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The Procedure for Determining the Time of Safe Service beyond the Design Service Time Based on Creep Testing

Janusz Dobrzański

Abstract

This article describes the method for determination of residual life and disposable residual life based on long- and short-term creep tests for different temperature levels above the operating one and stress level equal to the operating one. The method for determination of the share of disposable life in total life and the time of safe service beyond the design service time was proposed. These characteristics of the steel are used for the evaluation of the structural changes and mechanical properties of the material after long-term operation. The result of this study is the database of material characteristics representing the mechanical properties related to the structure analysis, and it can be used for diagnosis of the components of pressure part of power boilers.

Keywords: microstructure, mechanical properties, short creep test, residual life, welded joint

1. Introduction

The extension in the service time of power units which have exceeded the design service life of 100,000 h is made using the calculation method based on the creep strength data for 200,000 h service and the positive results of comprehensive diagnostic tests, with particular consideration given to those of the critical pressure components of boilers and turbines. Out of them, the components working at above the limit temperature, that is, under creep conditions, are of particular importance. In the assessment of these components, it is important and necessary to assess the condition of their materials [1–7]. Such an assessment is carried out based on non-destructive materials testing, and its result is referred to the available characteristics of materials after service [8–15]. The results of these tests provide good estimation of the condition of material and its exhaustion degree and allow for determination of the time of further safe service until the next inspection [16–28].

However, to reach the level of 200,000 h service for the material of components, not only good estimation of residual life but also its determination based on the destructive testing on a representative test specimen is required in a number of cases.

Yet, it is not always possible in practice. It can be made to assess the condition of the material of the main steam pipeline or transfer pipeline as well as for certain chambers and desuperheaters. However, it must be preceded by a cost-effectiveness calculation for such a procedure.

The problem related to the assessment of creep resistance in case of materials operated for a long time under creep conditions is the time required to carry out the creep tests to assess the residual life and the remaining safe time of service. This paper shows how to use long-term creep tests at the temperature and stress parameters corresponding to the actual operating ones, which allow for determination of the actual residual life, to make such an assessment. The method for using short-term creep tests for such an assessment where test duration is reduced by increasing one of the parameters in relation to the actual ones is also presented.

2. Creep tests

2.1 Long-term creep tests

In the assessment of residual life and disposable residual life, the main source of information is still creep tests in spite of the fact that their disadvantage is a long time until the test results are obtained. Creep tests are usually carried out under uniaxial tension and at strain rates from 10 to 9 to 10–12 s^{-1} (corresponding to the actual service conditions) on test specimens taken directly from the material of component after long-term service at a temperature exceeding the limit one tg (te > tg).

Long-term creep tests can be divided into:

- Creep rupture tests without measurement of elongation during test

- Creep test with measurement of elongation during test

Based on the results of creep rupture tests without measurement of elongation during test, the residual life can be determined using one of the two procedures:

- Lifetime fracture rule

- Extrapolation of creep rupture test results

The lifetime fracture rule relies on the assumption that changes in temperature T or stress σ during service can be divided into degrees characterised by specific temperature Ti and stress σ_i.

Thus, the lifetime fracture rule concept by Robinson assumes that

$$\sum_i \left[\frac{t(\sigma, T)}{t_r(\sigma, T)} \right] = 1$$

where T is the time of stress σ at a temperature T, tr is the time to rupture under stress σ and at temperature T, and i is the number of degrees of stress and temperature T from the beginning of service until rupture of the material.

For each of these degrees, the creep rate in steady state (secondary creep) or the time to rupture tri based on the experimental data measured under preset stress and temperature is determined. The total creep strain is assumed to be the sum of strains corresponding to the consecutive degrees, that is, $\varepsilon_c = \sum_i \varepsilon_i$.

For the materials after service, the lifetime fracture rule can be presented as

$$\frac{t_s}{t_{r_s}} + \frac{t_t}{t_{r_t}} = 1$$

where t_s is the time of previous service of the material, t_{r_s} is the time to rupture under service conditions (σ_e, Te), t_t is the time to rupture of the test specimen determined under the accelerated creep test conditions for the material after service ($\sigma_t > \sigma_e$ and/or Tt > Te), and trt is the time to rupture of the material in the as-received condition under the accelerated test conditions ($\sigma_e = \sigma_t$, T = Tt).

Assuming that the further operating conditions will not differ from the previous ones, the time equal to the residual life can be determined from

$$t_{r_s} - t_s = \frac{t_t t_s}{t_{r_t} - t_t}$$

The need to know the time to rupture of the material in the as-received condition t_{rt} restricts the use of this method.

In the event when the test specimens for destructive testing are taken from the operated material after two different times of service ts1 and ts2 and the creep tests are carried out for both conditions of one material, the time to rupture of the material in the as-received condition trt can be eliminated. Then, the knowledge of the properties of material in the as-received condition is not required.

The use of this method is particularly useful in the modernisation of boilers when some critical boiler components operating under creep conditions are replaced and the basic operating parameters are recorded and controlled on-line.

The residual life can also be determined by extrapolating the results of creep rupture tests carried out on material after service at a temperature equal to or different from the design service temperature (Tr) and stress values equal to, but usually higher than, those characteristic of the service conditions (σ_r). Obtained in this way, the results of creep rupture tests with a time of usually approx. 10,000 h are presented in the parametric way by expressing one variable as a product of the function of two other variables, that is, stress and temperature and time, respectively, using the Larson-Miller parameter in the following form:

$$H\,(\sigma)LM = T\,(C + \log\,t_{re})$$

where $H\,(\sigma)$ is the stress function, σ is the stress, T is the temperature in K, C is the material constant at 1/T = 0, and t_{re} is the time to rupture of material after service.

This method for determination of residual life is shown graphically in **Figure 1**. Knowing the operating temperature T_r and the operating stress σ_r (resulting from the component's geometry and operating pressure p_r) of further service, the time to rupture t_{re} can be determined following which the component destruction should be expected. However, the determined time t_{re} is of no practical value. The practical value is the time to end of secondary creep, which is called disposable residual life t_{re} 0.6 and which is part of the residual life. This value is specific to each of the test grades of material.

The duration of the tests allowing for determination of the residual life t_{re} can be reduced by carrying out the creep tests with measurement of elongation during test in order to determine the creep rate in steady state for the properly selected creep parameters (σb, Tb). Using the obtained curve of maximum creep rate vs. stress = $f(\sigma)$ at the constant temperature Tep of further service, the time of further safe service can be determined, expressed by the following formula:
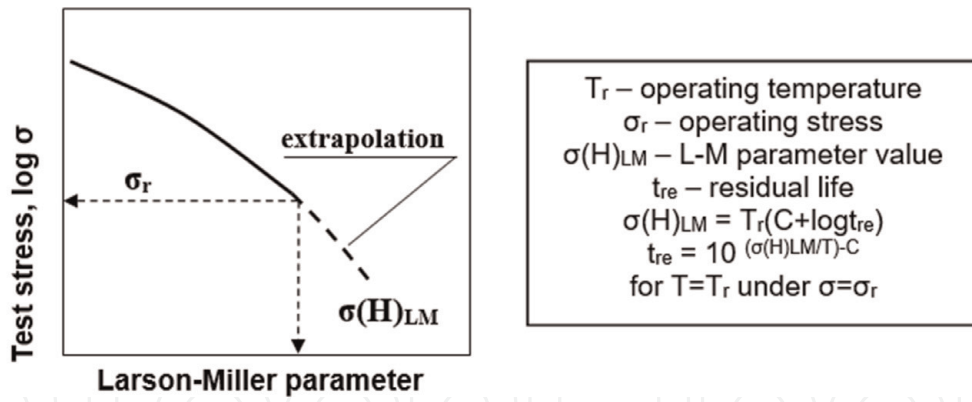
Figure 1.
Determination of residual life using extrapolated Larson-Miller parameter curve for creep strength of the material after service at above limit temperature.

$$t_{e_p} = \frac{\varepsilon_{c_{dop}}}{\dot{\varepsilon}^{\cdot sep}}$$

where $\varepsilon_{c\ acpt}$ is the acceptable total strain (adopted based on the operating experience and creep test results)—creep rate for parameters of further service (ε_e, Te) provided that the relation $\varepsilon_e \leq \varepsilon_{c\ acpt}$ is met.

The method for determination of creep rate for the parameters of further service is shown graphically in **Figure 2**.

The creep rupture tests with measurement of elongation during test are also used to determine:

- The time to end of secondary creep t_{II} and the corresponding elongation ε_{II}

- The time to rupture t_r and the corresponding elongation ε_c

- The share υ of the time of secondary creep t_{II} in the overall time to rupture t_r
  $\left(\upsilon = \frac{t_{II}}{t_r}\right)$

The tests are carried out at a constant test temperature T_b, which is similar to the operating one, and at stress σ_b values higher than those corresponding to the operating one. As a result of each of the tests, the creep curves $\varepsilon = f(t)$ at σ_b = const are obtained (**Figure 3a**). The test results are plotted on the diagram in the coordinate system $\upsilon = f(\sigma)\varepsilon_c = f(\sigma)\varepsilon_{II} = f(\sigma)$ at $T_b \approx T_e$ = const (**Figure 3b**). The characteristics obtained in this way allow for determination of the disposable residual life, which is the time of further safe service for the adopted operating parameters.
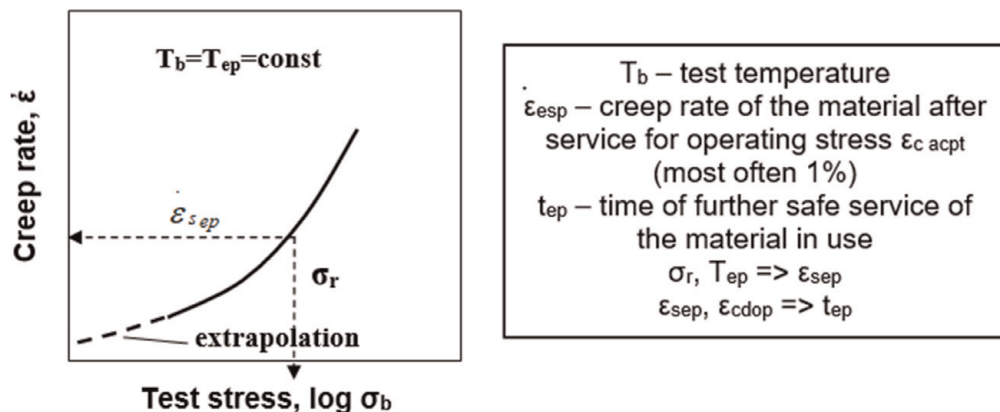
Figure 2.
Relationship between creep rate $\dot{\varepsilon}_s$ in steady state of the material after service under creep conditions and test stress for determination of the time of further safe service t_{ep}.
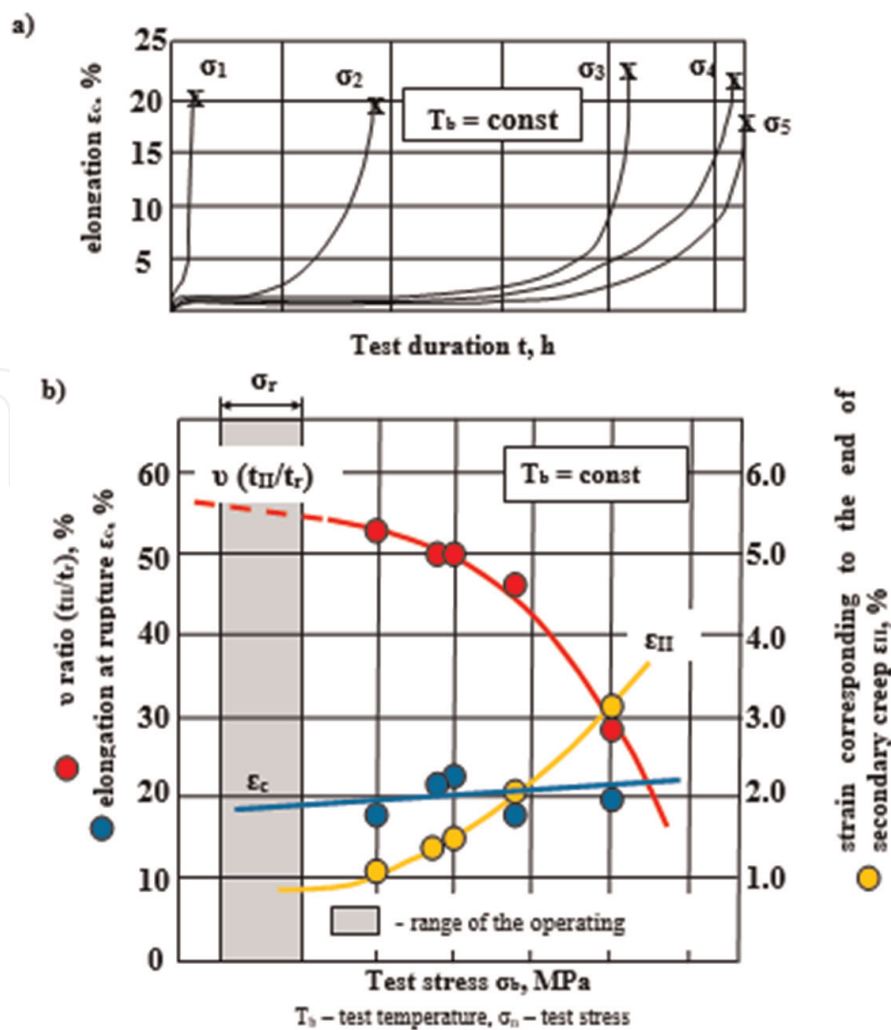
Figure 3.
The results of creep rupture tests with recording of elongation. (a) Creep curves at constant temperature
T_b = const. *(b) Strain corresponding to the end of secondary creep, elongation at rupture, and v coefficient*
depending on test stress.

2.2 Short-term creep tests

The disadvantage of the method for determination of residual life using long-term creep tests is the time of waiting for test results, which takes at least 2–3 years. To reduce the duration of these tests and the assessment of residual life, the so-called short-term creep tests with a duration from a few dozen to max 3000–10,000 h are used in the engineering practice. This opens up the possibility for obtaining test results within a maximum of several months and providing good estimation of residual life.

The acceleration of the creep process and the reduction in the duration of tests is obtained in creep tests carried out under uniaxial tension on test specimens taken from the material of a power system component and:

- Under constant test stress equal to the operating stress and at different test temperature levels much higher than the operating temperature

- At constant test temperature equal to the operating temperature and under different test stress levels much higher than the operating stress

T_b, test temperature; T_r, operating temperature; σ_b, test stress; σ_r, operating stress; t_r, time to rupture; $R_{z\,av}$, average temporary creep strength (result of long-term creep tests); $t_{r(r)s}$, time to rupture for the operating parameters obtained by

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short-term creep tests as a result of extrapolation; $t_{r(r)}$, time to rupture for the operating parameters obtained by long-term creep tests of up to 100,000 h.

The manner of presenting results of short-term creep tests conducted under constant stress equal to the operating one ($\sigma b = \sigma r$ = const) for different levels of test temperature Tb and at a constant temperature equal to the operating one (Tb = tr = const) and under different levels of test stress σb as well as the reliability of their estimation is shown graphically in **Figures 4** and **5**.

Based on at least 40 years' experience of the Creep Test Laboratory of the Institute for Ferrous Metallurgy in comparing results of short-term creep tests and extrapolating them with results of long-term tests of even up to 100,000 h, they were found to be useful for and applicable to the estimation of life and residual life. The determination of residual life for the material after service does not require knowledge of its history and previous operating conditions, and the only requirement is to define the operating parameters of its further service (σ_{rp}, T_{rp}). Strong convergence of the results obtained in short- and long-term creep tests allows the method of short-term creep tests conducted under constant stress equal to the operating one to be used in practice. A disadvantage of this method is the restriction with regard to the applied test temperature levels arising from precipitation processes that occur in the material. The temperature levels must therefore be selected individually for each grade of material being tested.

Therefore, in the diagnostic practice, only short-term creep tests under constant stress and at different levels of temperature significantly higher than the operating one should be used to determine the residual life of the materials of components operating under creep conditions (pipelines, steam superheater coils). Such tests are recommended for use after exceeding the design service time, which is most often equal to 100,000 h. When the design time is exceeded by 50% (1.5 of t_o), these tests are obligatory.

The reliability of the obtained results of short-term creep tests depends on the requirements for compliance with constant level of preset test temperature T_b over the measurement length of the test specimen throughout the duration of the test. The determination of residual life with an error of no more than 20% in relation to the time determined based on long-term creep tests ensures that short-term creep tests are carried out at the test temperature T_b (much higher than the operating
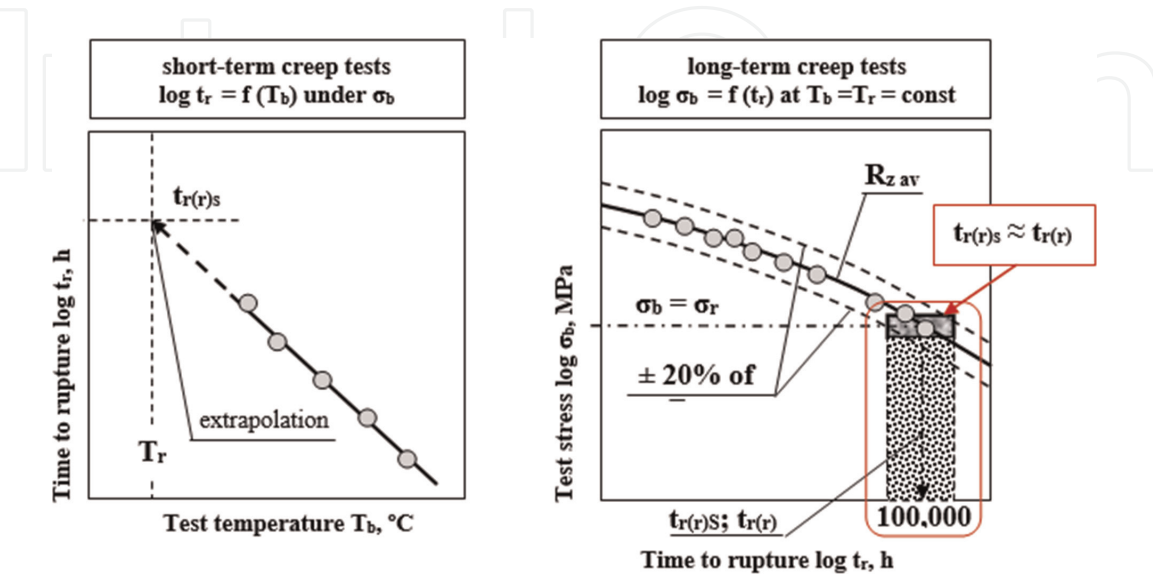
Figure 4.
Reliability of the estimation of time to rupture t_r for the operating parameters based on the results of short-term creep tests under constant test stress equal to the operating one $\sigma_b = \sigma_r$ = const and at different test temperatures T_b higher than the operating one.
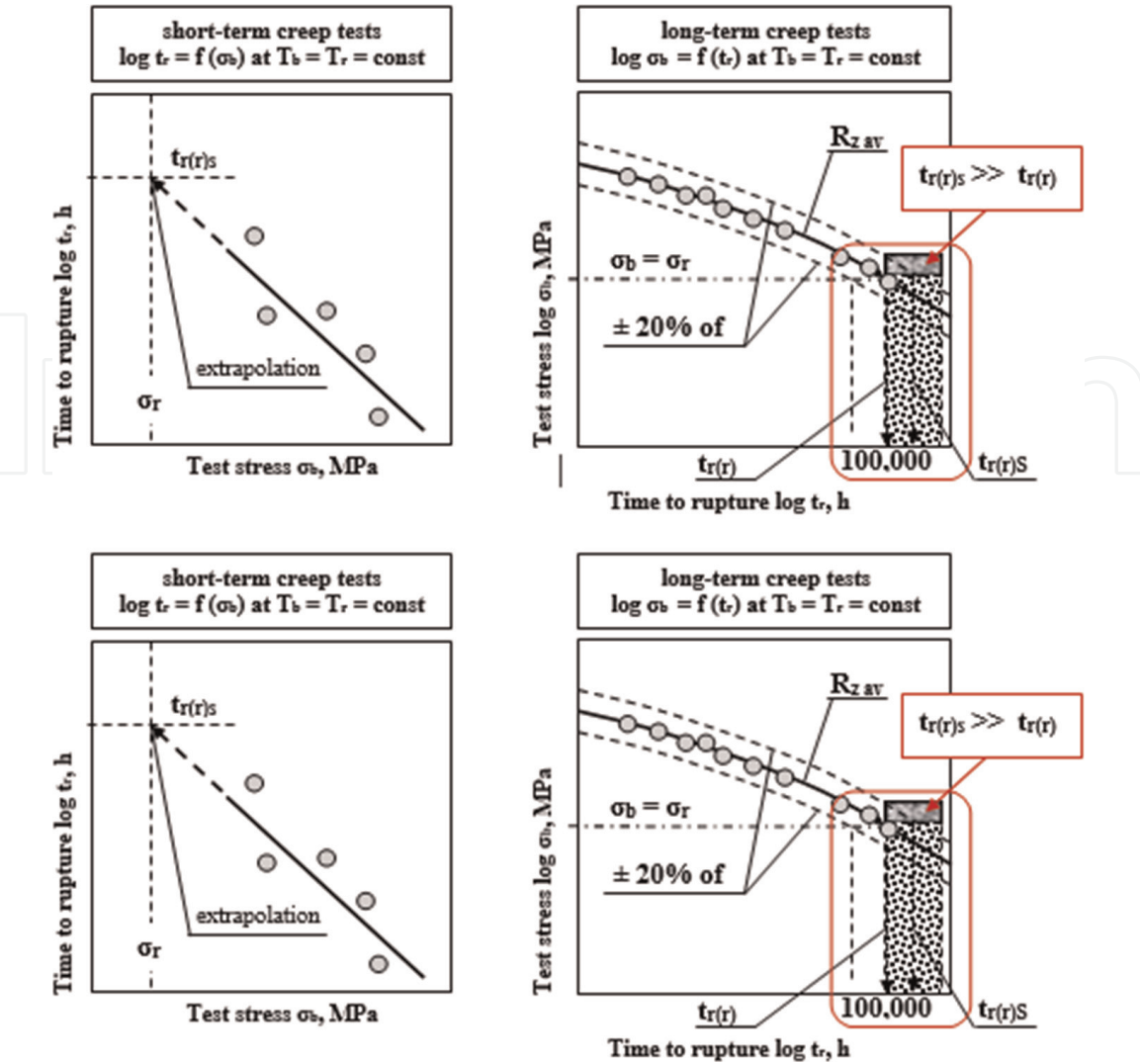
Figure 5.
The reliability of the estimation of time to rupture tr for the operating parameters based on the results of short-term creep tests at a constant temperature equal to the operating one Tb = Tr = const and under different levels of stress σb higher than the operating one. T_b, test temperature; T_r, operating temperature; $σ_b$, test stress; $σ_r$, operating stress; t_r, time to rupture; $R_{z\ av}$, average temporary creep strength (result of long-term creep tests); $t_{z(r)s}$, time to rupture for the operating parameters obtained in short-term creep tests as a result of extrapolation; $t_{r(r)}$, time to rupture for the operating parameters obtained in long-term creep tests of up to 100,000 h.

one) with an accuracy equal to or higher than ±0.5°C over the measurement length of the test specimen, regardless of what the test temperature level is.
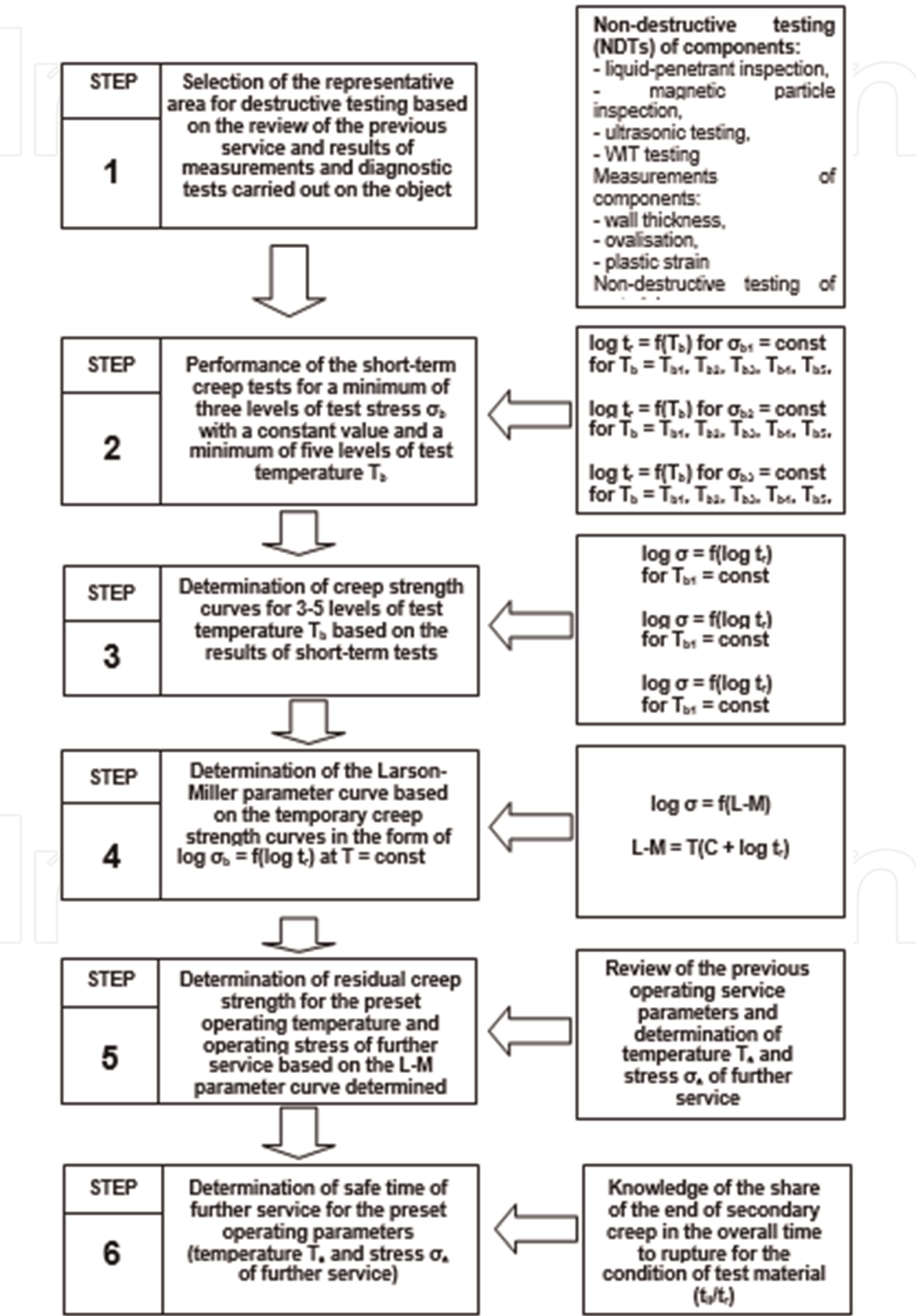
3. Method for determination of the time of safe service for material after long-term service under creep conditions beyond the design service time

The main step in the proposed method for determination of the time of further safe service is to determine the residual life. Its determination is based on creep test results. These tests have been so far the only known method for determination of service life for actual operating parameters of the materials in use. In creep tests, the decisive factor for their duration is the time to rupture. It cannot be reduced in the development of material characteristics. However, such a possibility exists for the assessment of specific material both in the as-received condition and after service. Nevertheless, the research methods used for this purpose have to be verified with results of long-term creep tests [16].

The proposed procedure for determination of residual life and disposable residual life, which is the time of safe service beyond the design time, is presented as the algorithm presented in **Figure 6**. This algorithm consists of six consecutive steps.

The **first step** is to select the representative areas for destructive testing. At the designated area in the material of test specimen, the short-term creep tests should

Figure 6.
Procedure for determination of the time of further safe service beyond the design time according to creep strength characteristics based on short-term creep tests under constant stress level.

be carried out under constant stress on at least three different levels (**step 2**). Based on the relationships obtained from the results of short-term creep tests, the curves of temporary creep strength at a constant temperature are determined for a few temperature levels (**step 3**). These creep strength curves allow for determination of the parameter creep strength curve where the parameter is a function of temperature and time to rupture (**step 4**). The obtained parameter creep resistance curve allows the residual creep strength to be determined for the operating parameters (temperature and stress) of further service (**step 5**). When the residual creep strength for the parameters of further service is known, the disposable residual life can be determined. It is the safe time of further service for the adopted operating parameters (**step 6**). The proposed procedure consisting of consecutive steps is presented below on the example of the material after long-term service under creep conditions far beyond the design time.

3.1 Selection of the representative areas for destructive testing and of the test material (step 1)

The selection of the representative areas for destructive testing is made after review of the previous service, results of measurements and diagnostic tests carried out on the object, verification calculations and determination of the temperature, and strain and stress distributions by the finite element method for the most strenuous areas [17–19].

The test materials selected in this way, with provision of the appropriate access to components for cutting them out and the possibility for repair/replacement, were an elbow and a straight section of the main primary steam pipeline made of 13 HMF steel after approx. 200,000 h service.

3.2 Short-term creep tests (step 2)

The short-term creep tests were carried out for six levels of test temperature T_b = 600, 620, 640, 650, 660, and 680°C under the constant level of test stress σ_b with three different values of σ_b = 50, 80, and 100 MPa.

The obtained results of tests on the primary steam pipeline elbow made of 14MoV6–3 steel in the form of $\log t_r = f(T_b)$ under σ_b = const, where t_r is the time to rupture in creep test, for three levels of stress σ_{b1} = 50 MPa, σ_{b2} = 80 MPa, and σ_{b3} = 100 MPa are shown in **Figure 7**.

3.3 Temporary creep strength curves at a constant temperature (step 3)

The extrapolation of the obtained relationships of $\log t_r = f(t_b)$ under σ_b = const towards a lower temperature allowed for determination of residual life t_{re} for temperature equal to the extrapolation one.

The results of this extrapolation for one level of temperature T_b = const and three levels of stress σ_{b1} = 50, σ_{b2} = 80, and σ_{b3} = 100 MPa allowed the creep strength curves to be plotted in the form of $\log \sigma_b = f(\log t_{re})$ for T_{b1} = 530, T_{b2} = 540, T_{b3} = 560, and T_{b4} = 580°C, which is presented graphically in **Figure 8**.

3.4 Parameter residual creep strength curve (step 4)

Based on the constant-temperature residual creep strength curves in the form of $\log \sigma_b = f(\log t_{re})$, the residual creep strength t_{re} was determined, and on its basis, the Larson-Miller parameter curve was determined in the form of $\sigma_b = f(L\text{-}M)$. Where: L-M = T_b (C + $\log t_{re}$); T_b, test temperature; C, material constant, t_{re}, residual creep strength (**Figure 9**).
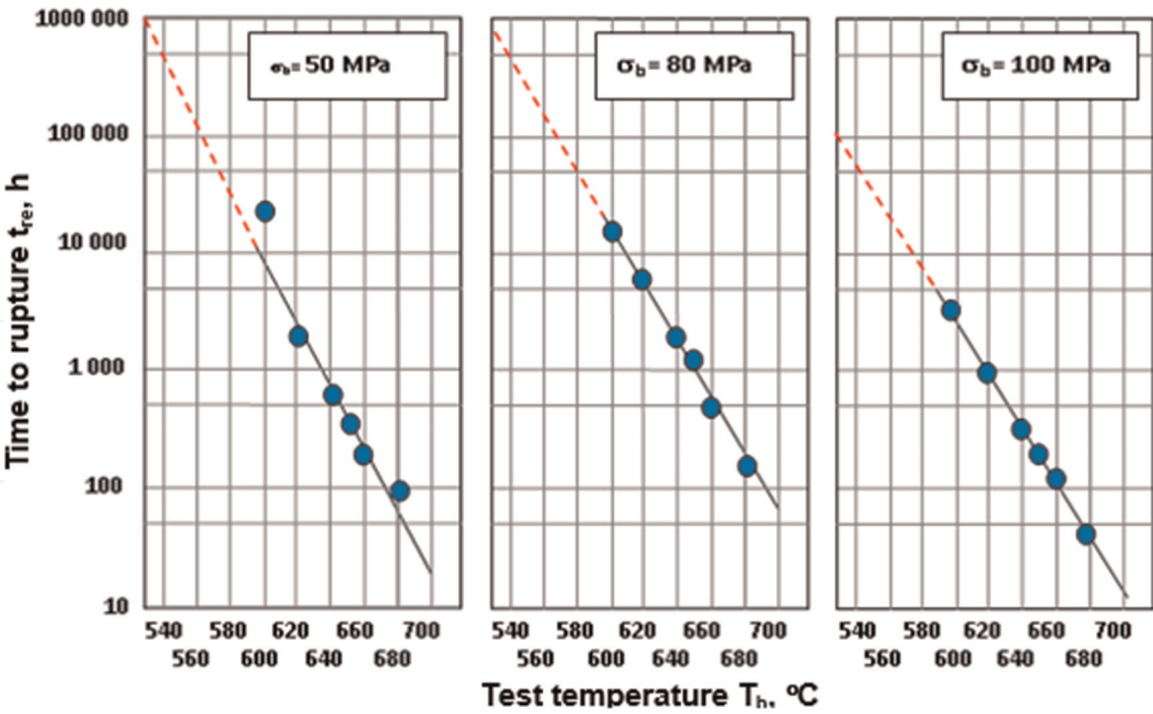
Figure 7.
The results of short-term creep tests on the material of primary steam pipeline elbow made of 13 HMF steel after approx. 200,000 h service under creep conditions in the form of log $t_{re} = f(T_b)$ under σ_b = const.
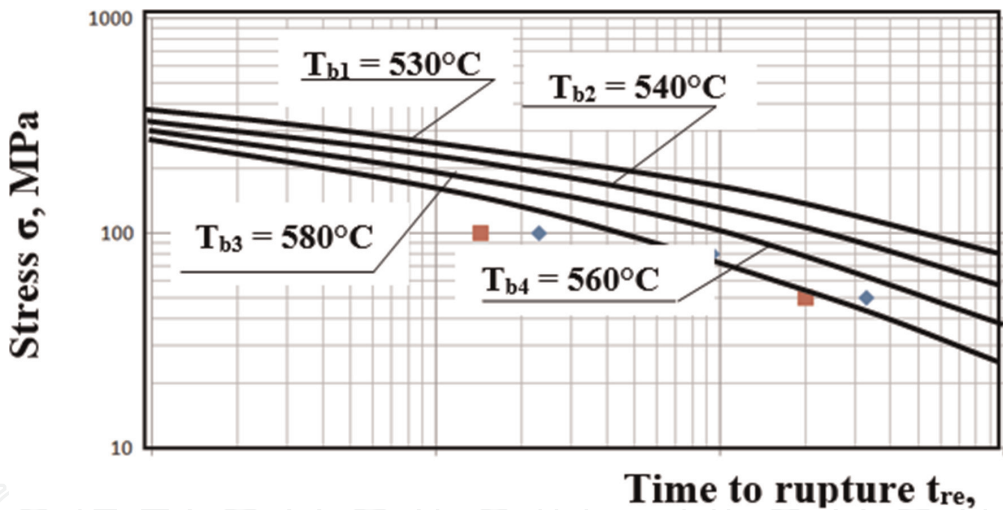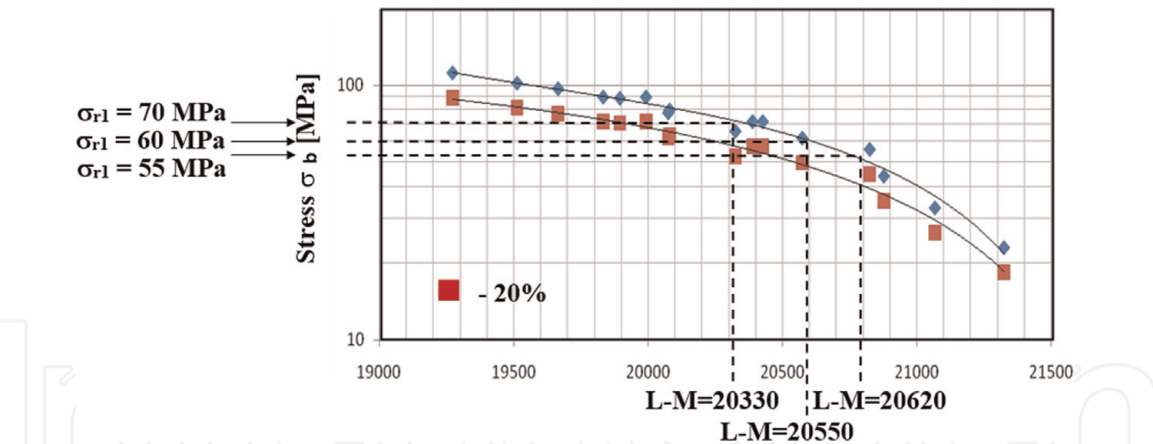

Figure 8.
Residual creep strength curves R_{Ze} determined based on the results obtained from extrapolation of creep tests carried out on test pipeline elbow material made of 13 HMF steel after 200,000 h service under creep conditions.

3.5 Safe time of service beyond the design time (step 5)

In contrast to the actual lifetime equal to the time to rupture of the material subject to creep, which is the residual life t_{re}, the disposable residual life t_{be} is of practical importance. The disposable life is the time until which a structural component can be safely operated under the assumed temperature and stress conditions.
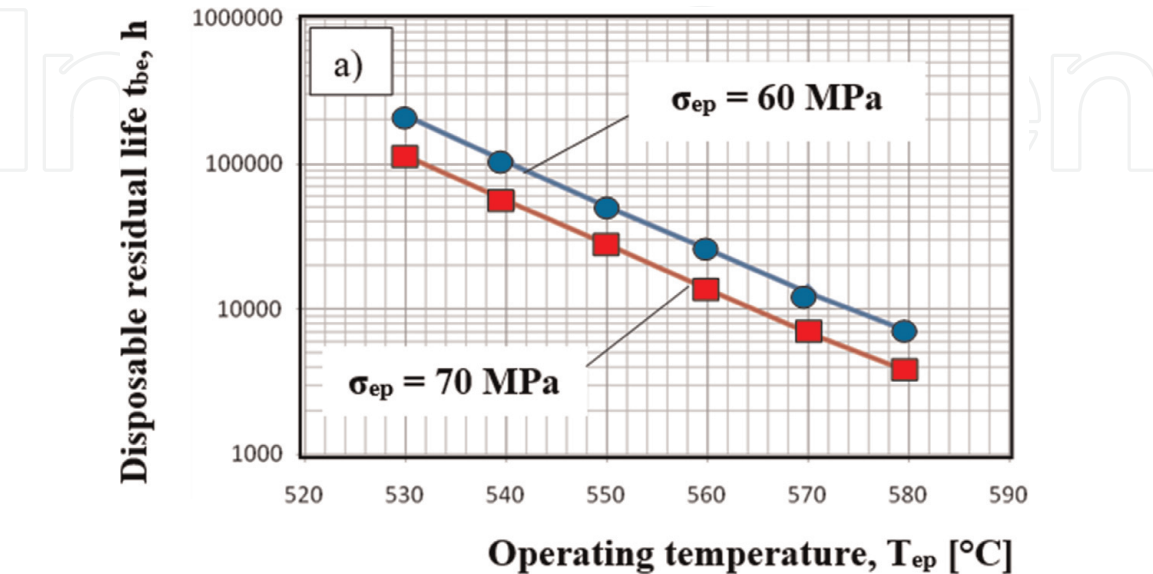
The disposable residual life is part of the residual life. To determine its share in the residual life, defined as the time to the end of the secondary creep t_{IIe} in relation to the time to rupture t_{re}, the rupture creep tests with measurement of elongation during test at a constant temperature T_b = 500°C similar to the operating one were carried out.

Figure 9.
Residual life t_{re} of the material of the test primary steam pipeline elbow made of 13 HMF steel after approx. 200,000 h service under creep conditions in the form of Larson-Miller parameter curve.

The results of the creep tests shown as creep curves $\varepsilon = f(t)$ at T_b = const and the ratio of the disposable residual life t_{be} to the residual life t_{re} depending on the test stress σ_b allowed to determine the t_{be}/t_{re} ratio for the stress level equal to the operating stress $\sigma_b = \sigma_{ep}$ = 50–60 MPa, which is written as t_{be} = 0.55t_{re} (**Figure 3**).

By knowing the residual life, the disposable residual life can be determined as the time of safe service for the adopted operating parameters. For the material of elbow, the relationships between the disposable residual life t_{be} and the operating temperature of further service T_{ep} for the adopted constant level of operating stress σ_{ep} at the selected levels of operating temperature T_{ep} = 540 and 550°C and under stress $\sigma_b = \sigma_{ep}$ = 60 and 70 MPa are shown in **Figure 10a** and for the circumferential welded joint at T_{ep} = 530 and 540°C and operating stress σ_{ep} = 50 MPa in **Figure 6**, whereas the safe service time of the material of test primary steam pipeline elbow and circumferential welded joint made of 13 HMF steel after approx. 200,000 h service under creep conditions for the operating parameters of further service, which was determined based on the above-mentioned relationships, is summarised in **Table 1**.

Figure 10.
Disposable residual life t_{be} of the material of primary steam pipeline elbow made of 13 HMF steel after 200,000 h service under creep conditions and stress σ_{ep} = 60 and 70 MPa equal to the operating one depending on operating temperature T_{ep}.

Component	Operating temperature T_{ep}, °C	Operating stress σ_{ep}, MPa		
		55	60	70
		Safe time of further service t_{be}, h		
Elbow	540	127,000	104,000	56,000
	550	62,000	51,000	28,000
Circumferential welded joint	Operating temperature T_{ep}, °C	Operating stress σ_{ep}, MPa		
		50		80
		Safe time of further service t_{be}, h		
	530	143,000		48,400
	540	77,000		26,000

Table 1.
Safe service time of the material of the test primary steam pipeline elbow and circumferential welded joint made of 13 HMF steel after approx. 200,000 h service under creep conditions for the operating parameters of further service.

3.6 Estimation of exhaustion degree caused by creep (step 6)

The exhaustion degree for materials working under creep conditions was defined in Chapter 3 of the study as the time of service until the time to rupture of this material under the temperature and stress operating conditions (t_e/t_r).

For the reviewed case, the residual life t_{re} (**Table 2**, column 9) was determined based on the developed relationship of $\log \sigma = f(t_{re})$ for the operating temperature of service T_e. It was determined for the level of operating stress σ_e of the test components as shown in **Figure 11**.

To determine the operating stress level using the formula

$$\sigma_e = \frac{p_e \cdot \left[D_z - g_{rz\min} \cdot (2 - z) \right]}{2 g_{rz\min} \cdot z}$$

where σ_e is the operating stress, $g_{act\ min}$ is the actual minimum wall thickness of component, p_e is the operating pressure of component, D_{Out} is the nominal outside diameter, and z is the weakening coefficient, it is necessary to know the specific quantities in the formula.

Component	Operating parameters			Geometrical dimensions of component		Weakening coefficient z	Determined operating stress σ_r, MPa	Residual life t_{re}, h for σ_r	Exhaustion degree t_e/t_r
	Operating pressure p_e, MPa	Operating temperature T_e,	Service time t_e, $h \times 10^{-3}$	Outer diameter of component D_{out}, mm	Wall thickness nominal g_n actual $g_{act\ min}$				
1	2	3	4	5	6	7	8	9	10
elbow	13.8	540	200	324	$\frac{40}{36.8}$	1	51.5	175,000	0.53
Circumferential welded joint	13.8	540	200	324	$\frac{40}{40}$	1	46.9	165,000	0.55

Table 2.
Exhaustion extent t_e/t_r of the material of test primary steam pipeline components made of 13 HMF steel after 200,000 h service under creep conditions for the operating parameters of service.
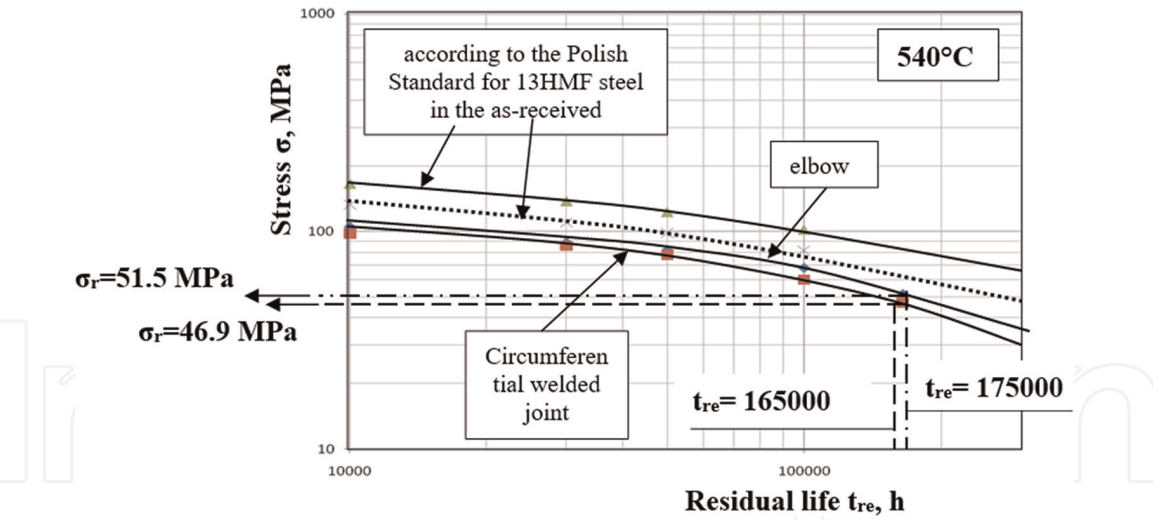
Figure 11.
Residual life t_{re} of the test primary steam pipeline components made of 13 HMF steel after 200,000 h service under creep conditions for the operating stress σ_e and operating temperature T_e.

Their designation and values for the test material of elbow and circumferential welded joint are summarised in **Table 2**, columns 2–7. The table also presents the operating stress σ_r values calculated for the test materials after service (column 8).

The life t_r is defined as the total time of the previous service t_e and residual life t_{re} for the parameters of the previous service (σ_e, T_e), that is, $t_r = t_e + t_{re}$. Since the exhaustion degree based on the above-mentioned definition can be written as t_e/t_r and $t_r = t_e + t_{re}$, then, in practice, $t_e/t_r = t_e/(t_e + t_{re})$. Using this relationship, the exhaustion degree (**Table 2**, column 10) was determined based on the residual life t_{re} determined and knowledge of the previous time of service.

4. Method for determination of the minimum component wall thickness necessary to transfer the actual service loads of the material after long-term service under creep conditions with known creep strength characteristics

The most important element necessary to determine the minimum required component wall thickness g_{oe}, which will be able to transfer the required service load (σ_{ep}, T_{ep}), is to have the characteristics of residual creep strength for the material of test component after service in the form of $\log \sigma = f(t_{re})$ for the operating temperature T_{ep}. This is the first step in the adopted procedure. Step 2 is to determine the residual creep strength $R_{Ze/Tep/tep}$ for the adopted temperature of further service T_e and the assumed time of further service t_e based on $\log \sigma = f(t_{re})$ at T_{ep} = const. The value of $R_{Ze/Tep/tep}$ obtained from the characteristics makes it possible to determine the acceptable stress k for the parameters of further service adopted in this way, which is step 3. To calculate the required minimum wall thickness g_{oe} for the adopted parameters of further service, the nominal outside diameter D_{Out} of the component, the operating pressure p_{ep}, and the construction weakening coefficient z should be defined, which is step 4. Step 5 is the determination of the required minimum wall thickness g_{oe} of the component for the adopted parameters of further service.

And the last, sixth, step is to compare the obtained value of the calculated required minimum wall thickness g_{oe} to the measured minimum actual thickness $g_{act\ min}$. If for the adopted time of further safe service t_{ep}:

- $g_{oe} < g_{act\ min}$, the component can be allowed for further service.

- $g_{oe} \geq g_{act\ min}$, the component cannot be allowed to continue the operation at the required parameters of further service for the adopted time t_{ep}.

If $g_{oe} \geq g_{act\ min}$ and the component cannot be allowed for further service, a shorter time of service should be adopted and the proposed procedure repeated. It may turn out that with a shorter time of further service t_{ep}, for the adopted parameters of further service, the condition of $g_{oe} < g_{act\ min}$ will be met. This will allow the test component to be operated for such a shorter time t_{ep}.

The proposed procedure in the form of an algorithm consisting of consecutive steps is shown in **Figure 12**. Its application is presented on the example of the primary steam pipeline elbow and circumferential welded joint made of 13 HMF steel after 200,000 h service.
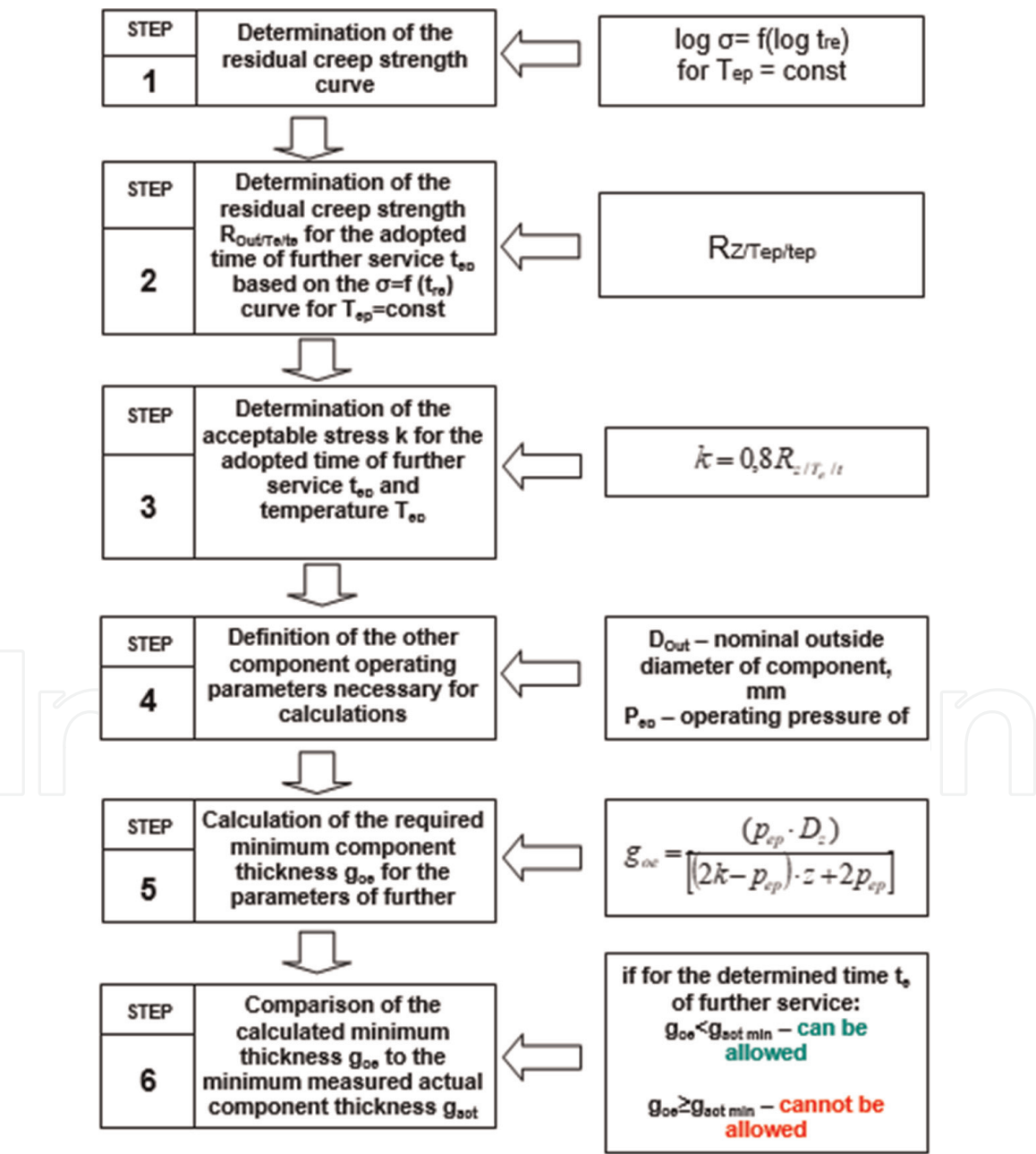
Figure 12.
Procedure for determination of the minimum wall thickness of a component after long-term service under creep conditions necessary to transfer the required service loads based on the residual life characteristics of the assessed material after service under creep conditions.

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4.1 Characteristics of residual creep strength

The temporary creep strength curve for the material of elbow after 200,000 h service under creep conditions plotted based on results of the tests discussed in Chapter 2 is shown in **Figure 13** in the form of lg σ = f(t_{re}) for the temperature of further service T_{ep} = 540°C.

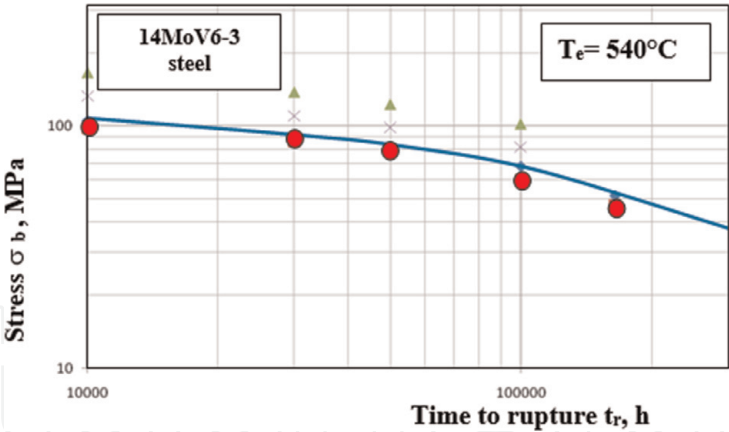### 4.2 Determination of residual creep strength for the adopted time of further service

Based on the characteristics in point 2, the residual creep strength at 530 and 540°C for 10,000, 30,000, 50,000, and 100,000 h was determined for the materials of test primary steam pipeline components after 200,000 h service. The obtained results are presented in **Table 3**.

4.3 Determination of the acceptable stress

The value of acceptable stress k is equal to the value of acceptable lower scatter band −20% from the obtained mean value of residual creep strength for the adopted time t_{ep} and temperature T_{ep}. It is calculated from the following formula:

$$k = 0.8R_{Ze/Te/te}.$$

The obtained values of acceptable stress k for the adopted levels of temperature T_{ep} = 530, 540°C, and times t_e = 10,000, 30,000, 50,000, and 100,000 h of further service are provided in **Table 4**.

Figure 13.
Temporary residual creep strength of the material of test elbow and circumferential welded joint made of 14MoV6–3 steel after 200,000 h service at 530°C under creep conditions.

Component	Designation of properties	Residual creep strength R_{ze}, MPa at the test temperature $T_e = 540°C$
Elbow	$R_{ze/10,000}$	105
	$R_{ze/30,000}$	89
	$R_{ze/50,000}$	82
	$R_{ze/100,000}$	68

Table 3.
Residual creep strength for the adopted levels of temperature T_{ep} = 530, 540°C, and times t_{ep} = 10,000, 30,000, 50,000, and 100,000 h of further service of the materials of test elbow made of 14MoV6–3 steel after 200,000 h service under creep conditions.

Component	Adopted time of further service t_{ep}, h	Acceptable stress k, MPa for temperature of further service $T_{ep} = 540°C$
Elbow	10,000	84
	30,000	71.2
	50,000	65.6
	100,000	54.4

Table 4.
Determined values of acceptable stress k for the adopted levels of temperature T_{ep} and times t_e of further service for the material of test primary steam pipeline component made of 14MoV6–3 steel after 200,000 h service under creep conditions

4.4 Definition of parameters of further service

The parameters of further service are defined to be the same as the previous ones. To calculate the required minimum wall thickness, in addition to pressure p_{ep} and temperature T_{ep} of the component, it is also necessary to define its nominal outside diameter D_{Out}, nominal wall thickness g_n, design pressure p_o, operating pressure of further service p_e, and construction weakening coefficient z. The required values are summarised in **Table 5**.

4.5 Calculation of the required minimum component wall thickness for the parameters of further service

The calculation of the minimum component wall thickness for the parameters of further service g_{oe} was made based on the following formula:

$$g_{oe} = \frac{\left(p_{ep} \cdot D_z\right)}{\left[\left(2k - p_{ep}\right) \cdot z + 2p_{ep}\right]}$$

where g_{oe} is the minimum component wall thickness for the parameters of further service, p_{ep} is the operating pressure of further service, D_{Out} is the nominal outside diameter, k is the acceptable stress, and z is the weakening coefficient.

No.	Parameter	Unit	Value
1	Nominal outside diameter D_{Out}	mm	324
2	Nominal wall thickness g_n	mm	40
3	Minimum actual wall thickness $g_{act\ min}$	mm	36.8
4	Time of further service t_{ep}	h	30,000
			50,000
			100,000
5	Temperature of further service T_{ep}	°C	540
6	Design pressure p_o	MPa	14.2
7	Operating pressure of further service p_{ep}	MPa	13.8
8	Weakening coefficient z	—	1

Table 5.
Parameters of further service and geometrical dimensions of test pipeline elbow made of 14MoV6 steel after 200,000 h service.

Temperature of further service T_{ep} = 540°C			
Time of further service t_{ep}, h	**30,000**	**50,000**	**100,000**
Operating pressure of further service p_{ep}, MPa	**Required minimum wall thickness g_{oe}, mm**		
14.2	29.38	31.64	37.40
13.8	28.62	30.84	36.47

Table 6.
Required minimum wall thickness of primary steam pipeline elbow made of 14MoV6–3 steel for the adopted parameters of further service.
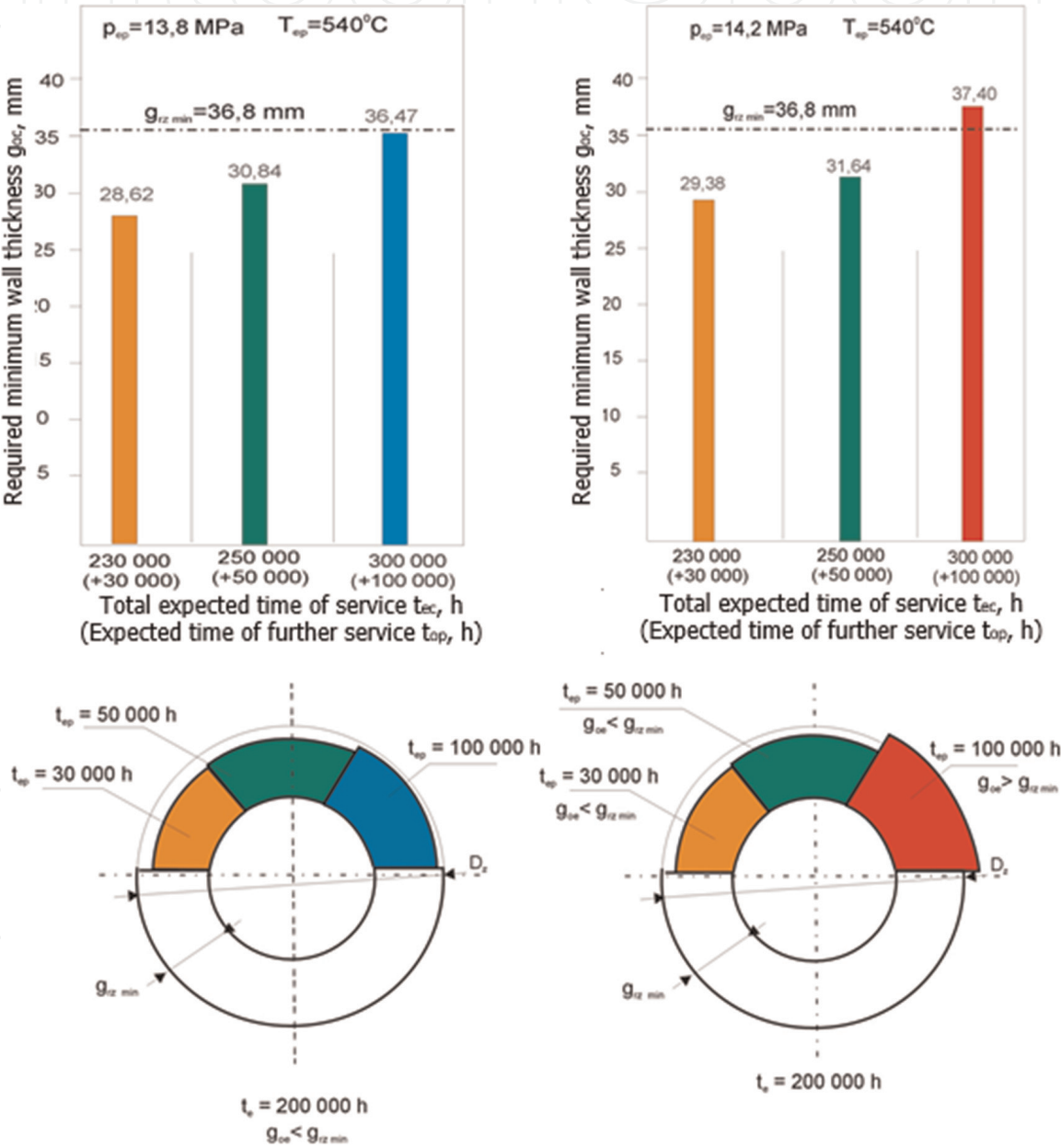
Figure 14.
Comparison of the required minimum pipeline elbow wall thickness g_{oe} for the adopted parameters of further service (p_{ep}, T_{ep}) to the minimum actual wall thickness $g_{act\ min}$ measured on the component for the adopted temperature of further service T_{ep} = 540°C.

The values obtained for pressure p_o and p_{ep} and for the adopted different times t_{ep} and temperature levels of further service T_{ep} for the material of test primary steam pipeline elbow made of 13HMF steel are summarised in **Table 6**.

4.6 Comparison of the calculated required minimum wall thickness to the actual minimum thickness based on measurements taken on the component

The obtained results of calculations of the required minimum wall thickness for the parameters of further service (**Table 6**) were compared to the actual minimum thickness based on measurements taken on the component (**Table 5**, item 3) as shown graphically in **Figure 14**.

These results meet the condition of $g_{oe} < g_{act\ min}$ except for the adopted temperature of further service $T_{ep} = 540°C$ and the time of further service $t_{ep} = 100,000$ h for which this condition is not met and the component could not be allowed for further service of 100,000 h at 540°C for the other adopted operating parameters.

Author details

Janusz Dobrzański
Institute for Ferrous Metallurgy, Gliwice, Poland

*Address all correspondence to: jdobrzanski@imz.pl

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