CONTRIBUTION TO THE DEVELOPMENT OF THE SIMULATION MODEL FOR THE ROTARY CAP BURNER IN THE MARINE STEAM BOILER

by

Joško DVORNIK* and Srdjan DVORNIK
Faculty of Maritime Studies in Split,University of Split, Split, Croatia

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This paper presents the simulation model for determining the intervals of preventive replacement of the system's components. The application of the Weibull distribution has been proved to be efficient in the approximation of many forms of delay, while numerical integration supported by Simpson formula and Fortran software has been applied to simulate optimum values of the preventive replacement of the components of the rotary cap burner SAACKE, type SKV 60 in the marine steam boiler, on the basis of the available data gathered through the system's exploitation and through empirical assumptions.

Key words: *maintenance, optimum interval, simulation, preventive replacement*

Introduction

Any mechanism intended for continuous or frequent operation requires maintenance. In recent years it has become increasingly apparent that the possibility and way of maintenance depend not only on the approach during exploitation, but on the design as well. In other words, when designing a new mechanism, its best possible maintenance capacities should be taken into consideration.

After designing and constructing, such a mechanism should be prepared for exploitation in an appropriate way. Therefore it is necessary to determine the running-in period under appropriate conditions, perform an overload experiment and define the scope of disassembling for checking the state of the components after the experiment and eventually to recommend the maintenance technology during the expected exploitation life.

Once a mechanism has successfully passed through the running-in period, it is ready for exploitation. It is then necessary to make periodical plans that include the indispensable maintenance parts and materials, ways of their supply and planning and organisation of adequate maintenance personnel.

Finally, the system should feature the methods for monitoring the behaviour of particular devices and components during exploitation in order to detect faults and to apply necessary enhancements with regard to the technology, characteristics of particular devices and compo-

* Corresponding author; e-mail: josko@pfst.hr

nents and the condition diagnostics with the purpose of preventive maintenance. Figure 1, according to [1], shows maintenance activities along with the associated actions.

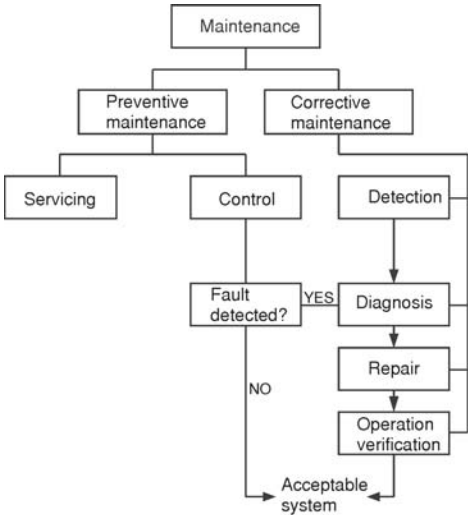

Figure 1. Maintenance activities [1]

Quantitative factors of maintainability

Maintainability is the probability that a system requiring maintenance will be kept in or returned to the specified operating state within a given period of time.

Maintainability function is a cumulative probability expressed in the function of shutdown period. It indicates the probability that a required maintenance action will be finished during the shutdown time *t*, according to [1]:

$$M(t) = \int_0^t f(t)\mathrm{d}t \tag{1}$$

where: $M(t)$ is the maintainability function and $f(t)$ – the probability density function of the total repair time.

Maintainability indicates the probability that a required repair action will be finished at active repair time *t*:

$$M_\mathrm{R}(t) = \int_0^t f_\mathrm{R}(t)\mathrm{d}t \tag{2}$$

where $M_\mathrm{R}(t)$ is the maintainability and $f_\mathrm{R}(t)$ – the probability density function of the active repair time.

Many quantitative maintenance parameters are based on the elements of maintenance time.

– Mean active time of corrective maintenance $\overline{M}_\mathrm{C}$ or mean time to repair:

$$\overline{M}_\mathrm{C} = \frac{\sum_{i=1}^{n} \lambda_i \overline{M}_{\mathrm{C}_i}}{\sum_{i=1}^{n} \lambda_i} \tag{3}$$

where λ_i is the failure rate of part *i* of the system ($i = 1, 2, \ldots, n$) and $\overline{M}_{C_i}$ – the mean active time of corrective maintenance of the system when a part *i* fails.

The time $\overline{M}_{C_i}$ is obtained from the expression:

$$\overline{M}_{\mathrm{C}_i} = \frac{\sum_{i=1}^{r} M_{\mathrm{C}_i}}{r} \tag{4}$$

where M_{C_i} is the active time of corrective maintenance of the system if a part i fails and *r* – the failure rate of the part *i*.

– Mean active time of preventive maintenance $\overline{M}_\mathrm{P}$

$$\overline{M}_\mathrm{P} = \frac{\sum_{i=1}^{n} f_i \overline{M}_{\mathrm{P}_i}}{\sum_{i=1}^{n} f_i} \tag{5}$$

where f_i is the frequency of preventive maintenance task of the *i* part of the system and $\overline{M}_{\mathrm{P}_i}$ – the mean active time of preventive maintenance of the system when the preventive maintenance task of the *i* part is carried out.

The time of $\overline{M}_{\mathrm{P}_i}$ will be:

$$\overline{M}_{\mathrm{P}_i} = \frac{\sum_{i=1}^{k} f_i M_{\mathrm{P}_i}}{k} \tag{6}$$

where M_{P_i} is the active time of preventive maintenance of the system when the preventive maintenance task of the *i* part is performed and *k* – the number of preventive maintenance tasks for the *i* part.

– Mean time between maintenance (MTBM):

$$\mathrm{MTBM} = \frac{1}{\lambda + f} \tag{7}$$

where λ is the failure rate of the system (frequency of corrective maintenance of the system) and f – the frequency of preventive maintenance of the system:

$$\lambda = \sum_{i=1}^{n} \lambda_i, \quad f = \sum_{i=1}^{n} f_i \tag{8}$$

– Mean active time of corrective and preventive maintenance $\overline{M}$:

$$\overline{M} = \frac{\lambda \overline{M}_C + f\overline{M}_\mathrm{P}}{\lambda + f} \tag{9}$$

Weibull distribution

Although complex, the Weibull distribution is often used in practice as it enables a very good approximation of many forms of delays. Unlike the exponential distribution of random failures, where the failure rate is not time-dependent and is always constant, the Weibull distribution can define distributions with decreasing, constant, and increasing failure rates, [1, 2].

Its failure density function is:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \mathrm{e}^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}, \quad t \ge \gamma, \ \beta > 0, \ \eta > 0 \tag{10}$$

where *t* is the failure time, γ – the position parameter, β – the shape parameter, and η – the scale parameter of the distribution. At the moment of the commissioning of the system, the parameter γ is equal to zero and the failure time *t* is greater or equal to γ:

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)\mathrm{d}t = \int_t^\infty f(t)\mathrm{d}t \tag{11}$$

where $R(t)$ is the reliability function, $F(t)$ – the unreliability function, $f(t)$ – the failure density function.

According to [1, 2], the reliability function is expressed as:

$$R(t) = \mathrm{e}^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{12}$$

The failure rate function is:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \mathrm{e}^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}}{\mathrm{e}^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}}} = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \tag{13}$$

Determining the intervals of the preventive replacement of the system's parts

Preventive maintenance is defined as a number of maintenance tasks that are necessary for preventing the failure occurrence, *i. e.* as maintaining the features of a technical system which is in exploitation within allowed deviation limits, according to [3]. The preventive replacement is applied to the system components which have an increasing failure rate with regard to the operating time. The preventive maintenance is planned to be performed when the use of the system is not anticipated or when the system is out of use. The costs of performing the preventive maintenance of a part of the system should be lower than the costs of the corrective maintenance, according to [1].

Most of the possible methods of preventive maintenance can be approximately integrated into two basic categories:
- according to operating parameters (running hours, number of start-ups ...) or time-determined constant cycle and
- according to technical condition.

There are two types of preventive replacement:
- replacement after certain period of operation and
- block replacement.

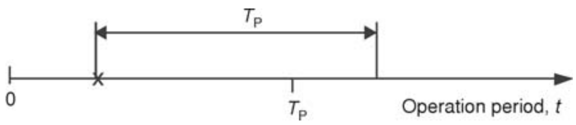

Figure 2. Replacement after certain period of operation

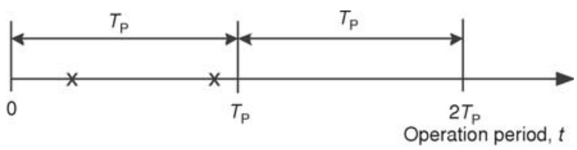

Figure 3. Block replacement

If a part of the system is preventively replaced whenever it completes the T_P period of operation and a failure occurs resulting in an unplanned replacement, so that the next replacement is carried out after the T_P period of operation, this represents the so-called replacement after certain period of operation, fig. 2, according to [1].

If the preventive replacement of a part of the system is performed exactly upon the T_P period of operation, whether an unplanned replacement of the failed part between the two planned replacement is performed or not, this represents the so-called block replacement, fig. 3, according to [1].

Preventive maintenance consists of a number of tasks which are necessary for preventing failure occurrences, *i. e.* maintaining the parameter functions within the allowed deviation limits for the longest period of time possible. The replacement of a faulty part is not possible exactly at the moment of failure, due to this uncertainty, the replacement of the component can be performed prior to failure occurrence. If the overall costs of replacement after the failure occurrence are lower or equal to the costs of replacement prior to the failure occurrence, the component should not be replaced before the failure occurs.

The technology of preventive maintenance defines the procedure and the method of performing preventive maintenance of technical systems in practice. The technology of preventive maintenance comprises a number of tasks which are carried out in the preventive maintenance process.

In general, the technology includes the following preventive maintenance tasks:

(a) periodical inspections
- preventive inspections,
- cleaning and anti-corrosion protection,
- lubricating.

(b) detecting and removing weak points of the technical systems,
(c) control,
(d) technical diagnostics, and
(e) planned checks
- minor,
- medium, and
- major (overhauls).

In practice, preventive maintenance is carried out in accordance with the system condition (with the aid of technical diagnostics). Therefore, in addition to the above mentioned activities, preventive maintenance of technical systems includes maintenance tasks related to the system condition, [1, 2].

When a preventive replacement after a set period of operation T_P is performed, the mean time between failure M_TP is:

$$M_\mathrm{TP} = \frac{\int_0^{T_P} R(t)\mathrm{d}t}{1 - R(T_\mathrm{P})} \tag{14}$$

The reciprocal value of eq. (14) produces the expression for the failure rate in case of unplanned replacements λ_cTP:

$$\lambda_\mathrm{cTP} = \frac{1 - R(T_\mathrm{P})}{\int_0^{T_P} R(t)\mathrm{d}t} \tag{15}$$

Mean time between corrective and preventive replacement, in the interval 0, T_P will be:

$$M_\mathrm{TOTAL} = \int_0^{T_P} R(t)\mathrm{d}t \tag{16}$$

The overall intensity of corrective and preventive replacements:

$$\lambda_\mathrm{TOTAL} = \frac{1}{M_\mathrm{TOTAL}} = \frac{1}{\int_0^{T_P} R(t)\mathrm{d}t} \tag{17}$$

The intensity of preventive replacements in case of replacement after certain period of operation λ_pTP is given by the equation:

$$\lambda_\mathrm{TOTAL} = \lambda_\mathrm{cTP} + \lambda_\mathrm{pTP} \tag{18}$$

By inserting eqs. (15) and (17) into eq. (18) the result is:

$$\lambda_\mathrm{pTP} = \frac{R(T_\mathrm{P})}{\int_0^{T_P} R(t)\mathrm{d}t} \tag{19}$$

In the case of block replacement, the intensity of preventive replacement is constant:

$$\lambda_{\mathrm{PTP}} = \frac{1}{T_{\mathrm{P}}} \tag{20}$$

The failure rate in case of unplanned replacements λ_{cTP}, can now be obtained from eqs. (17), (18), and (20):

$$\lambda_{\mathrm{cTP}} = \frac{T_{\mathrm{P}} - \int_0^{T_P} R(t)\mathrm{d}t}{T_{\mathrm{P}} \int_0^{T_P} R(t)\mathrm{d}t} \tag{21}$$

Procedure for determining the intervals of preventive replacement

When trying to prolong the intervals of preventive replacement in the stage of construction, the common procedure is to determine these intervals in line with previous experience and to adjust them according to the information gathered during the exploitation.

A complex system comprises sub-systems whose construction remains unchanged for years because an optimum has been achieved with regard to all available technical and economical possibilities.

The criterion for determining the optimal preventive replacement interval is represented by the overall costs of maintenance of a part in the long term. The overall costs for corrective and preventive maintenance $C_{\mathrm{T}}(t)$, according to [1], will be:

$$C_{\mathrm{T}}(t) = C_{\mathrm{c}} t \lambda_{\mathrm{cTP}} + C_{\mathrm{P}} t \lambda_{\mathrm{PTP}} \tag{22}$$

where C_{c} is the costs of corrective replacements, C_p – the costs of preventive replacements, λ_{cTP} – the failure rate in case of corrective replacements, and λ_{pTP} – the frequency of preventive replacement.

Whenever $C_{\mathrm{c}} > C_p$ and when this refers to the system parts having an increasing failure rate, there is an optimal preventive replacement interval T_{po} which results in minimum overall maintenance costs, in addition to meeting the required reliability of the system.

When the failure rate is constant, the preventive replacement action would not have any influence on achieving reliability, whereas the maintenance costs would be higher. The optimal procedure for such parts is to replace them only in case of failure.

If the overall replacement costs after the failure occurrence are lower or equal to the costs prior to failure occurrence, the component should not be replaced before it fails.

The overall maintenance costs in a unit of time:

$$C_{\mathrm{T}} = C_{\mathrm{c}} \lambda_{\mathrm{cTP}} + C_{\mathrm{P}} \lambda_{\mathrm{PTP}} \tag{23}$$

If a block replacement is applied, the replacement intensity values are obtained from eqs. (20) and (21), therefore C_{T}, is, according to [1]:

$$C_{\mathrm{T}} = C_{\mathrm{c}} \frac{T_{\mathrm{P}} - \int_0^{T_P} R(t)\mathrm{d}t}{T_{\mathrm{P}} - \int_0^{T_P} R(t)\mathrm{d}t} + C_P \frac{1}{T_{\mathrm{P}}} \tag{24}$$

The minimum value for T_{po} is defined by the equation per T_{p}:

$$\frac{\mathrm{d}C_{\mathrm{T}}}{\mathrm{d}T_{\mathrm{P}}} = 0 \tag{25}$$

If the failures of the observed parts follow the rule of the Weibull distribution, each part of the system can be expressed by a general equation, taking into consideration the value of parameters β and η as well as the value of costs C_p and C_c:

$$C_{\mathrm{Ti}} = C_{\mathrm{Pi}} \frac{1}{T_{\mathrm{Pi}}} + C_{\mathrm{Ci}} \frac{T_{\mathrm{Pi}} - \int_0^{T_{Pi}} \mathrm{e}^{-\left(\frac{t}{\eta_i}\right)^{\beta_i}} \mathrm{d}t}{T_{\mathrm{Pi}} \int_0^{T_{Pi}} \mathrm{e}^{-\left(\frac{t}{\eta_i}\right)^{\beta_i}} \mathrm{d}t} \tag{26}$$

Owing to the complexity of this distribution, the analytical solving method can not be used; hence the optimal values of preventive replacement intervals are obtained using graphics and software. Appropriate respective costs are calculated for various values of T_{pi} in the eq. (26). This results in functions $C_{\mathrm{Ti}} = f(T_{\mathrm{pi}})$ which have a point where the costs are minimal, representing the optimal preventive replacement interval for the observed unit of the system.

Simulation model for the preventive replacement interval

The optimal values of the interval of preventive replacement, *i. e.* the eq. (26), can be calculated in Fortran software, using the numerical integration and Simpson's formula, according to [4]. According to [5], the eq. (26) can be shown in a block diagram, see fig. 4, where $b = \beta$, $e = \eta$.

Determining the optimal intervals of preventive replacement of parts of the rotary cup burner type SAACKE-SKV 60 of a marine steam boiler

The task of a fuel oil system is to prepare and ensure optimal fuel oil combustion in line with the plant requirements. Combustion is a complex multi-stage process through which a fuel oil particle passes before it burns completely.

When using liquid fuel oil, the combustion process involves several stages: mixing with air, heating, evaporating, thermal atomization, creation of combustible mixture, ignition and combustion. Each stage considerably affects the combustion process, and if one of the stages is not met, the fuel oil will burn incompletely.

One of the essential prerequisite for the complete combustion is a good atomization of fuel oil, the quality of atomization depending on [6-8]:
– way of atomization,
– design features of the atomization nozzle,

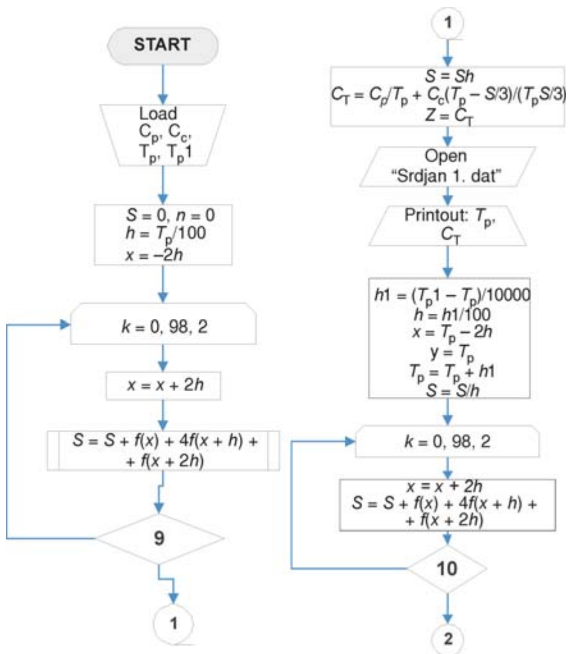

Figure 4. Block diagram (a)

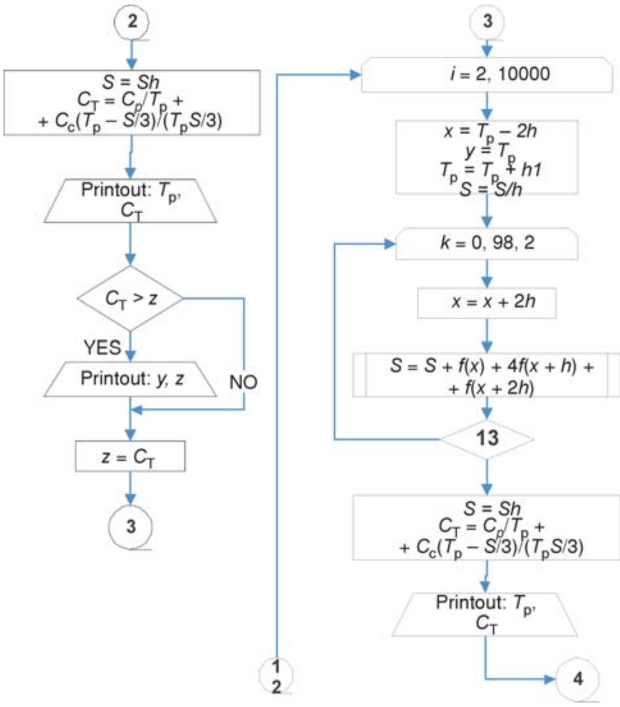

Figure 4. Block diagram (b)

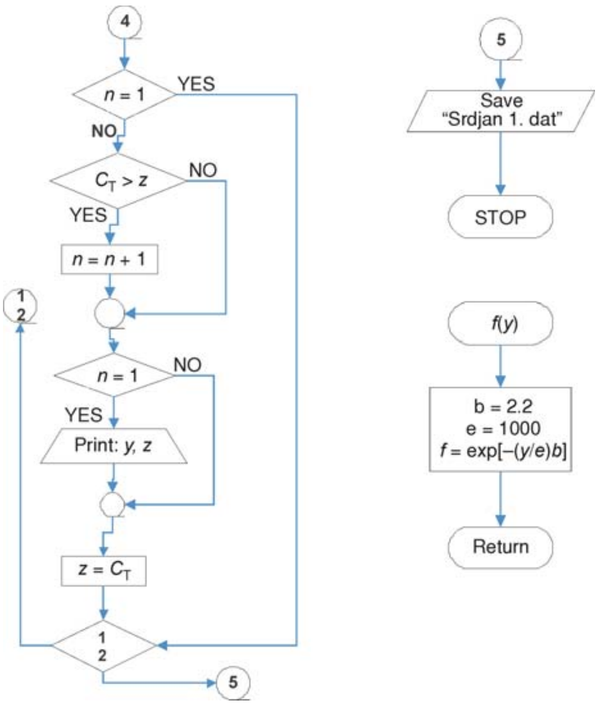

Figure 4. Block diagram (c)

– viscosity of fuel oil, and
– surface tension of fuel oil.

Atomization is converting the liquid fuel oil into fine spray in order to facilitate the most efficient fuel-air mixing in a given period of time, under actual combustion conditions within a furnace. The rotary cup burner type SAACKE-SKV 60, providing the rotational fuel oil atomization, is used for observing the fuel combustion, fig. 5, according to [6].

The basic requirement for the preventive replacement of a system's part is its increasing failure rate. When analysing the sub- systems of the rotary cup burner type SACKE-SKV 60 and the elements of these sub-systems, it can be concluded that the light oil igniter and the rotary cup atomizer are the most sensitive components of the burner.

The values of the parameters β and η in the Weibull distribution applied to the light oil igniter and the rotary cup atomizer are taken from [9], shown in tab. 1, as it is exceptionally hard to obtain parameters from exploitation.

On the basis of the available information, the costs of preventive replacements C_p and the costs of corrective replacements C_c of the observed components are shown in tab. 2, according to [6] and empirical assumptions.

The diagram of the functional dependency of maintenance costs and the period of replacement of the light oil igniter is shown in fig. 6.

The optimum preventive replacement interval is T_{Pmin} = = 617,285 hours, whereas the minimum costs are C_{Tmin} = = 37,967.

The diagram of the functional dependency of maintenance costs and the period of replacement of the rotary cup atomizer is shown in fig. 7.

The optimum preventive replacement interval is T_{Pmin} = 578,94 hours, whereas the minimum costs are C_{Tmin} = 38,934.

In order to avoid frequent shutdowns of the systems due to the preventive replacement actions, optimum intervals of the preventive replacement of the rotary cup atomizer and the light oil igniter can be the same, *i. e*. 600 hours. The administrative planning of the preventive replacement actions is simplified in this way.

Figure 5. Rotary cup burner type SAACKE – SKV 60 [6]

Table 1. Values of parameters β and η in the Weibull distribution of the light oil igniter and the rotary cup atomizer

Name of component	Parameter	
	β	η
Light oil igniter	2.2	1000
Rotary cup atomizer	1.8	1000

Table 2. Costs of C_p and C_c for the rotary cup burner parts

Name of component	Costs of preventive replacement C_p [kn]*	Costs of unplanned replacement C_c [kn]*
Light oil igniter	12800	98020
Rotary cup atomizer	10200	90840

* 1€ = 7.541095 kn

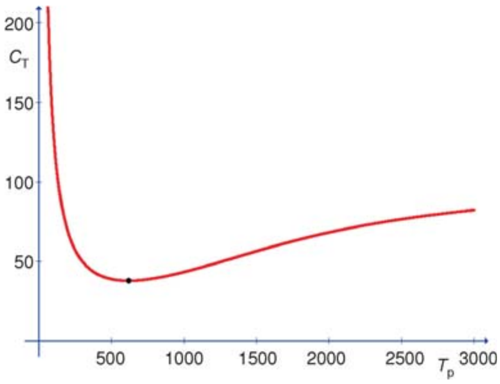

Figure 6. Optimum interval of the preventive replacement of the light oil igniter

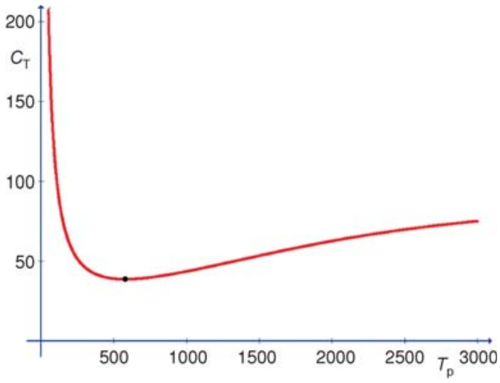

Figure 7. Optimum interval of the preventive replacement of the rotary cup atomizer

Conclusions

Maintenance of technical systems is an exceptionally complex process requiring integral research and thorough understanding aimed at achieving the set objectives of the operational organisation at the appropriate level.

In order to meet the requirements of the optimisation of preventive replacement intervals (hence the operation process), it is necessary to take actions from the very start, *i. e*. from designing a new technical systems to its ultimate decommissioning.

The complexity of construction of technical systems has resulted in growing diversity of their components and changes in their characteristics and load levels, hence the various levels of reliability of each component and the system as a whole, [1, 10].

Therefore the optimum timings of preventive maintenance actions in such complex systems can not be set in advance. For most components of the system, the realisation of the previously planned scope of tasks within a set period of time results in a slight reduction of failure probability.

The very design has to foresee the possibility of dismantling each component which is subject to wear, in order to perform inspection or repair. The design should also allow accessing the component as directly as possible, reducing the need for dismantling the neighbouring components and, where feasible or necessary, allow the inspection of critical components without dismantling.

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