Risk-Based Planning of Diagnostic Testing of Turbines Operating with Increased Flexibility †

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Abstract: An increase in the share of renewable sources in the energy mix makes coal-fired power plants operate in new conditions that require more dynamic operation and adequate flexibility. The frequency of the power unit start-ups increases and so does the frequency of changes in loads. This intensifies some life consumption processes, such as low-cycle fatigue and crack propagation in the turbine components. Further operation of power unit elements that have already been in service for a long time has to be supplemented with new diagnostic and repair procedures that take into account the intensification of life consumption processes. This article gives predictions about the propagation rate of potential cracks in the turbine rotor for different scenarios of the power unit's long-term operation. A method is presented of rational selection of the diagnostic testing time based on risk analysis. The method is used to estimate the optimal interval after which diagnostic testing of a 200 MW turbine rotor should be carried out. Changes in the rotor steel crack toughness are evaluated based on the results of testing of microspecimens cut out of the rotor. Turbines with more frequent start-ups and shorter start-up times necessitate performance of diagnostic testing of the rotor central bore after about 12 years of turbine operation.

Keywords: maintenance planning; risk; turbine

1. Introduction

The changes in the structure of electricity generation sources observed in many countries are dictated by the natural process of replacing old power plants with a long in-service time. Another reason for the replacement is the need to satisfy current environment and climate protection requirements. This necessitates an increase in the share of renewable sources in the energy mix and gradual elimination of sources responsible for carbon dioxide emissions, which are coal-fired power units in the first place. The pace of changes in the energy mix varies from one country to another, which is due, e.g., to the investment capacity to replace coal with renewable energy sources without compromising the reliability of electricity supplies to all customers. Example shares of different energy sources in the production of electricity in Poland [1], Germany [2] and France [3] are shown in Figure 1. The share of coal-based sources in the energy mix in the first two countries is very high, especially in Poland [4,5]. In France, the situation is completely different. Electricity obtained from coal in that country is minimal. This means that in Poland, to ensure an appropriate level of availability of electricity supplies, it will be necessary in the transition period to keep energy generation from currently operated coal-fired power units.
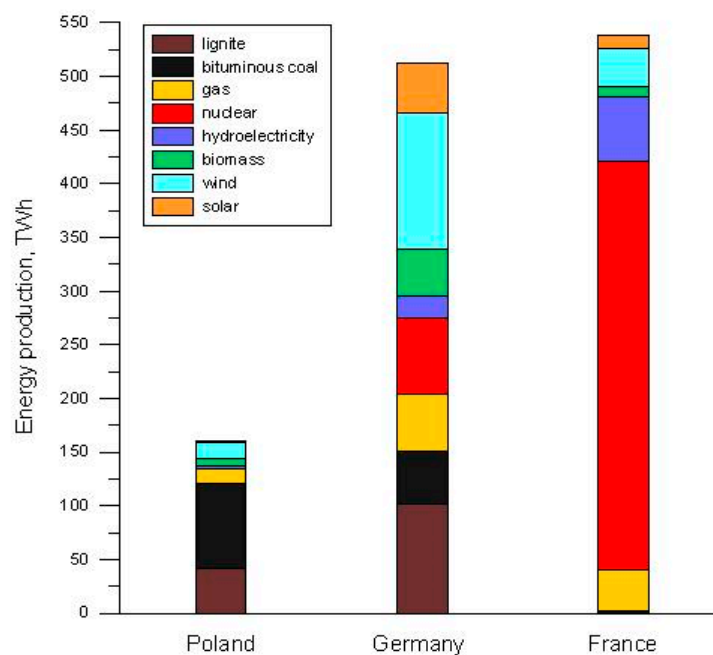
Figure 1. Energy production from different energy sources in selected European countries in 2019 [1–3].

Considering the priority of energy generation from renewable sources, conventional power plants increasingly have to play the role of source for balancing the demand for electricity in the power system. This in turn necessitates a change in the operation of individual power units from constant-load operation to cyclical operation characterized by frequent shut-downs and start-ups, as well as variable loads. A change like this obviously brings about far-reaching consequences. The impact of the method of power unit operation control on plant efficiency under cyclic loads is described in [6]. A procedure is presented in [7] for the estimation of the extra cost related to flexible operation. Reference [8] shows the results of investigations concerning fatigue-related life consumption and damage accumulation in cyclic operation of power plants.

Another issue is that a great number of the conventional power units have already exceeded their design service life and, despite many upgrades, their further operation requires special supervision. This problem is considered, e.g., in [9] and [10]. These reports describe the methods and examples of the assessment of technical risk created by long-term operation of steam turbines. Despite the fact that state-of-the-art low-emission supercritical power units are gradually replacing "old" power plants with a long design service life, a few dozen 200 MW and 400 MW power units will still be operated for about 15 more years.

As already mentioned, ensuring appropriate reliability of energy supplies requires high availability of power units, which in turn requires activities enabling early detection of symptoms of wear to avoid a serious failure of the power unit main elements. This is where diagnostic testing has a crucial role to play. Its basic aim is to detect symptoms pointing to the degree of wear of the element under consideration. The wide variety of wear processes that degrade components of power machines and equipment results in a similar variety of wear symptoms. A common symptom of increased material degradation is the appearance of microcracks and then macrocracks. In the case of turbine rotors, propagation of cracks reaching critical dimensions will potentially create the most dangerous scenario of a failure. Diagnostic testing, being the first stage of maintenance procedures, must ensure early identification of potential cracks and enable further activities to guarantee safety. Safety strategies for power units and the safety management methods are the subject of research projects described, e.g., in [11,12]. These activities include changes in the method of operation [13,14], repair of a damaged element or element replacement. The possibilities of improving the flexibility of the power unit operation by optimizing the turbine start-up procedure to substantially shorten the start-up time

are described in [15]. The thermal and strength analysis of the turbine high pressure (HP) part was performed using the finite element method (FEM). The optimization was carried out using genetic algorithms (GAs). The steam turbine start-up optimization and the optimized start-up impact on the life consumption of the turbine elements are also analyzed in [13].

However, before the diagnostic testing results can be used effectively, the rational scope and time of the testing performance have to be determined. Different models of maintenance strategies are considered in the literature, e.g., failure-related repairs, routine maintenance [14], criticality-based maintenance [16] and condition-based replacement [17,18]. Cost-optimal maintenance planning of wind turbines is presented in [19]. One helpful tool that enables optimal selection of the maintenance strategy is risk analysis, which makes it possible to assess the real hazard posed by the operation of machinery, equipment and systems in many branches of industry, especially in the chemical industry and oil refining [20–22]. Risk management of petrochemical plants is discussed in [20]. Reference [21] presents the framework for the estimation of the risk-based shut-down interval for a processing plant. Risk-based inspection and maintenance procedures for an oil refinery are described in [22]. Risk analysis is also the basis for planning maintenance procedures in power plants [23,24]. The method of identifying critical equipment for a power unit's operational performance and availability based on risk concepts is shown in [25]. A risk-based approach to the assessment of boiler tube thinning is presented in [26]. The issue of quantitative maintenance optimization for a power system with renewable energy sources is the subject of the investigations in [27]. Reference [28] discusses maintenance planning in hydroelectric power plants.

Descriptions of the most known maintenance types are included in Table 1.

Table 1. Available types of maintenance used for power plants.

Maintenance Type	Description
Reactive	It is the most popular type of maintenance, commonly used for noncritical assets with low failure probability. It relies on repairing elements only after breakdown or poor performance [29,30].
Preventive	This type of maintenance is based on preventing failure through periodic inspection, diagnosis and observation. It is used for assets with a predictable failure frequency connected with wear processes. Its main purpose is to extend the lifetime of elements [29,31].
Predictive	This is a prediction-based maintenance type using algorithms and machine learning to provide the most reliable condition monitoring and failure alerting. For this method, it is necessary to carry out appropriate measurements [18,29].
Routine	It is strongly connected with time-based maintenance that relies on regular inspections and servicing. Actions lead to decrease of breakdown possibility owing to continuous care of the technical condition [14,32].
Prescriptive	It is the method complementary to the predictive one in which the diagnosis process and repair guidance is provided. It is also focused on failure impact and the action priority [29].
Opportunistic	In this method, downtime of the plant caused by element failure is the opportunity to take care of other areas, even when the breakdown is not found [31].
Condition-Based (CBM)	CBM requires real-time monitoring of a specific parameter to detect failure symptoms. Early detection of irregularities allows prevention from serious breakdown or reduction of the undesirable effects. This method requires data collection, effective results interpretation, decision making and intervention. In CBM, the most frequently used techniques are vibration analysis, infrared thermography, ultrasonic analysis and oil analysis [29,33].
Time-Based (TBM)	It is one of the most basic maintenance types. Element repair or replacement takes place at a specific interval without condition assessment. The method is popular for objects in which failure is cyclic and appears in fixed time. It is also used when diagnosis tests or measurements are not economically justified. The TBM is based on routine tasks often implemented by contracted services [34,35].

Table 1. *Cont.*

Maintenance Type	Description
Cost-Optimal	This is the type of maintenance in which the main purpose is to minimize costs while ensuring the appropriate technical condition for assets. The main parameters that are taken into consideration during optimization process are cost of downtime due to a breakdown, cost of corrective maintenance (repair/replacement), cost of preventive maintenance, acceptable degree of degradation and inspection time [19].
Criticality-Based	In criticality-based maintenance, the most important aspects are the critical elements of the power plant. Main activities should focus on assets that have the largest effect on performance in the case of a breakdown [16].
Risk-Based (RBM)	RBM is the maintenance type which places the greatest emphasis on protecting assets with the greatest failure risk (failure probability times consequences). These assets are subjected to more frequent conservation and inspection. RBM is a preventive method of maintenance that allows for the reduction of costs and scope of activities [34,36].
Reliability Centered (RCM)	In the RCM method, three issues are taken into consideration: genesis of failure, its consequences and purpose of present prevention effort. The aim is to ensure high reliability of the system. It helps to find elements whose failure threaten further operation of the plant and which are not included in other maintenance types [18].
Failure Finding (FFM)	The aim of FFM is to find the hidden problems in elements which are not in constant use before the breakdown occurs. The searching process for latent failure is based on fixed time intervals or risk calculation [34]

The further part of this research presents a concept of using the avoided risk criterion to forecast the time to carry out diagnostic testing of rotors of turbines operating under flexible load regimes. The rotor failure criterion is assumed to reach critical dimensions when potential defects or cracks arise in the rotor. For this reason, the endoscopic testing of the rotor central bore is adopted as the basic testing technique. The other method of rotor testing will be to examine rotor material microspecimens to establish the current rotor steel material toughness.

2. Planning for Testing Based on the Avoided Risk Criterion

Planning the intervals at which diagnostic and repair activities should be performed has to take account not only of the level of risk created by a given facility, but also the rational costs related to the risk identification and reduction. Therefore, the optimization model of the process of planning for diagnostic testing should take into account the following:

- avoided risk value—R_{Tu};
- outlays made to reduce risk—C_{rt};
- other risk value—R_{TnN}.

Because the time horizon of the power unit operation stretches for up to a few dozen years, the model has to take into account discounted values. A procedure is described below for optimal planning for the turbine elements diagnostic testing and repairs using the net present value (*NPV*) discounted cash flow index. A different definition of cash flows is assumed to assess whether it is justified to carry out preventive replacement of an element posing a risk rising over time [37,38]. Potential costs of future failures are described as technical risk related to the further operation of the facility. The risk is the product of the probability of a failure occurrence P_f and the financial consequences thereof (the sum of all losses sustained due to the failure). Defining the *NPV* index, it is assumed that positive cash flows are the values of avoided risk R_{Tu} in the entire planned service life, i.e.,

$$R_{Tu} = \sum_{t=0}^{t=N} P_f \cdot C_t \tag{1}$$

where C_t is cash flows related to a loss of production due to failure and other failure-related costs.

Negative values of cash flows, on the other hand, result from real operation-related risk incurred in subsequent years from the beginning of the facility operation to the performance of activities reducing this risk (R_{Ton}), and the risk in the further period after the activities are conducted (R_{TnN}). The negative cash flows also comprise maintenance outlays C_{rt} made in year n and in subsequent years to reduce or eliminate risk. Based on these assumptions, the *NPV* index is defined as:

$$NPV = -C_{rt} - R_{Ton} - R_{TnN} + R_{Tu} \tag{2}$$

Taking account of discounted values, the following can be written:

$$NPV = -\sum_{t=n}^{N} \frac{C_{rt}}{(1+r)^t} - \sum_{t=0}^{n} \frac{P_{f0} C_t}{(1+r)^t} - \sum_{t=n}^{N} \frac{P_{f1} C_t}{(1+r)^t} + \sum_{t=0}^{N} \frac{P_{f0} C_t}{(1+r)^t} \tag{3}$$

where:

C_{rt}—cash flows related to costs of repairs, diagnostic testing or replacement in year t;
P_{f0}—probability of failure in the period prior to diagnostic testing, repairs or replacement;
P_{f1}—probability of failure in the period after diagnostic testing, repairs or replacement;
r—discount rate;
t—year index;
N—total planned service life (years);
n—year in which the element is tested, repaired or replaced.

Equation (3) can be used to optimize the process of selecting the intervals at which diagnostic tests or repairs should be performed. The optimal time to carry out diagnostic testing, repairs or replacement will be the year for which the *NPV* index defined by Equation (3) reaches the maximum. The actions enabling the optimal selection of diagnostic testing intervals and described further below include:

- defining hazardous scenarios, selecting the most hazardous scenario;
- working out a model of the development of wear processes, determining the failure criterion;
- calculating the change in the element failure probability;
- optimizing the times of maintenance activities that ensure maximization of the *NPV* index.

The flowchart of calculations making it possible to determine the optimal time to carry out diagnostic testing is illustrated in Figure 2. The algorithm details are presented in the subsections that follow.
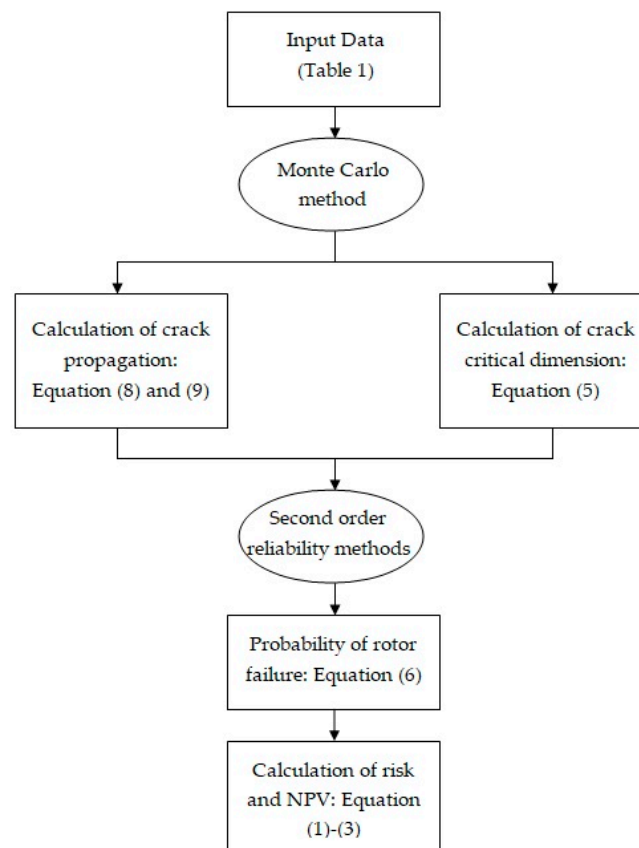
Figure 2. Flowchart for calculating the optimal time to carry out diagnostic testing of the rotor central bore.

3. Turbine Rotor Failure Scenario

3.1. Rotor Failure Criterion

The optimization procedure presented in Section 2 is now used to determine the optimal time to perform diagnostic testing of turbine rotors. For these devices, the main failure scenario is potential crack propagation. Among other things, the scenario results from the fact that power units now have to operate in a different way—to ensure improved operating flexibility under variable load regimes. This change in the character of the power unit operation is the effect of the increasing share of rather unstable renewable energy sources, especially wind farms, in the energy mix. Such a working mode involves a higher number of start-up/shut-down operating cycles. It also necessitates accelerated start-ups. This in turn results in higher thermal stresses and causes enhanced fatigue life consumption and a higher rate of potential crack propagation. The processes are especially dangerous in the case of turbine rotors that have already been in service for a long time, as they may cause a decrease in rotor steel toughness.

For this particular scenario, the so-called performance function describing the rotor failure criterion can be written as:

$$g = a_{cr} - a \tag{4}$$

where a_{cr} is assumed as the critical crack dimension (m) causing the rotor immediate failure and a is the current crack dimension (m). The crack critical dimension can be found by comparing the stress intensity coefficient K_I with the coefficient limit value, i.e., material toughness K_{IC}. The following is then obtained:

$$a_{cr} = \left(\frac{K_{IC}}{M\sigma}\right)^2 \tag{5}$$

where K_{IC} is material toughness (MPa· $\sqrt{m}$), M is the coefficient dependent on the defect location in the element and σ is the tensile stress component acting on the defect or crack (MPa).

The current crack value a depends on the number and type of start-up cycles and the turbine operating time. It is calculated as described in Section 3.2.

The two quantities mentioned above should both be treated as random quantities. Under these assumptions, the probability of rotor failure can be written as:

$$P_f = P(g \leq 0) \tag{6}$$

The probability calculated in this way will be a quantity increasing over time. In order to protect the rotor from destruction, preventive diagnostic testing should be carried out to localize potential cracks, evaluate their real dimensions and, if necessary, take action to eliminate them. This requires the turbine shut-down and involves expenses to cover the preventive testing costs. The selection of the time when diagnostic testing should be carried out can be rationalized using the relations given in Section 2. Based on Equation (3), it is possible to optimize the time of the performance of diagnostic tests that will confirm the advancement of the processes of potential crack propagation. Equation (3) should make use of Equation (6), which will make it possible to calculate the rotor failure probability. The scenario of diagnostic and maintenance activities assumes that the crack detected during the tests will be eliminated. Consequently, it is justified to assume further that after the diagnostic tests are performed, there are no defects in the rotor with dimensions exceeding the measuring apparatus sensitivity limit. Probability P_{f1} in Equation (3) is thus the probability after the performance of diagnostic testing and after the rotor repair (if needed). This means that if the rotor is operated further, it may be destroyed due to the propagation of a defect with initial dimensions smaller than 2 mm, which is the value adopted as the measuring apparatus sensitivity limit.

Following such a sequence of testing will make it possible to keep the risk related to further operation of the rotor at a safe level, and using Equation (3) will enable finding the optimal time to perform such diagnostic tests.

3.2. Crack Propagation in the Turbine Rotor

In order to calculate the rotor failure probability, it is necessary to calculate the rate of crack propagation in the rotor. The way in which a crack behaves in an element subjected to fatigue and creep processes is described by correlations between the crack propagation rate and the stress intensity coefficient K_I, expressed as:

$$K_I = M\sigma \sqrt{a} \left[MPa \cdot \sqrt{m} \right] \tag{7}$$

where M is the nondimensional function of geometrical parameters of the crack and the element and σ is the tensile stress acting on the crack (MPa). Crack propagation under variable loads is described by Equation (8) [39]:

$$\frac{da}{dN} = C(\Delta K)^m \left[m \cdot cycle^{-1} \right] \tag{8}$$

where C and m are material constants, $\Delta K = K_{Imax} - K_{Imin}$ is the amplitude of stress intensity coefficient (MPa· $\sqrt{m}$), and N is the number of fatigue cycles.

Crack propagation in a material under creep conditions can be described using the following general Equation (9) [39]:

$$\frac{da}{dt} = AK^n \left[m \cdot h^{-1} \right] \tag{9}$$

where A and n are material constants and t is the steady-state operation time (h).

Before the above formulae can be used to calculate the crack propagation rate, it is first necessary to determine stresses arising in conditions of steady- and unsteady-state operation. The rotor under consideration is a disk-type impulse rotor with a control stage and 11 regular stages. The rotor central bore diameter is 100 mm. The maximum stress value occurs in the central bore and may cause

propagation of cracks located there. The details concerning computer simulations of the rotor thermal and strength states in different phases of the turbine start-up are presented in [15]. To calculate the crack propagation rate under creep conditions, it is necessary to know the values of creep-related equivalent (von Mises) stress. In this case, computer simulation was also used.

Knowing steady- and unsteady-state stress values for different types of the turbine start-up (cold, warm and hot), the propagation rate of potential cracks in the rotor central bore can be calculated based on Equations (7)–(9). Considering that different maximum stresses may arise in real start-ups from the same initial thermal state, in further analyses the values of these stresses are treated as random quantities. A similar assumption is also made in relation to the material constants in Equations (7)–(9). The adopted mean values and standard deviations are listed in Table 2. It is assumed that in approximation they can all be treated as random quantities with a normal distribution.

Table 2. Mean values and standard deviation of input data.

Input Data	Mean Value	Standard Deviation
$\Delta\sigma_1$	200 MPa	10 MPa
$\Delta\sigma_2$	250 MPa	12.5 MPa
$\Delta\sigma_3$	300 MPa	15 MPa
C	2×10^{-12}	1×10^{-13}
m	3.4537	0.173
σ_{creep}	65 MPa	3.25 MPa
A	3×10^{-14}	1.5×10^{-15}
n	5.6572	0.283
M	1.98	0.086
a_0	2–5 mm	0.5 mm
K_{Ic0}	100 MPa $\sqrt{m}$	5 MPa $\sqrt{m}$

The potential crack propagation rate is calculated for a crack with initial values of 2 mm and 5 mm. The first value corresponds to the assumed sensitivity limit of the measuring apparatus and it is commonly adopted if no cracks are found in the element. The calculation results for the two initial crack dimensions are shown in Figure 3. The curves in the figure illustrate the assumed individual variants of further operation.
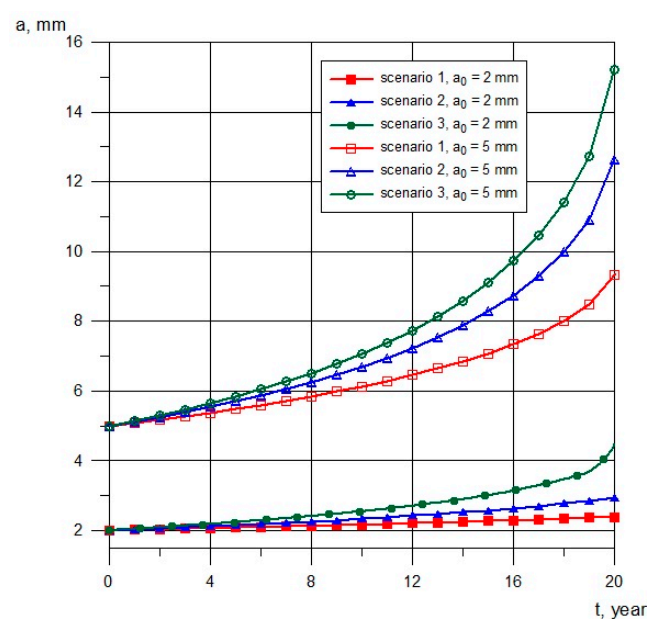

Figure 3. Crack propagation over time for different operating scenarios ($a_0 = 2$ mm and $a_0 = 5$ mm).

The first scenario of the further turbine operation assumes that the turbine will be started 200 times a year on average and all start-ups will be carried out relatively slowly so that the amplitudes of stress arising in the rotor central bore area should have a mean value of about 200 MPa. Scenario 3 describes the turbine operation at the power unit increased dynamics with faster start-ups. As indicated by numerical simulations of such processes, stresses arising in the rotor under such conditions are much higher and reach a level of about 300 MPa. Scenario 2 is a variant in between scenarios 1 and 3, i.e., one half of the start-ups are carried out at the rotor low heating rate and the other half at faster heating rates. In each of the variants, it is assumed that the turbine operation time per year totals ~6000 h.

Depending on the operating scenario, for the crack initial value of 2 mm after 20 years, the crack may get only slightly bigger at slow start-ups, or it may reach the size of about 4.5 mm at fast start-ups. The propagation of the initial 5 mm crack is much faster. After 20 years the crack may reach the size of more than 15 mm. Treated as determined quantities, these values are smaller than the crack critical dimension, the value of which (as a determined quantity) exceeds 20 mm. However, the nature of crack propagation processes indicates that these quantities have a random character. This assumption should therefore be used to establish the rotor failure probability.

4. Optimization of Diagnostic Testing Intervals

4.1. SPT-Based Estimation of the Decrease in Rotor Steel Toughness

The next stage in the procedure for the assessment of hazards due to the propagation of potential cracks must be the assessment of the state of the rotor material, especially the evaluation of changes in material toughness being the effect of the previous operation. This can be done using the quasi-nondestructive small punch test (SPT) method [40–46]. An example application of the method in the procedure for planning diagnostic testing of turbine elements is presented below [47].

The current mechanical properties of the material, including increased embrittlement of a rotor operated for a long time, can be identified and assessed by performing small punch tests of micropecimens of rotor steel (the SPT method). The method consists of punching a small specimen using a hemispherical indenter. The SPT method enables determination of the material's basic mechanical properties, otherwise specified typically by means of static tensile tests and impact strength testing, such as the yield point, tensile strength, brittle-to-ductile transition temperature and the material fracture toughness. The SPT specimen is sampled from the rotor using a special device that is shown in Figure 4a. A specimen sampled from a 200 MW turbine rotor and the microspecimens in the form of discs with the diameter of 8 mm and thickness of 0.5 mm are shown in Figure 4b.
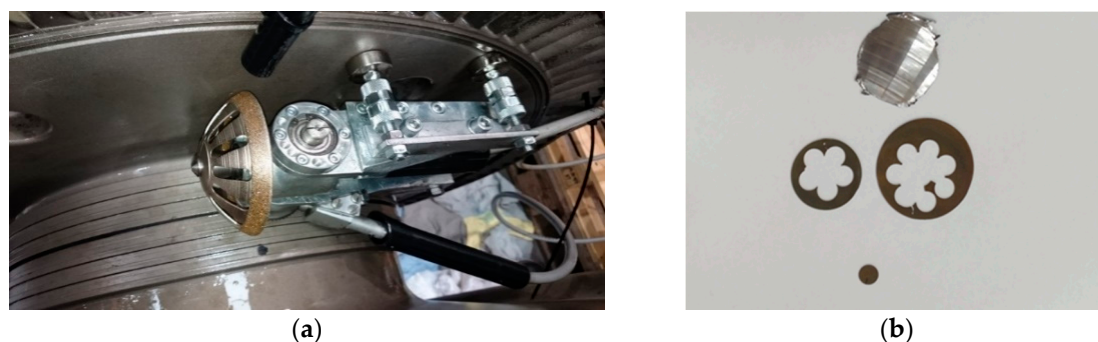

(**a**)　　　　　　　　　　　　　　　　　　　　　　　　　(**b**)

Figure 4. Specimen sampling from a 200 MW turbine rotor disc (**a**) device for specimen sampling; (**b**) rotor material specimen and the microspecimens made from it.

The specimens sampled from the rotor inlet and outlet part are then tested by means of the SPT method in ambient temperature and low temperatures. The results of the testing of the properties of the rotor outlet part, which is not loaded thermally, are considered as close to the rotor steel initial

properties. Example curves illustrating the SPT results obtained in ambient and low temperatures for microspecimens sampled from the HP rotor inlet and outlet are shown in Figures 5 and 6.
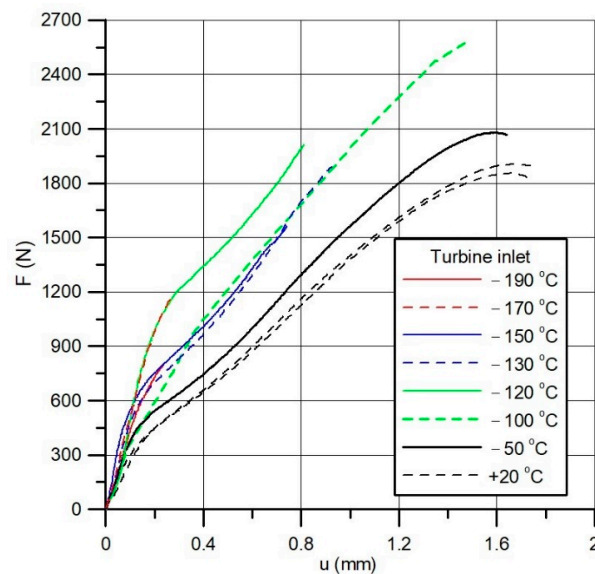

Figure 5. Testing in ambient and low temperatures–SPT curves obtained for inlet part specimens (F, force; u, displacement).
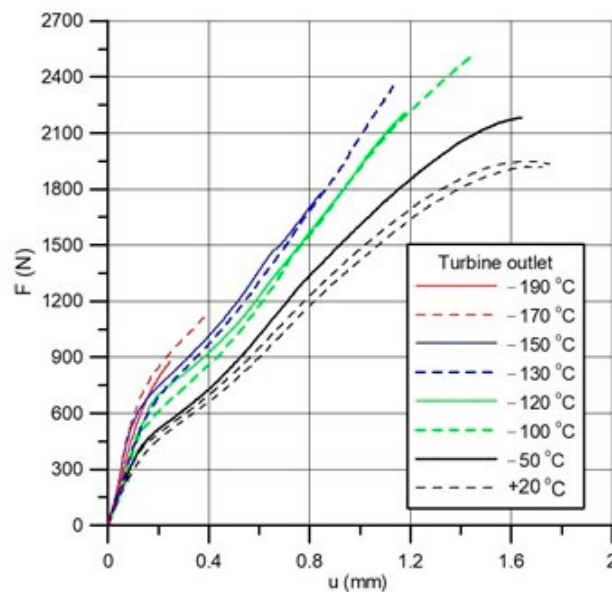

Figure 6. Testing in ambient and low temperatures–SPT curves obtained for outlet part specimens (F, force; u, displacement).

The results of such testing are used to establish the energy needed to destroy the specimen. After that, using appropriate correlations, it is possible to determine the temperature of the fracture appearance transition temperature (FATT). The details of the analyses are given in [47]. By conducting these tests of specimens sampled from the rotor inlet and outlet part, it is possible to assess the decrease in the rotor steel fracture toughness due to previous operating conditions.

The results obtained from the testing of rotors operated for more than 200,000 h indicate that the decrease in material toughness may reach from a few to about fifteen percent of the initial value [47]. Such a change may have an essential impact on the safety of the turbine with further operation at increased intensity.

4.2. Probability of the Turbine Rotor Failure

Considering the above algorithms, the rate of propagation of potential cracks was calculated for different initial crack dimensions and different operating scenarios, as discussed in Section 2. Using the Monte Carlo method, the time-dependent change in the crack size mean value *a* and the standard deviation of the value were determined. These crack propagation values, combined with the estimated change in the material toughness of a specific rotor, made it possible to calculate the rotor failure probability according to Equation (6). The probability was calculated using second-order reliability methods (SORMs) [48]. Example results of the calculation of the rotor failure probability, where the rotor material toughness was decreased due to the previous operation to the level of 60% of the nominal value, are shown in Figures 7 and 8.
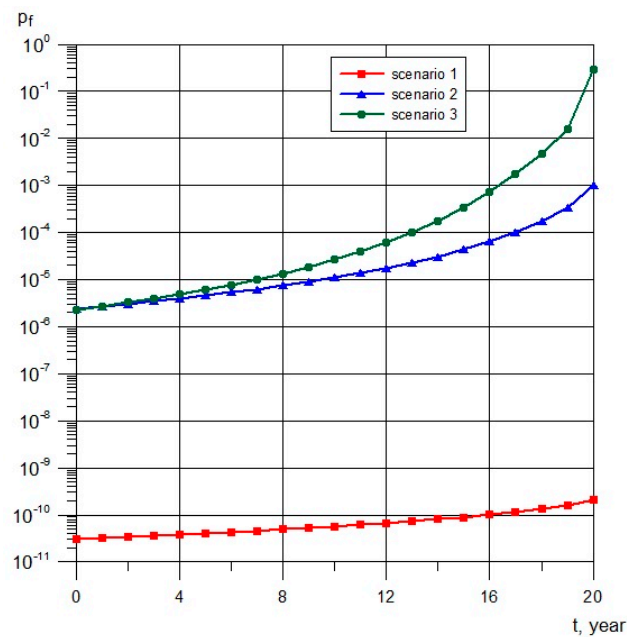

Figure 7. Change in the probability of rotor failure for different operating scenarios (a_0 = 2 mm).
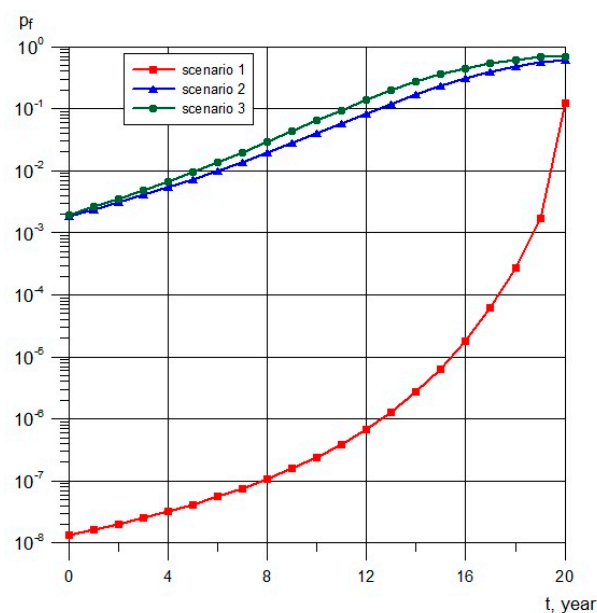

Figure 8. Change in the probability of rotor failure for different operating scenarios (a_0 = 5 mm).

The curves in the figures correspond to the three operating scenarios described above. In the analyzed operation period of 20 years, scenario 1 does not lead to high levels of the rotor failure probability. In this case, it is smaller than 10^{-6}. Scenario 2 and 3, after 20 years of operation, indicate very high levels of rotor failure hazard. Assuming that the turbine is operated according to scenario 3 and that no cracks or defects are found in the rotor, the rotor failure probability after 16 years of operation exceeds 10^{-3}. If a 5 mm defect is found in the rotor, the failure probability after about 5 years exceeds the level of 10^{-2}. If the turbine is operated according to scenario 1, i.e., with slow start-ups that do not produce high stresses in rotors, this level of the failure probability is reached after about 19 years.

4.3. Optimization of Diagnostic Testing Intervals

The calculations of crack propagation due to fatigue and creep processes make it possible to estimate the rate of the increase in potential cracks and the change in the rotor failure probability in subsequent years of operation. To prevent such a failure, preventive diagnostic testing of the rotor should be carried out and, depending on the results, adequate repair action should be taken. The optimal time of the testing performance was determined based on the optimization of the *NPV* index expressed by Equation (3). The results of the optimization performed for three different operating scenarios described in Section 3 are shown in the figures below. Figure 9 presents the change in the *NPV* index value in subsequent years of operation assuming that at the beginning of the period there may have been a crack in the rotor central bore, but smaller than 2 mm (the value assumed as the measuring apparatus sensitivity limit). It also presents the change in the *NPV* index in subsequent years, assuming, however, that at the beginning there was a 5 mm crack in the rotor central bore.
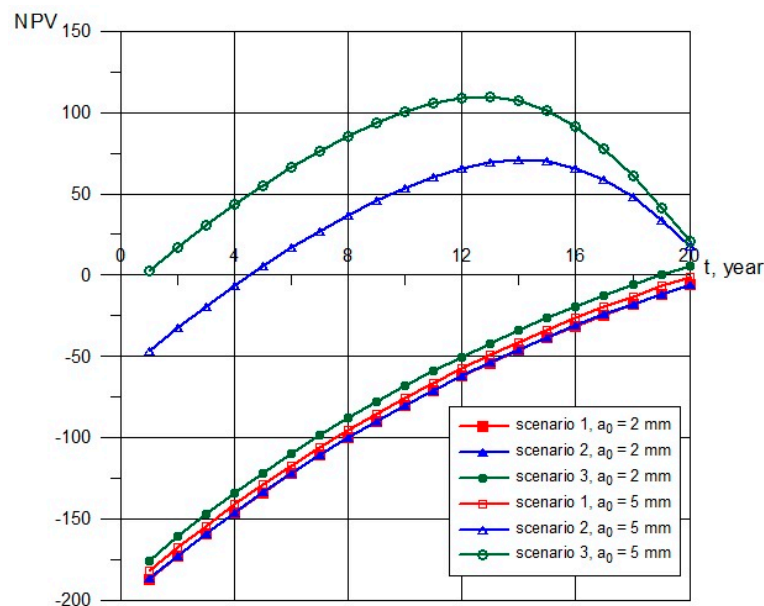

Figure 9. Change in the net present value (*NPV*) index over 20 years for different operating scenarios (for $a_0 = 2$ mm and $a_0 = 5$ mm).

The calculation results presented in Figure 9 were obtained assuming that the value of losses C_t related to the rotor failure and destruction totalled 100 conventional units and the value of outlays C_{rt} for the rotor diagnostic testing and repair to eliminate detected cracks totalled 15 conventional units.

In the first case (cf. Figure 9), i.e., assuming the presence of defects smaller than 2 mm in the rotor, the *NPV* index does not reach positive values. In the second case, with the initial crack size of 5 mm, the *NPV* index value reaches its maximum. For scenario 2, the optimal time to carry out diagnostic testing is the 14th year of operation. For scenario 3, i.e., intensive operation characterized by a large

number of start-ups, the rotor diagnostic testing should be carried out in the 12th year of operation. It should be noted that the *NPV* index positive values already appear after a few years of operation, which indicates that it is justified to carry out diagnostic testing even that early.

The analysis also covered the impact of the diagnostic testing costs on the selection of the optimal time for the diagnostic testing performance. The results for three C_{rt} values of 5, 15 and 30 conventional units are shown in Figure 10.
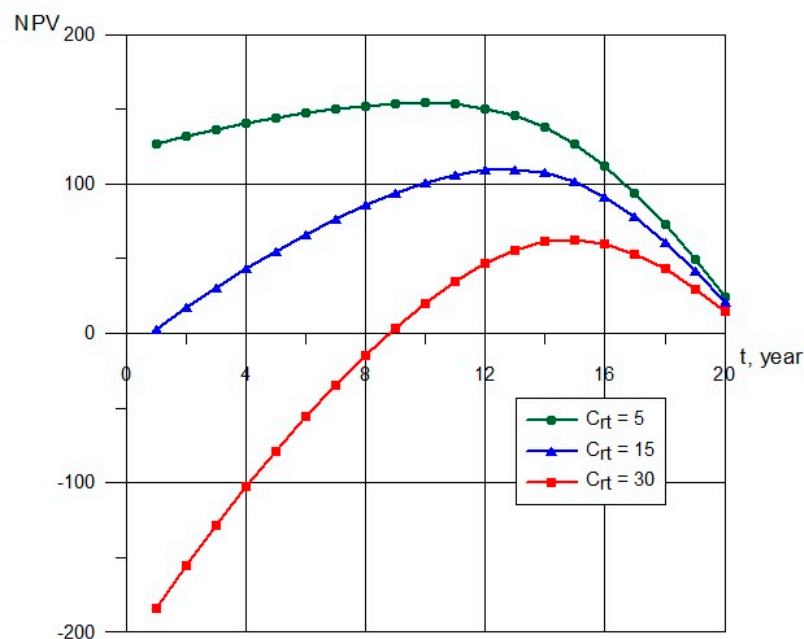

Figure 10. Impact of costs C_{rt} related to diagnostic testing and repair on the change in the *NPV* index over 20 years of operation, according to scenario 3.

The optimization of the time to perform maintenance activities is substantially affected by the relative value of the costs incurred due to their relationship to costs arising from the failure. If the costs related to the maintenance activities are less than 5% of the failure-related costs, it is justified to perform those activities practically at any time during turbine operation (cf. Figure 10). At higher C_{rt} costs in relation to the C_t value, the optimal time for the performance of the maintenance activities should be determined by taking account of both the risk created by the turbine operation and the level of rational costs incurred to reduce the risk. If the testing and maintenance costs total about 30% of the failure-related costs, the *NPV* is positive after 9 years of operation and the maximum *NPV* occurs after 15 years. This is the time interval in which the performance of the rotor central bore diagnostic testing is justified.

5. Conclusions

The method presented for analyzing the risk created by further operation of turbines that have already been in service for a long time used both materials testing and numerical simulations. The first stage of the analysis was to establish the propagation rate of potential cracks in the rotor central bore. After that, the turbine rotor failure probability was determined for different operating scenarios.

To protect the rotor from destruction, preventive diagnostic testing should be carried out to confirm the real dimensions of the crack and enable a rational decision whether to continue the turbine operation, repair some of the turbine elements or replace them.

The testing should include identification of the location and size of potential cracks, especially if they are located in tensile stress concentration zones, i.e., in the central bore of rotors, for example. Another important quantity the value of which should be verified by diagnostic testing is the change

in rotor steel toughness. This can be done using the quasi-nondestructive SPT method described in the manuscript.

The optimal time to perform diagnostic testing and carry out repairs (if needed) can be determined based on the results of the modified NPV index optimization. In the proposed approach to the *NPV* index, the values of the avoided risk of turbine rotor failure in the planned period of further operation were assumed as positive cash flows. Negative cash flows assumed the remaining residual risk during this period and the costs associated with maintenance activities, including rotor diagnostic tests. The proposed diagnostic tests include endoscopic inspection of the rotor bore and SPT of the collected microspecimen of the rotor material. The results of the analyses presented indicate that the optimal time for such testing is substantially affected by the character of the turbine operation. Intensive operation being the effect of the efforts to improve operating flexibility, i.e., a larger number of the power unit fast start-ups and shut-downs, significantly shortens the time after which diagnostic testing should be carried out. Depending on the information on the presence of possible cracks and defects in the rotor central bore, the time intervals after which the rotor diagnostic tests should be carried out to confirm these findings total from a few to several years. The time is first and foremost dependent on the character of the turbine operation. For the analyzed operation method involving fast start-ups, it is 12 years. Another essential element that has an impact on the optimal selection of the times of diagnostic testing and repairs is the relative value of costs related to those activities compared to costs arising due to the turbine potential failure. If the anticipated testing and maintenance costs are less than 15% of the costs of a potential failure, the testing can be performed as early as after 2 years of the turbine operation. If these costs are higher, the optimal interval after which such diagnostic testing should be carried out is longer.

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