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113

Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100th Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Operation decision support regarding components of steam turbines wear in steady state

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Abstract

This paper discusses chosen operation and diagnostic problems with steam turbines in steady states. Wear rate monitoring is the main goal. The material creep affects components wear under heat load in steady state. The paper presents the methodology of comprehensive diagnostic information development, which supports operation, repair and modernization decisions. An example is shown of such a support based on operation decision making in order to decrease its components wear rate.

Keywords: Steam turbine; Creep; Operation; Component wear

1 Introduction

Applying diagnostic investigations is essential to optimal operation of steam turbines. These investigations may be either periodical or a permanent on-line monitoring. The results of the investigations should create a basis of any operation, repair or modernization decision. It depends on thermal measurement data processing methods whether the measurements results are in fact useful [1-6].

Data processing means supplying comprehensive and well-ordered diagnostic information. In the scope of turbine components durability this final diagnostic information includes:

- components technical state conclusions,

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- further operation time evaluation,
- guidelines for eliminating defects in turbines operation.

The measurement diagnostic investigations results should be completed with theoretical analysis and multi-optional numerical simulations. These supplies additional information regarding for example the influence of future operating conditions on the components wear rate. It is also possible to evaluate the future effects of present decisions.

Respecting the notes described above, there are procedures, their applications and numerical modeling results presented in this paper, which support operating decisions. They regard turbine components wear in steady operation states. The wear of components operating under these conditions and under high temperature levels is affected by material creep.

2 The aim and scope of investigations

Operation decisions suggest modernizations of turbines operating conditions. New, adjusted operating conditions must satisfy the machine user demands.

Generally, each alteration of operating conditions alters the components wear rate. The components remaining time of operation changes. As a consequence the remaining time of operation of the whole unit also changes.

The of remaining time operation of chosen turbine components is analyzed here. It is assumed that the unit operating conditions until present are known (its operating history). Main components (rotor, casing, valves) construction data are also known. The detailed investigation includes modeling of the operating conditions influence on the components remaining time of operation. The procedures are developed, which allow multi-optional simulation of various parameters influence on remaining time of operation. Several detailed problems are analyzed, such as:

- remaining time of operation prediction,
- remaining time of operation verification with regard to increased number of turbine start-ups,
- designed temperature excess influence on components remaining time of operation,
- steam temperature oscillations influence on components remaining time of operation,
- assessment of turbine components creep wear rate decrease caused by steam temperature lowering.

The modeling results complete the thermal measurements and diagnostic investigations results. The developed procedures are a part of comprehensive operating and repair decision support system based on diagnostic investigations. This system, its assumptions and sample applications are described in [4]. The operation decision support system main input data are:

(a) turbine components technical state,

(b) turbine operating history including for example:

- operation characteristics, which is the frequency of start-ups as well as the frequency of power alteration;
- steam parameters oscillations (temperature, pressure)
- all other operating conditions that might increase the wear rate.

(c) the expected time of further operation,

(d) further operation characteristics (described as in b.).

The main information used when deciding about turbine operation is its actual technical state and derived remaining time of operation. The assessment of components durability is a superior task. For example, it is useless to start a modernization that would increase unit effectiveness without prior determination of safety and possible time of further operation for its main components.

3 Assumptions regarding the initial state assessment in the scope of turbines durability

- The main parameter describing steady state operation until present is the hitherto time of operation (t_d). If there are several levels of temperature in the steady state, then

$$t_d = \sum_{i=1}^{n} t_{di}, \tag{1}$$

where: t_{di} – hitherto time of operation at T_i temperature level,

- Usually livesteam temperature time dependence is not known for the whole time of operation until present. It renders difficulty to divide the t_d period into t_{di} sub-periods.
- With respect to the above, it is assumed that the component, which operated under constant temperature equal to the design temperature ($T_d =$

T_0) during whole t_d period and for such a condition the creep wear Z_t is determined as:

$$Z_t = \frac{t_d}{t_{B0}}, \tag{2}$$

where: σ^c – maximal stress determined respecting material creep, t_{B0} – maximal operation period duration under stress σ^c and temperature T_0 determined on the basis of creep characteristic

$$t_B = f(T, \sigma^c). \tag{3}$$

- The main parameter describing turbine conditions during start-ups until present is the hitherto number of start-ups (N_d). It is essential to divide the start-ups with respect to their initial states:
  - cold (c) – $N_{d,z}$
  - warm (w) – $N_{d,c}$
  - hot (h) – $N_{d,g}$
- An equivalent maximal stress σ_{max} and equivalent stress amplitude $\Delta\sigma$ of the whole load alteration cycle are determined for each of the start-ups groups. The load alteration cycle includes:
  - start-up and power alteration,
  - steady operation at design or partial load,
  - turbine shut-off and self or forced cooling.
- A special attention should be paid to occurrences, which significantly affect components wear degree. These would be extraordinary operating states and faults.
- An equivalent maximal stress σ_{max} and an equivalent stress amplitude $\Delta\sigma$ might be determined with use of the methodology, which is described in [5,6]. As for this paper it is assumed that the results of such an analysis are known.
- Hitherto material fatigue wear equals:

$$Z_N = \sum_i \frac{N_{di}}{N_{Ai}} \quad i = c, w, h, \tag{4}$$

where: c, w, h – cold, warm or hot unit start-up, N_A – number of cycles until first cracks are observed; taken from material fatigue characteristic:

$$N_A = f(\Delta\sigma). \tag{5}$$

- Total hitherto (actual, initial) component wear Z_0 is the sum of creep and fatigue wear:

$$Z_0 = \frac{t_d}{t_{B0}} + \sum_i \frac{N_{di}}{N_{Ai}}, \quad i = c, w, h. \tag{6}$$

4 Prediction of turbine remaining time of operation

4.1 Remaining time of operation under arbitrary conditions

On the basis of linear cumulative damage theory, total component wear Z_c may be described as a sum of actual (hitherto) wear degree Z_0 and remaining (prospective) wear degree Z_p

$$Z_c = Z_o + Z_p = Z_o + Z_{Np} + Z_{tp}, \tag{7}$$

where: Z_{tp} – remaining (prospective) creep wear

$$Z_{tp} = \frac{t_p}{t_B}, \tag{8}$$

Z_{Np} – remaining (prospective) fatigue wear

$$Z_N = \sum_i \frac{N_{pi}}{N_{Ai}}, \; i = c, w, h, \tag{9}$$

t_p – remaining time of operation, N_{pi} $(i = c, w, h)$ – remaining number of start-ups from cold, warm and hot initial state.

Remaining time of component operation t_p may be determined from the term:

$$Z_c = Z_g, \tag{10}$$

where: Z_g – fatigue limit Term (10) for $Z_g = 1$ and with respect to (7) - (9) yields:

$$\frac{t_p}{t_B} + \sum_i \frac{N_{pi}}{N_{Ai}} = 1 - Z_0, \quad i = c, w, h, \tag{11}$$

from which derives:

$$t_p = t_B \left(1 - Z_0 - \sum_i \frac{N_{pi}}{N_{Ai}} \right), \quad i = c, w, h. \tag{12}$$

The equation above shows that the remaining time of component operation (t_p) depends on the actual wear degree Z_0 and on future operating conditions of a steady (stress σ^c and temperature T) and unsteady state (amplitude $\Delta\sigma$, remaining number of load alteration and remaining number of start-ups from various initial thermal states N_{pi}).

4.2 Remaining time of operation under unmodified conditions

If the operating conditions are to remain the same as until present, then the following assumptions are true:

- stress σ^c and temperature T remain unchanged

$$\sigma_p^c = \sigma_d^c = \sigma^c, \quad T_p = T_d = T_0, \tag{13}$$

- the frequency of turbine start-ups remains unmodified. The number of remaining start-ups per unit of time N_{pi} does not change. It may be described as:

$$\frac{N_{pi}}{t_p} = \frac{N_{di}}{t_d}, \quad i = c, w, h. \tag{14}$$

Substituting (13) and (14) into (12) yields:

$$t_{p0} = \frac{1 - Z_0}{\frac{1}{t_{B0}} + \sum_i \frac{N_{di}}{t_d N_{Ai}}}, \quad i = c, w, h, \tag{15}$$

where:

$$t_{p0} = t_p(T_0), \quad t_{B0} = t_B(T_0). \tag{16}$$

In order to simplify further analysis input data is assumed to be as follows:

- hitherto operation time t_d
- hitherto wear degree Z_0

Using these two parameters it is possible to eliminate the hitherto number of start-ups (from various initial states) N_{di} from Eq. (15). Deriving from (6):

$$\sum_i \frac{N_{di}}{N_{Ai}} = Z_0 - \frac{t_d}{t_{B0}}. \tag{17}$$

Final equation describing the remaining time of operation under unmodified conditions yields:

$$t_{p0} = t_d \frac{1 - Z_0}{Z_0}. \tag{18}$$

5 Remaining time of operation verification against increased turbine start-up frequency

Load alteration is characteristic for power systems. This requires adjustment of the produced power to the actual power demands. Also, the electrical power demand has significantly decreased.

All these cause that some of the power units are put in the stand-by state, while others operate at lower loads or operate discontinuously with frequent shut-offs and start-ups. Generally this increases the number of start-ups and decreases the number of turbine operating hours.

Assuming that future start-ups proportions would be the same as until present it may be written that:

$$\frac{N_{pi}}{t_p} = a_r \frac{N_{di}}{t_d}, \quad i = c, w, h. \tag{19}$$

The coefficient a_r determines the turbine start-ups frequency increase and then component operation period under temperature T_1 (various from T_0) equals:

$$t_{p1} = \frac{1 - Z_0}{\frac{1}{t_{B1}} + \frac{a_r}{t_d}\left(Z_0 - \frac{t_d}{t_{B0}}\right)}, \tag{20}$$

where:

$$t_{p1} = t_p\,(T_1)\,, \quad t_{B1} = t_B\,(T_1)\,. \tag{21}$$

Remaining time of operation dependence on coefficient a_r as well as on temperature T_1 is presented in Figs. 1a, 1b. Two components were chosen of wear degree $Z_0 = 48$ % and 60 % (Fig. 1a).

A special case is emphasized in Fig. 1. This is when start-up frequency remains unchanged ($a_r = 1$). Under these conditions the remaining time of operation yields:

$$t_{p1} = \frac{1 - Z_0}{\frac{1}{t_{B1}} - \frac{1}{t_{B0}} + \frac{Z_0}{t_d}}. \tag{22}$$

Increasing the number of start-ups (a_r>1) shortens the remaining time of operation. For example with $a_r = 1$ and $a_r = 1.5$ it is respectively:

for $Z_0 = 48\%$ $\quad$ $t_{p1} = 171500$ and 140500 hours
for $Z_0 = 60\%$ $\quad$ $t_{p1} = 105500$ and 82700 hours

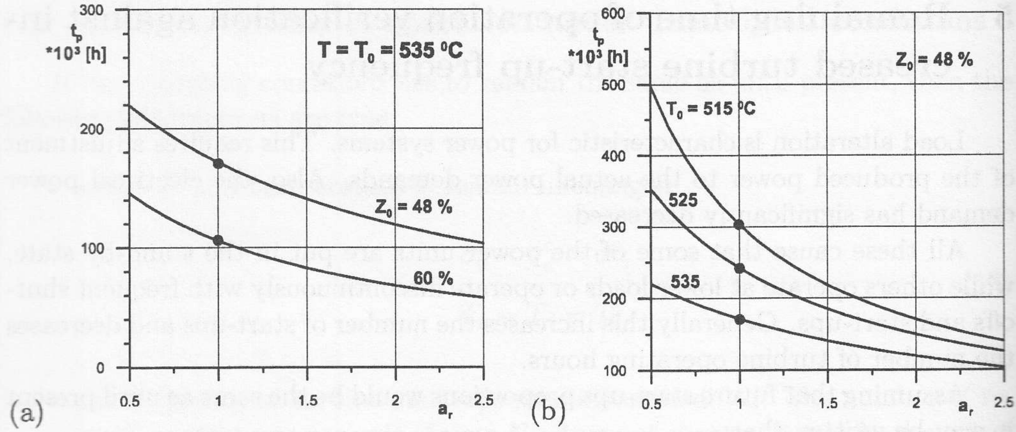

Figure 1. Remaining time of operation dependency on: coefficient a_r and wear degree (a), coefficient a_r and temperature (b).

6 Dependence between remaining time of operation the design temperature excess

Analysis prior to this paper assumed that component temperature is constant under steady operation conditions. However livesteam temperature is not constant and neither is the temperature of the steam flowing around turbine components. Therefore component material temperature also changes.

Assuming that there is a component temperature increase (in relevance to design temperature T_0) during time period t_1, a question arises: how does the design temperature excess affect the decrease of component creep durability?

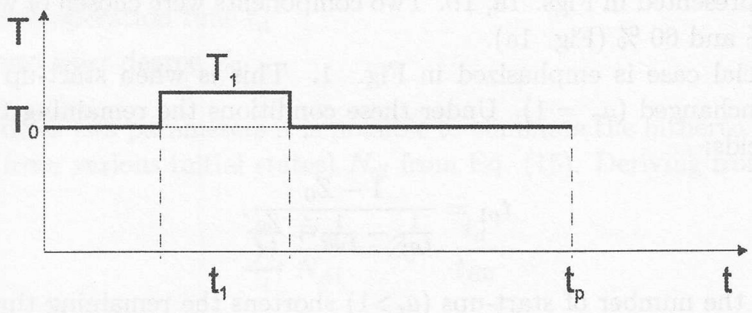

Figure 2. Component temperature time dependency.

If design temperature excess occurs then creep wear is defined as (notation according to Fig. 2):

$$Z_{tp} = \frac{t_p - t_1}{t_{B0}} + \frac{t_1}{t_{B1}}. \tag{23}$$

Substituting (23) in (7) and (10) for $Z_g = 1$ it is:

$$Z_0 + \sum_i \frac{N_{pi}}{N_{Ai}} + \frac{t_p - t_1}{t_{B0}} + \frac{t_1}{t_{B1}} = 1 \tag{24}$$

and the remaining time of operation regarding design temperature excess yields:

$$t_p = t_1 + t_{B0}\left(1 - Z_0 - \sum_i \frac{N_{pi}}{N_{Ai}} - \frac{t_1}{t_{B1}}\right), \quad i = c, w, h, \tag{25}$$

which might be transformed into

$$t_p = t_1 + t_{p0}\left(1 - \frac{t_1}{t_{p1}}\right), \tag{26}$$

where: t_{p0} and t_{p1} – remaining times of component operation respectively under temperatures T_0 and T_1 defined by the Eq. (12)

$$t_{p0} = t_{B0}\left(1 - Z_0 - \sum_i \frac{N_{pi}}{N_{Ai}}\right), \quad i = c, w, h, \tag{27}$$

$$t_{p1} = t_{B1}\left(1 - Z_0 - \sum_i \frac{N_{pi}}{N_{Ai}}\right), \quad i = c, w, h. \tag{28}$$

If the future start-up number is proportional to the this number until present (19), then Eqs. (27) and (28) may be substituted with

$$t_{p0} = \frac{1 - Z_0}{\frac{1-a_r}{t_{B0}} + \frac{a_r \cdot Z_0}{t_d}}, \tag{29}$$

and

$$t_{p1} = \frac{1 - Z_0}{\frac{1}{t_{B1}} + \frac{a_r}{t_d} \cdot \left(Z_0 - \frac{t_d}{t_{B0}}\right)}. \tag{30}$$

Remaining times of operation t_{p0} and t_{p1} for hitherto conditions may be calculated using Eq. (18) and (22).

A sample remaining time of operation dependency on excess temperature T_1 and excess period duration t_1 is shown in Fig. 3.

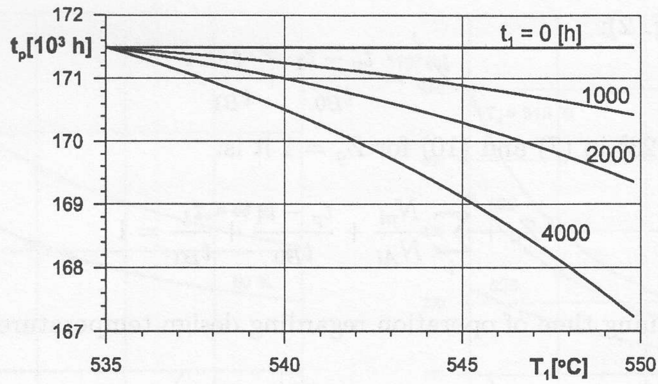

Figure 3. Remaining time of operation dependency on excess temperature and period duration.

7 Dependence of remaining time of operation on steam temperature oscillations

Let us assume that the livesteam temperature change causes temperatures changes of components, which may be approximated as shown in Fig. 4. Time periods t_i are related to respective temperatures T_i.

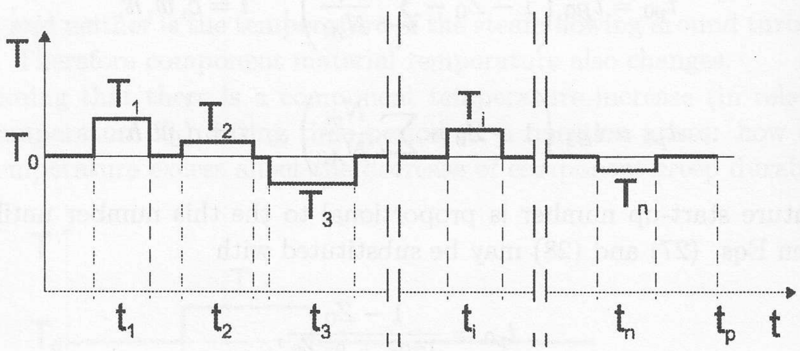

Figure 4. Component temperature time dependence approximation.

Describing the remaining time of operation as a sum of operation under each of the temperature levels it may be written that:

$$t_p = t_0 + \sum_{i=1}^{n} t_i \quad \text{hence} \quad t_0 = t_p - \sum_{i=1}^{n} t_i. \tag{31}$$

Creep wear with notation according to Fig. 4 equals:

$$Z_{tp} = \frac{t_0}{t_{B0}} + \sum_{i=1}^{n} \frac{t_i}{t_{Bi}}. \tag{32}$$

Substituting (32) in (7) and (10) for $Z_g = 1$ it is:

$$Z_0 + \sum_j \frac{N_{pj}}{N_{Aj}} + \frac{t_0}{t_{B0}} + \sum_{i=1}^{n} \frac{t_i}{t_{Bi}} = 1, \quad j = c, w, h. \tag{33}$$

Repeating the calculation sequence from the previous section the remaining time of operation with regard to steam temperature oscillations may be written as:

$$t_p = t_{p0} \cdot \left(1 - \sum_{i=1}^{n} \frac{t_i}{t_{pi}}\right) + \sum_{i=1}^{n} t_i, \tag{34}$$

where: t_{p0} and t_{pi} – remaining times of component operation respectively under temperatures T_0 and T_i defined according to conditions at turbine start-up by the equations:

- arbitrary start-up number increase – Eqs. (27) and (28),
- proportional start-up number increase – Eqs. (29) and (30),
- hitherto operating conditions – Eqs. (18) and (22).

In the Eqs. (22), (28) and (30) the term t_{p1} should be substituted with t_{pi} and t_{B1} with t_{Bi}.

8 Sample modeling results

As an example, a remaining time of operation dependency on design temperature excess as shown in Fig. 5 is analyzed. It is an extension of the example presented in section 6 (Fig. 2 and 3). It is now assumed that the period t_2 of lower temperature level T_2 compensates for the period t_1 of design temperature T_0 excess up to temperature T_1.

The temperature T_2 and duration t_2 are both adjusted in order to maintain an average temperature equal to design temperature T_0 throughout the remaining time of operation. The results of modeling are shown in Fig. 6.

It is interesting to compare (Fig. 7) the remaining times of operation shown in Figs. 3 and 5. In the case of the first one (Fig. 3) there is only the design temperature excess. In the second case (Fig. 5) the T_2 temperature period compensates for the T_1 temperature excess in order to maintain average temperature equal to the design temperature T_0. The decrease in remaining time of operation is significantly lower but it should not be omitted.

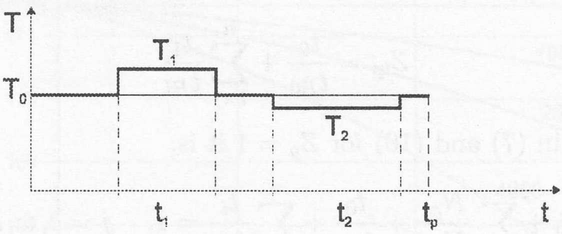

Figure 5. Component temperature time dependence.

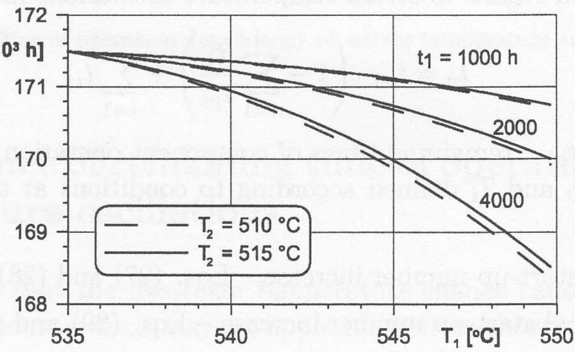

Figure 6. Decrease of remaining time of operation caused by temperature oscillations shown in Fig. 5.

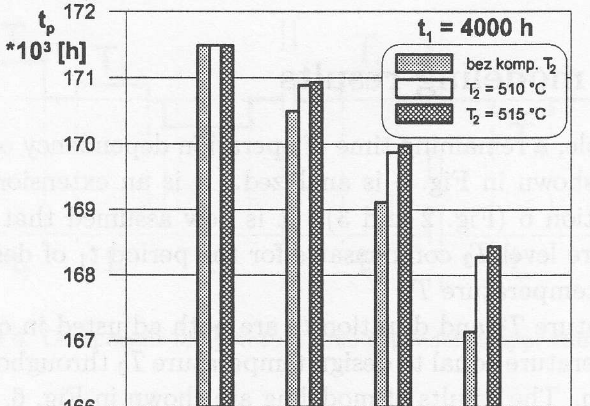

Figure 7. Comparison of remaining operation time decreases.

9 Conclusions

Presented procedures are a part of comprehensive operating and repair decision support system in the scope of turbine durability, which was developed at the Institute of Power Engineering and Turbomachinery. System application is presented as a set of diagnostic guidelines. These guidelines are the basis for numerical decision support procedures [4]. The general form of the guidelines yields:

IF - circumstance - THEN - conclusion

The "circumstance" is a collection of various conditions created from the input data. The operation decision support system main input data are: turbine components technical state, turbine operating history, the expected time of further operation and further operation characteristics.

This system was applied to determine the optimal steam turbines repair cycle. The latest application of the system involves assessment of turbine components creep wear rate decrease caused by steam temperature lowering.

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