total number of failed tubes Σn_i	Operation time $t_i(t_i)$, thousand h	Censoring (0 if yes and 1 if no)	Number of plants being observed, N_u	Equivalent amount of sampling, N_{eq}	Distribution function of censored sampling F_{cen}	Distribution function of complete sampling F_{com}	Absolute value $(F_{cen}-F_{com})$
1	2	3	4	5	6	7	8	9
938*	938	111	0	18654	18654	0.00000	0.00000	0.00000
2	940	111	1	18654	–	0.00011	0.00011	0.00000
5	945	119	0	18647	17716	0.00011	0.00038	0.00027
12	957	125	1	18647	–	0.00079	0.00102	0.00023
4	961	133	1	18647	–	0.00101	0.00123	0.00022
3	964	133	1	18647	–	0.00118	0.00139	0.00021
5	969	167	1	18647	–	0.00146	0.00166	0.00020
5	974	168	1	18647	–	0.00174	0.00193	0.00019
39	1013	201	0	18579	17711	0.00174	0.00403	0.00229
226	1239	212	0	18353	17672	0.00174	0.01634	0.01460
25	1264	217	0	18328	17445	0.00174	0.01771	0.01596
11	1275	220	1	18328	–	0.00238	0.01831	0.01593
114	1389	224	0	18203	17420	0.00238	0.02457	0.02220
4	1393	226	1	18203	–	0.00260	0.02479	0.02219
40	1433	239	1	18203	–	0.00490	0.02699	0.02209
638	2071	240	0	17521	17306	0.00490	0.06340	0.05850
11	2082	242	1	17521	–	0.00554	0.06403	0.05849
609	2691	248	0	16901	16664	0.00554	0.10006	0.09453

* Difference between the total number of blanked-off tubes and the number of tubes for which the time of their blanking off is known.

For condensers with tubes made of CuNi5Fe1 alloy, their failure curves (*4–6* in Fig. 1) have a different pattern: the failure rate shows a gradual growth, and mass-scale failures of tubes are not observed.

In our opinion, different patterns of failures that are typical for condensers with brass tubes and tubes made of CuNi5Fe1 alloy are due to the specific features of corrosion damages that occur in tubes made of these materials. For brass, gradual loss of zinc is typical, manifesting itself in general thinning of the walls [1, 7]. When the residual wall thickness reaches the critical value (see above), mass-scale failures of tubes begin to occur. According to our data, tubes with worn inlet parts comprise a considerable portion (up to 53%) of the total number of failed brass tubes. For tubes made of CuNi5Fe1 alloy, pitting corrosion damages are typically observed. Different patterns of tube failures for condensers with brass tubes and tubes made of CuNi5Fe1 allow generate the need to impose certain requirements for the procedure of substantiating the replacement terms of their tube systems.

The main idea of the proposed procedure is that the state of the condenser as a whole is characterized by the number of tubes blanked off during the turbine (power unit) repair process. The operation age of these tubes constitutes a censored sampling; i.e., the exact time of their failure in the course of condenser operation is unknown. Indeed, on completion of a turbine repair process, the condenser is subjected to hydraulic tests: its steam space is filled with pure condensate, and its faulty tubes are blanked off. During the turbine startup and shutdown processes the condenser tubes (especially the zone of rolled connections) experience more intense effects than during normal operation,

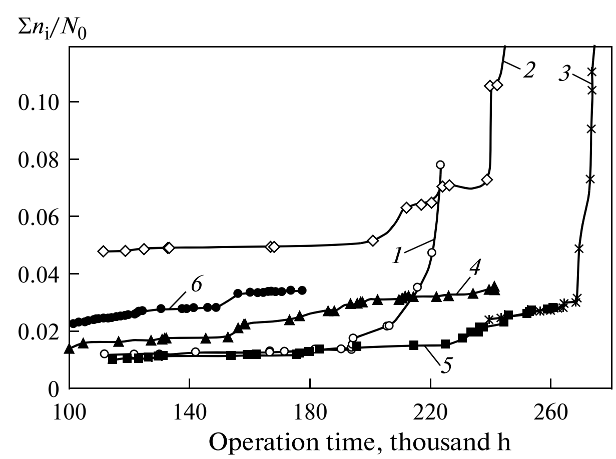

Fig. 1. History of condenser tube failures. (*1*) K-15240, Unit 2 at the Reftinsk DPS, brass tubes; (*2*) K-15240, Unit 4 at the Reftinsk DPS, brass tubes; (*3*) K2-300-2, turbine No. 2 at the Nevinnomyssk DPS, brass tubes; (*4*) K-15240, Unit 5 at the Reftinsk DPS, CuNi5Fe1 alloy; (*5*) K-15240, Unit 6 at the Reftinsk DPS, CuNi5Fe1 alloy; and (*6*) K-11520, Unit 7 at the Reftinsk DPS, CuNi5Fe1 alloy.

although these effects are insignificant. In [11], the influence of thermal cycles (thermal drying operations) on tube samples made of CuZn32As0.05, CuNi5Fe1, and CuNi5Fe1 alloys was studied. It was found that multiple thermal cycles (up to 210) do not affect the serviceability of steam turbine condenser tubes; as regards the corrosion resistance of tubes and physical-chemical properties of their metal, they change insignificantly. If failures of condenser tubes occur during their hydraulic tests carried out in the course of turbine repair process, this means that these tubes have worked out their service life almost completely (failed) during operation prior the repair; i.e., the operation time of these tubes is uncertain. The interval of uncertainty (censoring interval) is taken equal to the interval from the current repair to the repair during which the tubes were blanked off last time.

The problem of substantiating the replacement term for the condenser tube system is formulated as follows.

—Two samplings are constructed on the basis of gathered data: a censored one, which describes the state of the condenser as a whole, in accordance with column 4 of the table and a complete sampling, which characterizes the operation times of individual tubes, for which all periods of operation (except for the first one) from the table are assumed to be complete ones. For tubes the state of which was not known to the moment at which the total number of blanked-off tubes (the first line of the table) was estimated, the censored time of operation is taken.

—Empirical distribution functions (F_n) are constructed for both samplings according to the algorithm described below.

—An agreement criterion is formulated, and the confidence interval is determined within which the difference between the censored and complete samplings can be regarded as insignificant with a preset confidence probability. The moment of time at which the complete sampling distribution function goes beyond the boundaries of the constructed confidence interval (critical region) is determined as the time of making decision about replacement of the condenser tube system.

The following requirement is imposed on the procedure: the gap between the moment at which the decision is made about replacing the condenser tubes and the moment at which the condenser loses its serviceability must be around 1–2 years. This period of time (1–2 years) is required for planning works on replacing the condenser tubes.

We will now construct the censored sampling distribution function using the method of sequential shift to a new system of coordinates [9]. To do so, we subdivide the period of observations into m nonintersecting intervals, the boundaries of which coincide with the values of operation time to censoring (times to repairs). Censored operation times are denoted by τ_i ($i = 1, \ldots m$), and the number of censored operation times by k_i. Complete operation times are denoted by t_i, and the number of complete operation times is denoted by r_i.

The total number of blanked off tubes for the time moment i is determined as follows: $\sum_{j=1}^{i} n_j = \sum_{j=1}^{i} k_j + \sum_{j=1}^{i} r_j$. After that, we calculate the number of objects for which observation is carried out (the subscript "u") in the ith interval (t_{i-1}, t_i):

$$\left.\begin{aligned} N_{u-1} &= N - \sum_{j=1}^{i-1}(r_j + k_j), \quad i > 1; \\ N_{u,i} &= N - k_0, \quad i = 1, \end{aligned}\right\} \qquad (1)$$

where $k_0 = 938$ is the difference between the total number of blanked off tubes and the number of tubes for which the time of their blanking off is known (including those blanked off during the repair), and N is the total number of tubes in the apparatus.

Each interval is characterized by an equivalent amount

$$\left.\begin{aligned} N_{\mathrm{eq},i} &= \frac{N_{u,i}}{1 - F(t_{i-1})} \\ &= N_{\mathrm{eq},i-1}\left[1 - \frac{k_{j-1}}{N - \sum_{j=0}^{i-2} k_j - \sum_{j=1}^{i-1} r_j}\right], \quad i > 1; \\ N_{\mathrm{eq},i} &= N - k_0, \quad i = 1. \end{aligned}\right\} \qquad (2)$$

The empirical distribution function in a current interval is constructed for complete operation times from the sampling of amount $N_{u,i}$ in the new system of coordinates with a constant scale along the time axis and with the scale coefficient $\{1 - F(t_i - 1)\}$ along the ordinate axis [9]. The distribution function for the censored sampling is a stepped curve the step width in which corresponds to the complete operation time denoted by "1" in the fourth column of the table, and its height is equal to the number of blanked off tubes for the given moment of time. The effect of censored operation times is such that the values of the distribution function are shifted rightward (along the abscissa axis) to the moment of time corresponding to this time of operation.

The distribution function for the censored sampling is calculated from the formula

$$\left.\begin{aligned} F_{\mathrm{cen}}(t_i) &= \sum_{j=1}^{i-1} \frac{r_j}{N_{\mathrm{eq},i}} + \frac{\sum_{j=0}^{i} n_j - \sum_{j=0}^{i-1} k_j - \sum_{j=1}^{i-1} r_j}{N_{\mathrm{eq},i}}, \quad i > 1; \\ F_{\mathrm{cen}}(t_i) &= \frac{(n_i - k_0)}{N_{\mathrm{eq},i}}, \quad i = 1. \end{aligned}\right\} \qquad (3)$$

The distribution function for the complete sampling is estimated from the following dependences:

$$\left.\begin{aligned} F_{\text{com}}(t_i) &= F_{\text{com}}(t_{i-1}) + \frac{n_i}{N_{u,i}}, \quad i > 1; \\ F_{\text{com}}(t_i) &= \frac{r_i}{N_{u,i}}, \quad i = 1. \end{aligned}\right\} \tag{4}$$

The results of calculations carried out according to formulas (1)–(4) are given in the table (columns 5–8).

Figure 2 shows the distribution functions for the samplings constructed according to formulas (3) and (4) for K-15240 condensers with brass tubes (Fig. 2a) and tubes made of CuNi5Fe1 alloy (Fig. 2b).

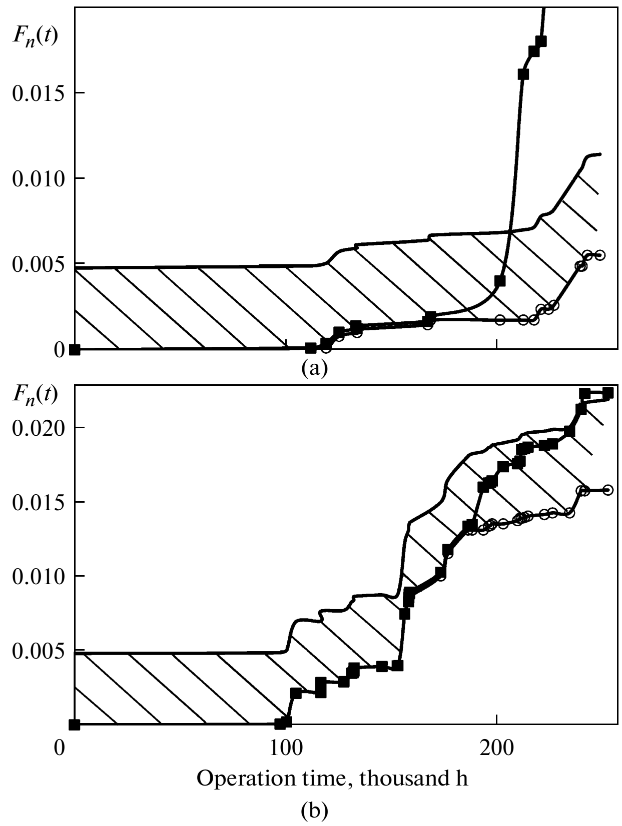

Fig. 2. Distribution function of the times to failure of K-15240 condenser tubes. (a) Condenser with brass tubes, (b) condenser with tubes made of CuNi5Fe1 alloy, (○) censored operation times, and (■) complete operation times.

We now consider a procedure for constructing a confidence interval (critical region) for estimating the time of replacing the condenser tubes. As is well known [12], if X is a random variable, its distribution function has a uniform distribution pattern in the interval [0, 1]. Hence, if two distribution functions are equal to each other, they must have equal mathematical expectations distributed according to the Gaussian law. In this case, it is possible to check the basic hypothesis about the equality of the mathematical expectations of the distribution functions of complete and censored samplings H_0: $MF_{\text{com}}(t) = MF_{\text{cen}}(t)$ against the alternative hypothesis H_1: $MF_{\text{com}}(t) \neq MF_{\text{cen}}(t)$. If a complete sampling of amount N is available, the basic hypothesis is rejected when the following is the case:

$$MF_{\text{com}}(t) - MF_{\text{cen}}(t) \geq \Phi^{-1}\left(1 - \frac{\alpha}{2}\right)\left(\frac{1}{6N}\right)^{0.5}, \tag{5}$$

where $\Phi^{-1}(1 - \alpha/2)$ is the level $(1 - \alpha/2)$ fractile of the standard Gaussian distribution, and α is the required criterion significance level. Here, we took into account that the variances for the random variables F_{com} and F_{cen} are known and equal to 1/12.

Instead of checking equality of the mean values of distribution functions in (5), we check the difference of the distribution functions (columns 7 and 8 in the table), because $(F_{\text{com}} - F_{\text{cen}}) \geq (MF_{\text{com}} - MF_{\text{cen}})$, and the basic hypothesis will be rejected in this case. Then, the expression for evaluating the confidence interval will be written as follows:

$$\Delta = F_{\text{com}} - F_{\text{cen}} = \left(\frac{1}{6N}\right)^{0.5}\Phi^{-1}\left(1 - \frac{\alpha}{2}\right). \tag{6}$$

An analysis of the structure of expression (6) for the confidence interval using which the tube system replacement term can be estimated shows that for each condenser it is possible to determine the maximal number of tube blanked off during a repair after exceeding of which the moment comes at which the entire tube system has to be replaced. For a condenser with the number of tubes N = 19 592 (the K-15240 condenser), such value, calculated from the formula

$$\Delta n_{\text{cr}} = \left(\frac{N}{6}\right)^{0.5}\Phi^{-1}\left(1 - \frac{\alpha}{2}\right) \tag{7}$$

at the significance level $\alpha = 0.05$ will be $\Delta n_{\text{cr}} = 94$ pcs.; for K-11520 condensers $\Delta n_{\text{cr}} = 115$ pcs.; and for K2-3000-2 condensers $\Delta n_{\text{cr}} = 45$ pcs. If such or greater number of condenser tubes is blanked off during one turbine repair, replacement of the entire condenser tube system must be planned.

With a growth of the number of repairs during which condenser tubes are blanked off, the critical region should become wider. Given the service life of heat exchangers equal to 30 years [2], the critical region's width is calculated from the dependence

$$\Delta n_{\text{cr}} = \left(\frac{N}{6}\right)^{0.5}\Phi^{-1}\left(1 - \frac{\alpha}{2}\right)\left(1 + \frac{\sum_{n}^{m} i}{30}\right), \tag{8}$$

where m is the number of power unit repairs during which condenser tubes are blanked off.

For the K-15240 condensers presented in Fig. 2a, with the total number of tubes $N = 19\,592$ and significance level equal to 0.05, the confidence interval Δ will be in the range from 0.0048 to 0.0115.

It follows from Fig. 2 that the time moments $t = 205\,000$ h (see Fig. 2a) and $t = 238\,000$ h (see Fig. 2b) are defined as the moments of making the decision to replace the condenser tubes, which corresponds to the case when the function $F_{п}(t)$ constructed on the basis of complete operation times goes beyond the critical region (confidence interval).

CONCLUSIONS

A number of conditions must be taken into account in using statistical methods for analyzing the damageability of condenser tubes used in steam turbine units:

—Damaged tubes should locate in a bundle uniformly; if part of tubes concentrates in a certain zone (half) of the condenser, it is necessary to clarify why a large number of tube failures occur in this zone (half) and to determine a sufficient scope of repair.

—Along with carrying out a statistical analysis and estimating the location of failed tubes in a bundle, it is necessary to analyze the state of the metal of tube samples cut from the condenser; these data must confirm the conclusions drawn from the statistical analysis and testify that the entire tube system has worked out its service life.

—The initial information used in an analysis of statistical data on the damageability of tubes may be incomplete and partially invalid; in this case, special data processing methods must be applied.

—Two damageability periods are typical for STI condenser tubes: a period of normal operation characterized by an approximately constant failure rate and a period of exhausting the service life characterized by a growing failure rate. The period of initial break-in is of insignificant importance for solving the formulated problem of substantiating a replacement term for the condenser tube system.

—By using the procedure described in this paper it is possible to determine the moment of time for a condenser under study at which a transition occurs from the period of its normal operation to the period of exhausting its service life; at this moment of time a decision must be made about replacement of the condenser tubes, which must be accomplished within 1–2 years.

—The replacement criterion for a condenser tube system is determined by the number of condenser tubes that are blanked off during a turbine repair; the decision about replacing the tube system can be made if the number of tubes blanked off in the course of turbine repair based on the results of condenser hydraulic tests exceeds the value calculated from formula (8).

The developed procedure has been approbated on 11 condensers of turbines with capacities ranging from 25 to 500 MW. The obtained results allow us to recommend this procedure for determining the terms of making decisions about replacing the condenser tubes of steam turbine installations.

ACKNOWLEDGMENTS

The authors are grateful to the Reftinsk DPS employees K.I. Romanenko and V.L. Bukharin for information about failures of condenser tubes at the Reftinsk DPS.

REFERENCES

1. Yu. M. Brodov, K. E. Aronson, A. T. Mutovin, et al., *Improving the Efficiency and Reliability of Heat-Transfer Apparatuses of Steam Turbine Installations under Field Conditions* (UrFU, Yekaterinburg, 2010) [in Russian].
2. *OST (Industry Standard) 108.005.31-83: Assessing the Quality Level of Heat-Transfer Equipment Used at Nuclear Power Plants.*
3. R. S. Reznikova, E. I. Benenson, Yu. M. Brodov, et al., "Estimating the optimal time of replacing the tube bundles of turbine machinery heat-transfer apparatuses," Therm. Eng., No. 2 (1085).
4. L. S. Baran, *Diagnostics and Optimization of the Operating Characteristics of Steam Turbine Condensing Installations*, Candidate's Dissertation in Technical Sciences (NPO TsKTI, Leningrad, 1989).
5. V. G. Kritskii and P. S. Styazhkin, "Corrosion of copper-alloy tubes in cooling systems of nuclear power stations," Therm. Eng., No. 8, 643 (1997).
6. V. I. Nikitin, "Corrosive damage to the condensers of steam turbines and determining the residual life of their tube system," Therm. Eng., No. 11, 923 (2001).
7. Yu. A. Tsagareli, "Service life prediction for a condenser tube bundle during its operation," Elektr. Stn., No. 8, 21–26 (1992).
8. K. E. Aronson, A. Yu. Ryabchikov, Yu. M. Brodov, and B. E. Murmanskii, "A procedure for evaluating and predicting the remaining life of the condenser tube systems used in steam turbine installations," Elektr. Stn., No. 2, 25–31 (2010).
9. V. M. Skripnik, A. E. Nazin, and Yu. G. Prikhod'ko, *Analyzing the Reliability of Technical Systems on the Basis of Censored Samplings* (Radio i Svyaz', Moscow, 1988) [in Russian].
10. K. E. Aronson, Yu. M. Brodov, P. N. Plotnikov, et al., "An analysis of indicators characterizing the reliability of auxiliary equipment of power units," Therm. Eng., No. 8, 623 (2011).
11. V. K. Sedov, V. V. Panchenko, and N. S. Gabriichuk, "Experience gained from operations on removing deposits from the condensers of steam turbines at the Novovoronezh nuclear power plant," Elektr. Stn., No. 5, 4–6 (1978).
12. B. V. Gnedenko, *A Course of Probability Theory* (Nauka, Moscow, 1998) [in Russian].

Translated by V. Filatov