TECHNICAL DEVICE WEAR-OUT PERIOD INFLUENCE ON QUANTITATIVE RISK ASSESSMENT RESULTS

Yuriy D. Kuznetsov[1], Evgeniy Yu. Kolesnikov[2]

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Peter the Great Saint-Petersburg Polytechnic University, Saint-Petersburg, Russia
[1]yura.kuz30@gmail.com
[2]key3108@yandex.ru

Abstract

Hazardous production facilities contain numerous technical devices, the reliability assessment of which is a part of quantitative risk assessment. The paper considers the pressure valve as a safety system element of equipment operating under excessive pressure and evaluates its reliability (survival function value) during the operational period. Valve reliability during the wear-out period has been modeled to assess wear-out period influence on this element failure probability. Modeling was carried out by approximating the failure rate tabular values obtained based on statistical data. Approximation was carried out by: a second-degree polynomial, the Weibull distribution law and a power function. Comparison of the obtained quantitative estimates with the element failure probability, calculated without taking into account the wear-out period, showed necessity of wear-out period influence consideration in risk assessment procedure.

Keywords: reliability, quantitative risk assessment, modeling, hazardous production facility, pressure valve

1. Introduction

One of the main tools for performing accident quantitative risk assessment (QRA) at hazardous production facilities (HPF) is logical-probabilistic modeling (LPM), in particular, fault tree analysis (FTA), [1, 2].

HPF are complex technical systems (TS) consisting of technological blocks, technical devices, and elements. HPF safety is ensured by specialized safety units / elements, used for technological process deviation prevention from escalating into an accident.

As is well known, there are no absolutely reliable technical devices. Any device (technical system) failure probability is calculated based on its components (elements) failure probabilities which are usually estimated by consideration of failure probability dependence from operating time described by exponential law. In this case, element failure rate is postulated by a constant, time-independent value.

The choice of described mathematical model for estimating element failure probability is based on:

- its mathematical simplicity.
- the fact that the longest period in the element life cycle is the useful life period which is characterized by failure rate approximate constancy, [1].

Described model does not consider elements wear-out period, characterized with failure rate significant increase. Neglect of this circumstance can result in inadequate technical device failure probability quantitative estimates, and, consequently, in distorted results of various accident scenarios probability assessment obtained from event tree analysis (ETA). ETA results are sensitive to the accuracy of initial data, including the probability of both the initiating event and the safety device's conditional failure probabilities.

At present time, there is not yet a single generally accepted approach to technical devices reliability assessment in the wear-out period. However, many researchers have repeatedly drawn attention to the need for wear-out period consideration in technical device reliability assessment [3, 4, 5, 6]. The prevailing opinion is that the Weibull distribution is the most suitable for elements reliability assessment in the wear-out period [4, 5, 7].

Besides, there is no consensus among researchers regarding technical devices' imperfect maintenance impact on the reliability/failure rate during the wear-out period. The most common are two concepts: PAR (Proportional Age Reduction) and PAS (Proportional Age Setback) [4, 6]. Described concepts implementation allows for assess maintenance impact on the technical device aging process, varying it from completely ignoring such an influence (BAO, Bad As Old, postulating that the degree of device degradation does not decrease after maintenance); to completely eliminating degradation during maintenance (GAN, Good As New).

The choice of the most suitable mathematical model for describing technical device wear-out period is carried out on the basis of the Akaike information criterion (AIC), which allows choosing among the models under consideration the one that has the least number of parameters and will have the best approximation to the available data. The authors of [4] argue that for the given purposes, the most suitable model is the Weibull distribution with maintenance effectiveness equal to 1 (GAN). Moreover, the authors believe that usage of the PAR/PAS concept with a different maintenance efficiency will result in significant failure rate value overestimation when predicting the state of the technical device, [4]. This conclusion is based on the technical device's statistical data acquired from 17 years of observance comparison with their mathematical assessment.

Yet another approaches for reliability assessment in the wear-out period exist. Research, [5], in addition to the widely recognized wear-out period modeling approach of the device by the Weibull distribution, proposes the usage of power distribution. The type of power distribution proposed by its author allows assessment of technical devices' reliability throughout their entire life cycle and various types of failure rate functions usage.

The authors of [3, 8] consider the elements' wear-out period consideration problem from a more general perspective, using algorithms [3], and complexes of techniques [8] to influence the assessment of the wear-out process on technical devices' overall performance.

The authors of this paper point out that none of the analyzed studies carried out a prediction of the technical device survival function values for its operational period. The articles reviewed describe only possible approaches to taking into account the device wear-out period influence on the process of its operation and predicting the failure rate magnitude. This results in the impossibility of different wear-out period reliability assessment approach comparisons. Due to quantitative assessment absence wear-out period impact on the value of survival function is unclear. Discovered uncertainty in technical system reliability assessment throughout its entire life cycle (including the wear-out period) leads to an increase of accident risk indicators value uncertainty.

This paper is dedicated to the demonstration of the fact that neglect of technical system elements wear-out period in its reliability assessment leads to an underestimation of their failure probability, which results in an underestimation of the magnitude of accident risk indicators (potential territorial, individual, etc.).

The purpose of this article is to substantiate the need for technical system element wear-out period consideration in the domain of a quantitative risk assessment.

2. Methods

In this paper authors have considered vessel operating under excessive pressure as an example of technical device and its safety valve as a technical device element. Reliability assessment has been conducted for safety valve (pressure valve) with operational period equal to 30 years [9]. For further analysis, it is necessary to describe the dependence of the failure rate [10] as a function of time (operating time). In this paper following assumptions are made: total duration of burn-in period and useful life period is 27 years, wear-out period duration is 3 years (figure 1).

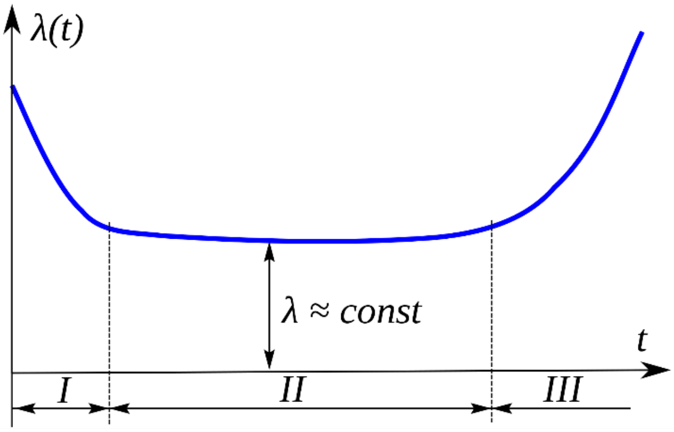

Figure 1: *The bathtub curve: I – burn-in period, II – useful life period, III – wear-out period*

Consider the valve failure rate value at three points in time during the wear-out period:

- at the beginning of wear-out period – λ_{min};
- at the middle of wear-out period – λ_{mean};
- at the end of wear-out period – λ_{max} (concurrently – at the time of decommissioning of the valve due to its reaching the limit state).

As reference values of the failure rate during the wear-out period statistical data was used [11]. it is assumed that during useful life period valve failure rate was equal to ◎min. The relation between the failure rates values and time points is shown in Table 1.

Table 1: *Tabular failure rate function*

Designation	Time point t, h	Value of λ(t), h^{-1}
λ_{min}	236520	$0{,}122 * 10^{-6}$
λ_{mean}	249660	$5{,}6 * 10^{-6}$
λ_{max}	262800	$32{,}5 * 10^{-6}$

The time point equal to 236520 hours, i.e. 27 years from the beginning of the device operation, is taken as the beginning of the wear-out period. The middle of the wear-out period corresponds to a time point equal to 249660 hours, i.e. 28 years from the beginning of device operation. The end of the wear-out period (device operation end) corresponds to a time point equal to 262800 hours, i.e. 30 years from the beginning of device operation. In order to quantify the valve wear-out period effect on its failure probability, different failure rate functions were proposed.

As it well-known, unrepairable element failure probability depends on its failure rate in a following way:

$$Q(t) = 1 - e^{-\int_0^t \lambda(\tau)d\tau} = e^{-\left(\int_0^{t_1} \lambda_2(\tau)d\tau + \int_{t_1}^{t_2} \lambda_3(\tau)d\tau\right)} \quad (1)$$

where λ_2 – failure rate, h^{-1}, of an element during the useful life period, can be equated to λ_{min};
λ_3 – failure rate, h^{-1}, of an element during the wear-out period;
t_1 – wear-out period beginning, h, equals to 236520 h.

2. 1. Approximation by a second degree polynomial

Considering the data given in Table 1 as a tabular function λ(t), it is possible to approximate it [12] with a second degree polynomial represented by a following expression (2):

$$\lambda_{app}(t) = 6{,}2 \cdot 10^{-14} \cdot t^2 - 2{,}97 \cdot 10^{-8} \cdot t + 3{,}56 \cdot 10^{-3} \quad (2)$$

The approximation parameters are given in Table 2.

Table 2: *Second degree polynomial approximation accuracy*

Parameter	Value
Correlation coefficient	1
Coefficient of determination	1
Average approximation relative error	0%

Therefore, the survival function of a process described by exponential law with failure rate (2) for wear-out period and constant failure rate for burn-in period and useful life period, can be represented by following expression (3):

$$P_{app}(t) = e^{-\left(\int_0^{t_1} \lambda_{min} dt + \int_{t_1}^{t} \lambda_{app}(t) dt\right)} \quad (3)$$

Where $P_{app}(t)$ – the probability of failure-free operation based on a wear-out period failure rate approximation by second degree polynomial;

λ_{min} – useful life period failure rate, h^{-1};

t_1 – time point corresponding to the end of the useful life period and the beginning of the wear-out period. It is assumed to be equal to 236520 hours;

t – time, measured in hours, $t > t_1$;

$\lambda_{app}(t)$ – the failure rate value during the wear-out period at time point t, obtained from the approximation of the tabular function by a polynomial of the second degree (2), h^{-1}.

2. 2. Calculation of failure rate function λ(t) on the basis of Weibull distribution law

The probability of failure-free operation of the element during the wear-out period in this case [7] will have the form (4):

$$P_{wb}(t) = e^{-\left(\int_0^{t_1} \lambda_{min} dt + (\beta t)^{\alpha} - (\beta t_1)^{\alpha}\right)} \quad (4)$$

Where $P_{wb}(t)$ – the probability of failure-free operation under the assumption that the failure rate obeys the Weibull distribution law;

β – the rate parameter of Weibull distribution;

λ_{min} – useful life period failure rate, h^{-1};

t_1 – time point corresponding to the end of the useful life period and the beginning of the wear-out period. It is assumed to be equal to 236520 hours;

t – time, measured in hours, $t > t_1$

α – the shape parameter of Weibull distribution.

Thus, in order to find the element failure-free operation probability value, Weibull distribution parameters (α and β) values must be determined. For this purpose, it is necessary to use the failure rate function for Weibull law (5):

$$\lambda_{wb}(t) = \alpha \cdot \beta^{\alpha} \cdot t^{\alpha-1} \quad (5)$$

Where β – the rate parameter of Weibull distribution;

α – the shape parameter of Weibull distribution.

Equating the values of this function to the available table values, a system (6) of two nonlinear equations for the failure rate was obtained:

$$\begin{cases} \lambda_{max} = \beta^{\alpha} {t_{max}}^{\alpha-1} \\ \lambda_{min} = \beta^{\alpha} {t_{min}}^{\alpha-1} \end{cases} \quad (6)$$

Its solution gives an expression for determining the parameters α:

$$\alpha = \frac{\ln\left(\frac{\lambda_{max}}{\lambda_{min}}\right)}{\ln\left(\frac{t_{max}}{t_{min}}\right)} + 1 \quad (7)$$

and β:

$$\beta = \left(\frac{\lambda_{max}}{{t_{max}}^{\alpha-1}}\right)^{\frac{1}{\alpha}} \quad (8)$$

Acquired values of the parameters (α and β) are shown in Table 3.

Table 3: *Weibull law parameter values*

Parameter	Value
α	54,82
β	$3{,}68 \cdot 10^{-6}$

2. 3. Power function approximation

Consider the following function describing failure rate in wear-out period:

$$\lambda_{deg}(t) = \lambda_0 + \zeta \cdot t^{\gamma} \quad (9)$$

where λ_0 – failure rate at the beginning of wear-out process, h^{-1};

γ and ζ – function parameters.

For parameters γ and ζ value determination equality of the function $\lambda_{deg}(t)$ to the failure rate values based on statistical data (Table 1) at two time points is required:

$$\begin{cases} \lambda_{max} = \lambda_0 + \zeta \cdot {t_{max}}^{\gamma} \\ \lambda_{mean} = \lambda_0 + \zeta \cdot {t_{mean}}^{\gamma} \end{cases} \quad (10)$$

Parameter γ can be determined from the following expression:

$$\gamma = \frac{\ln\left(\frac{\lambda_{max} - \lambda_0}{\lambda_{mean} - \lambda_0}\right)}{\ln\left(\frac{t_{max}}{t_{mean}}\right)} \quad (11)$$

Substituting the obtained value of the parameter γ into any of the equations (10), calculation of parameter ζ is possible:

$$\zeta = \frac{\lambda_{max} - \lambda_0}{{t_{max}}^{\gamma}} \quad (12)$$

For the case under consideration, the values of the parameters γ and ζ obtained by us are shown in Table 4.

Table 4: *Weibull law parameter values*

Parameter	Value
γ	34,61
ζ	$8{,}7 \cdot 10^{-193}$

3. Results

As a result of this research, five functions that characterize the failure probability during the wear-out period were determined and compared:

- $Qp_{min}(t)$ – a function describing the simulation of the failure probability at a constant failure rate λ_{min} in a process obeying an exponential law. Thus, the effect of the wear-out process on the failure probability is completely ignored.
- $Qp_{mean}(t)$ – a function describing the simulation of the failure probability at a constant failure rate λ_{mean} in a process obeying an exponential law. Wear-out process is taken into account by changing the parameter in the process, obeying the exponential law by the average failure rate value during wear-out period.
- $Q_{wb}(t)$ – a function describing the simulation of the failure probability with a failure rate varying according to Weibull law with parameters α, β. Choice of this distribution allows accounting of failure rate growth due to aging.
- $Q_{app}(t)$ – a function describing the simulation of the failure probability with a failure rate varying according to the law $\lambda_{app}(t)$. Wear-out process is taken into account by approximating statistical data on the failure rate during the wear-out period.
- $Q_{deg}(t)$ – a function describing the simulation of the failure probability with a failure rate varying according to the law $\lambda_d(t)$. The approximating function is obtained based on the assumption that the number of failed elements of the same type obeys the normal distribution law.

Failure probability of the pressure relief valve is calculated according to equation (1), the results are presented in Figure 2.

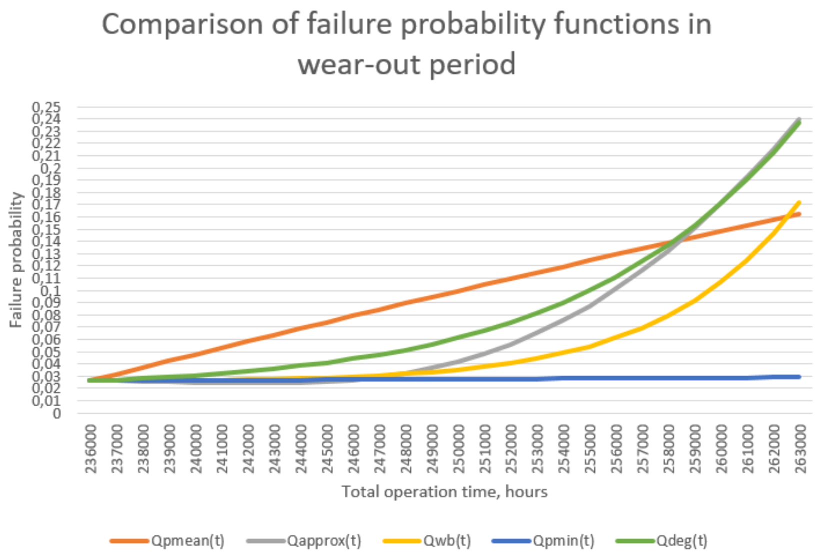

Figure 2: *Comparison of failure probability functions in wear-out period*

Values of the considered failure probability functions at the end of device operation period are given in Table 5.

Table 5: *Valve failure probability at the end of its operation period*

Type of function	Function value at time point t = 263000 h
Qpmin(t)	0,0290264
Qpmean(t)	0,16275
Qwb(t)	0,171749
Qapprox(t)	0,239714
Qdeg(t)	0,236512

4. Discussion

The analysis of Figure 2 shows that the graph of the function $Q_{app}(t)$ decreases in some area, which is determined by the type of the approximating function. Since this contradicts the meaning of the concept of the failure probability, which is a non-decreasing function of operating time, further consideration of this function is pointless.

From the data given in Table 5, it follows that the most conservative estimate of the options considered is the $Q_{deg}(t)$ function. Moreover, it becomes most conservative estimate only at the final stage of the wear-out period. As follows from the graph shown in Figure 2, up to a certain point, the most conservative estimate is $Qp_{mean}(t)$. Assessment of failure probability provided by this type of function is rather rough, but at the same time calculation of this function value is rather simple.

It is also important that the complete disregard of the wear-out period in QRA (which is a fairly common practice) leads to an underestimation of the device failure probability (compared with other methods of assessment).

In this work, a quantitative assessment of pressure relief valve failure probability during wear-out process was obtained, justifying the need to take this period into account when conducting the QRA. This study can be considered as the first stage of assessing the impact of taking into account the wear-out period of technical devices on the risk indicators assessment. Obtained estimates clearly show that accounting of wear-out process in reliability assessment will result in accident risk magnitude increase. Yet it remains unclear how strong is impact on accident risk magnitude. Next studies will be aimed on evaluation of technical systems elements wear-out process impact on the subsequent stages of QRA.

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