THE MERITS OF ISOSTRESS CREEP TESTS AND QUANTITATIVE CREEP DAMAGE IN RESIDUAL LIFE ASSESSMENTS

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The merits of the isostress creep test method have been investigated with the aid of a five-year programme during which tubes were exposed to internal pressure at higher temperatures (till leakage). Periodically material has been removed from these tubes and tested in accordance with the (uniaxial) isostress test method. The test results are compared with the actual life of the tubes. Probabilistic aspects of the extrapolation of test results are being dealt with. Also hardnesses of the tubes during exposure are studied. The creep cavity evolution is being studied quantitatively with the aid of automated procedures. Positive results are useful for residual life assessments because creep damage can be determined by surface replica extraction without destroying the component.

INTRODUCTION

The electricity supply companies in The Netherlands need to assess the remanent life of components which have operated at high temperatures for extensive periods (to approximately 150,000 hours) and of components approaching their design time base (usually 100,000 hours). These requirements arise from three main considerations:

- safety aspects can be involved.
- high temperature failures and unscheduled outages must be prevented.
- component replacement must be predicted and extension of life, even far beyond the original design life, might be necessary.

The last consideration is a result of the change in policy in The Netherlands to switch from oil and gas to coal firing. When reconstructing units to make coal firing possible large capital outlays have to be made

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and a new design life has to be defined for the components not being replaced, resulting in a total unit life of 200,000 hours or more. The reconstruction of units concerns in total 1,650 MW.
The circumstance that for several units the operation has been changed recently from base load operation to cyclic operation, might reduce the life expectation significantly.
KEMA is involved in remanent life investigations, failure analyses, regulating work and research projects. Emphasis is put here on ferritic boiler tubing, headers and steam piping, which are operating in the creep regime (>400°C).

ISOSTRESS CREEP TESTING

The technique. At KEMA experimental residual life assessments are performed using the isostress testing technique (1,2) with samples Ø 3 mm since about 15 years.
Acceleration is obtained by testing at enhanced temperatures, applying the representative service stress.
The decision to choose for increased temperature testing instead of increased stress, is based on the fact that creep is a thermally activated process. For ferritic materials however, the maximum test temperature is limited to about 720°C (depending on the material), with regard to the risk of phase transformations at temperatures in excess of 720°C (by approaching the A_{C1} temperature). Test specimens are loaded under tension to a stress equal to the (main or reference) service stress (often the hoop stress) of the component under investigation. Usually five to six specimens are exposed to mutually different temperatures, chosen such that creep rupture times are invoked in the range of 100 to 1,000 hours.
Finally, the test results are extrapolated linearly to the service temperature in the co-ordinate system $\ln(t_f)$ vs $1/T(K)$, with t_f = time to failure (h).
The above is illustrated in Figure 1. Also indicated are the 95% confidence limits in the extrapolation.

The representativity. When removing samples of a component in general the component is destroyed and has to be replaced. For boiler tubing this is no problem and one isostress creep test seriesis regarded representative and slightly conservative for a tubing assembly provided the specimens were removed from the hottest location (which is known in most cases).

However, in assemblies like a steam piping system containing components with different stress patterns (e.g. elbows, T-branches) it is not enough to confine oneself to one isostress test serie with five to six specimens.
In such a case an elbow can be removed with specimen sampling be performed as well on the outer side as on the inner side of the elbow, followed by two isostress creep test series, resulting in two residual life estimations at two different stresses. By interpolation or extrapolation of the residual life estrimations at two different stresses, life estimations of other components in the steam piping system (fabricated from the same heat as the elbow but operating under different stress levels) can be made.

<u>The verification</u>. KEMA initiated in 1980 an originally five year verification programme to validate the isostress creep test method for residual life predictions.
Six tubes fabricated from 1Cr½Mo and 2¼Cr1Mo were pressurized internally with argon and heated in furnaces at 550 to 585°C, till failure (leakage) of the tubes occurred. Periodically tube sections have been removed from the tubes, out of which specimens for isostress creep testing were machined.
The results of the verification programme (2) show that isostress creep testing up to approximately 1,000 hours is capable in predicting the residual life of components. The predictions yield in general conservative results, i.e. the predicted life is shorter than the actual life. The conservatism decreases with an increasing degree of creep damage, as shown in Figures 2 and 3 for 2¼Cr1Mo and 1Cr½Mo tubes. The 95% confidence limits in the life predictions are also indicated. For example, the (bad) second isostress creep test seriesfrom Figure 3, taken from the tube at a life fraction of 0.2275, yields remanent lives from 4,346 to 171,880 hours with 95% confidence. For comparision: the time or actual remanent life is 32,000 hours. The main reason for the bad remanent life prediction is the low correlation coefficient of the linear best-fit curve through the single test results, in this case 0.9403. For comparison: the third test serie from Figure 3 yields a correlation coefficient of 0.9968.
However, from the probabilistic point of view, the outcome of the second creep test serie is such that there is a 60% failure chance before 32,000 hours are reached, see Figure 4. The outcome of the third test series is such that there is a 1% failure chance before

16,000 hours (the true remaininglife) are reached, see Figure 5, thus much better than the second test serie. The main conclusion from the verification programme is that the isostress creep test method is capable in predicting remanent lives reliably or conservatively, provided the correlation coefficient of the linear curve through the single test results is better than 0.995.

CREEP SOFTENING AND CAVITY EVOLUTION

The isostress creep test method involves component removal and replacement in most cases, which in general is considered as a disadvantage of the technique.
To get round this disadvantage, remanent life potentials should be determined with the aid of non-destructive testing techniques.
Amongst others, hardness measurements and quantitative creep cavity evolutions seem to be very promising.

Creep softening.Hardness measurements have been performed on the base materials from the tubes used in the forementioned verification programme, the results are shown in Figure 6. Due to the softening of the materials exposed to higher temperatures a decrease in Vickers-hardness-10 kg (HV_{10}) occurs, as expected.
The decrease is approximately 15 points HV_{10} per 0.5 life fraction, as determined under laboratory conditions.
However, one should keep in mind that creep damage primarily developes in the heat-affected-zones of weldments.
Although softening also occurs in weldments, the basic variation of hardness in weldments with their heat-affected-zones, is such (typically 265 $\pm$ 45 points) that a sensitivity of 15 points per 0.5 life fraction is regarded insufficient to determine the remanent life potential of these weldments, specially when hardness measurements are (necessarily) performed under field conditions.

Creep cavity evolution. Besides that softening occurs during creep, creep cavities are formed on grain boundaries, finally leading to intergranular creep cracking. Figure 7 shows the widely used cavity or void classification. The cavity classification, and the general metallurgical condition, is determined by microscopic investigations of replica extractions of the metal surface.

However, it is not clear to what remanent life potential a certain cavity class leads. It is believed that this potential is not equal for different materials under different leading (temperature/pressure) conditions.
The most promising parameter to evaluate creep -void-damage seems to be the "A"-parameter as advocated by (former) CEGB (3). The "A"paramter being the fraction of cavitated grain boundaries.
Round Robin tests in which KEMA also participated (3,4) showed the existence of a relation between the "A"-parameter and the spent life fraction although a dependence of the procedure used could be established. The results of these tests are mainly limited to the specific microstructural condition of course grained weld heat-affected material. This because the "A"-parameter is based on a model of constrained cavity growth. It is still uncertain whether the "A"-parameter is also applicable to base material, the fine grained zone or even weld metal.
The main disadvantage of the "A"-parameter is that the determination is manual and thus very time consuming. With this a dependence of the observer's experience and skill is introduced. Another feature is that the "A"-parameter values are influenced by the direction of the line-scan in relation to the principal stress in the component. It is likely that lower "A"-parameter values emerge when the principle stress direction is not taken into account as shown in Figure 8. But it is likely that area-based "A"-parameter values are more reproducible.

The "A"-parameter becomes less sensitive at higher levels of damage because the number of voids on a boundary is not taken into account.
In order to investigate the behaviour of "A"-parameter values in different material conditions and at different levels of damage and to facilitate the determination an automated procedure has been developed. The procedure uses a light-optical microscope and a digital image processing system. The image of the microstructure is digitized followed by reconstruction of the original grainboundary network. By superimposing the image of the voids and the reconstructed boundary network the fraction of damaged boundaries is determined. All grainboundaries which are intersected by the image frame are left out. This procedure deviates from the original line scan and lower values are expected. This is not considered a problem since the correlation with the spent life fraction should not be affected seriously.

Preliminary measurements using the automated procedure show a fairly accurate reconstruction of the grainboundary network in case of 1Cr½Mo and ½Cr½Mo¼V steels, specially in service-exposed condition.
The microstructure of 2¼Cr1Mo contains many bainite lath packet and subgrain boundaries which aggravate the reconstruction of the true grainboundary network.
Further validation of the procedure is going on and measurements are in progress.

CONCLUSIONS

The isostress creep test method is capable in predicting the remanent lives of ferritic components reliably or conservatively, provided the correlation coefficient of the linear curve through the single test results is better than 0.995.
Hardness measurements cannot be used in weld remanent life assessments.

The most promising structural parameter to evaluate remaining lives of ferritic components non-destructively seems to be the "A"-parameter as determined from surface replica extraction, provided the determination of this parameter is being automated.

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CEGB TPRD L/3199/R87, Nov. 1987

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ERA project 2023. Interlaboratory Metallographic Examination.
KEMA report WSK/60055-1, 1986.

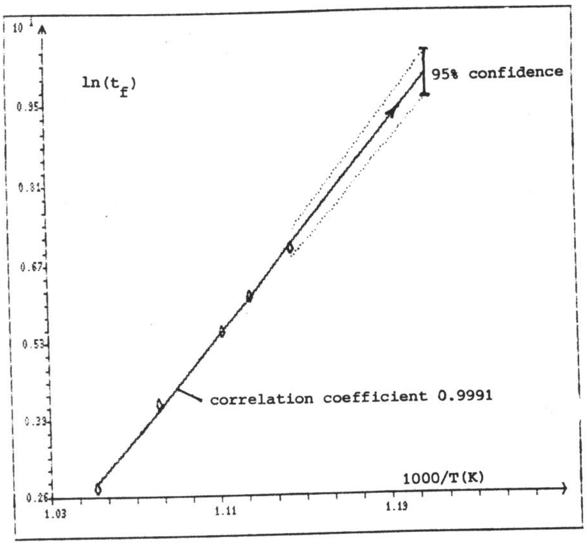


Figure 1. Example of an isostress creep test serie.

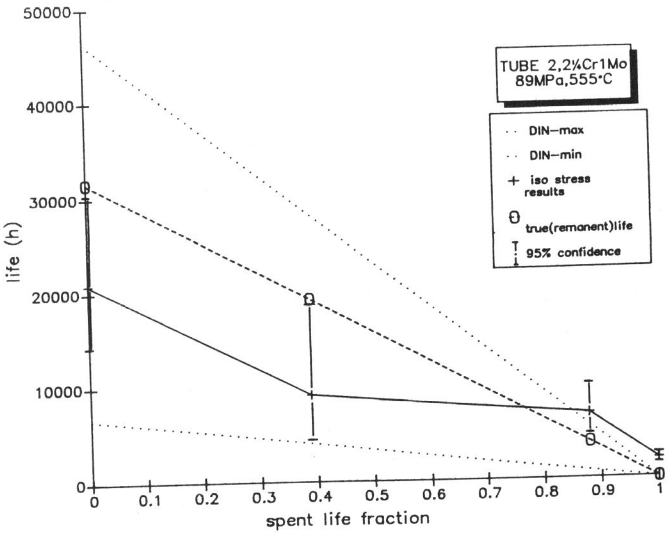


Figure 2. Verification example isostress creep test method for 2¼Cr1Mo.

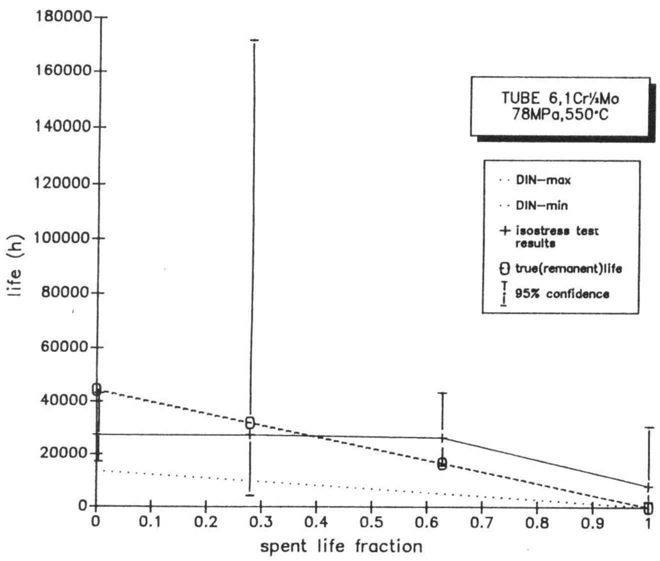


Figure 3. Example verification isostress creep test method for 1Cr½Mo.

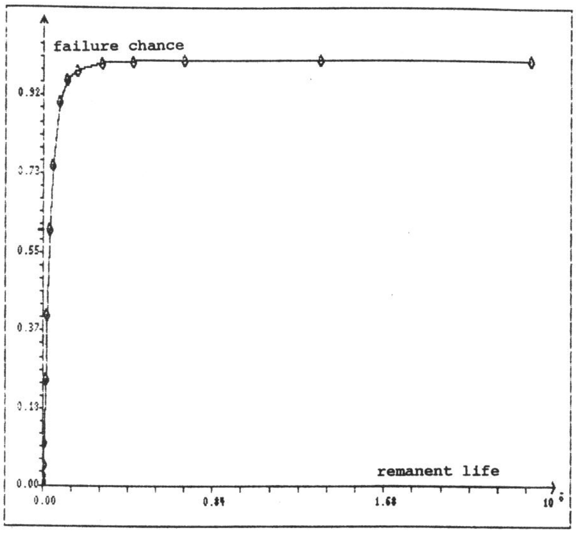


Figure 4. Failure chance during remanent life, as determined by the second isostress creep test serie from Figure 3.

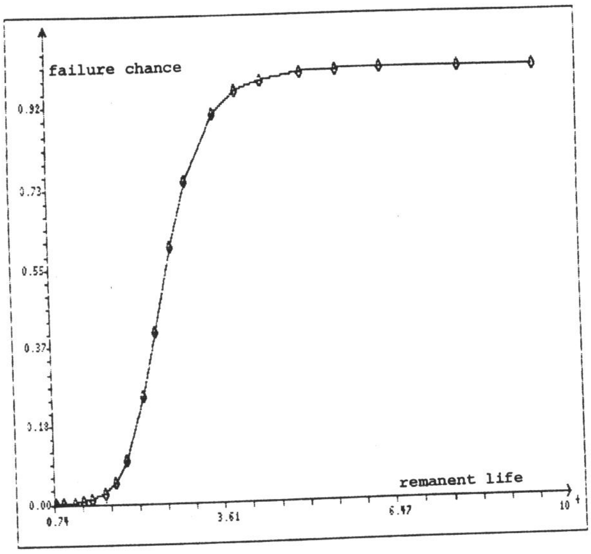


Figure 5. Failure chance during remanent life, as determined by the third isostress creep test serie from Figure 3.

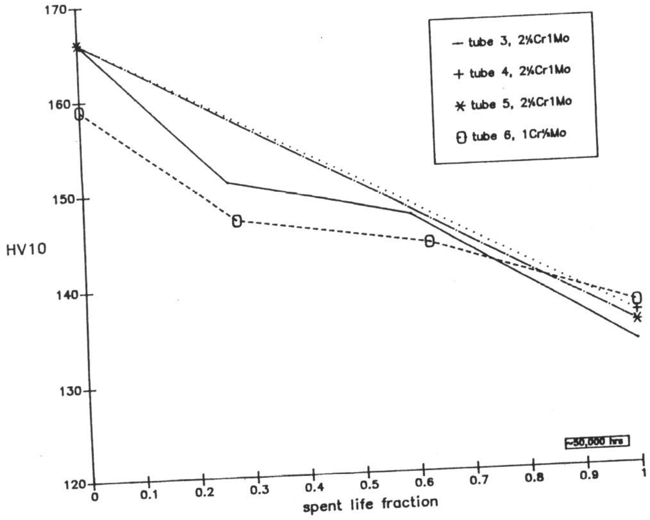
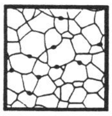
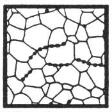
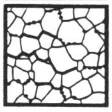
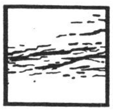


Figure 6. Hardness, as determined during exposure of the tubes in the isostress creep test method verification programme.

Gefügeklasse		kennzeichnende Merkmale
0		ohne thermisch bedingte Gefügeänderungen
1		Gefüge zeitbeanspruchter Bauteile ohne Mikroporen
2		Gefüge nach fortgeschrittener Zeitstandbeanspruchung mit vereinzelten Mikroporen[1]
3		Gefüge mit Anzeichen beginnender Zeitstandschädigung in Form von Mikroporenketten
4		Gefüge mit fortgeschrittener Zeitstandschädigung in Form von Mikrorissen
5		Gefügeschädigungen in Form von Makrorissen

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[1] Kriechhohlräume auf Korngrenzen

Figure 7. Void classification in accordance with VdTüV Merkblatt Dampfkessel 451-83/6 8.83.

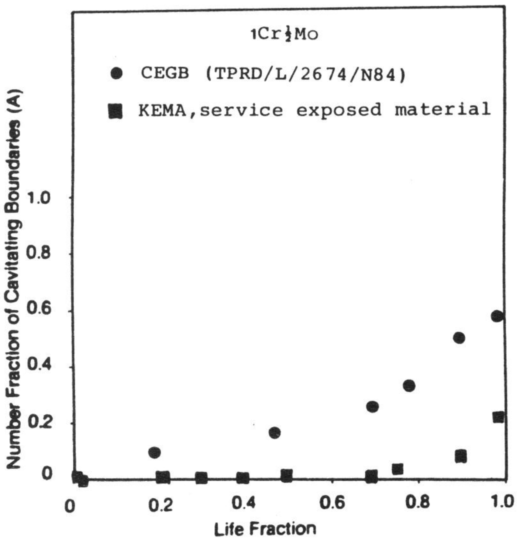

Figure 8. Influence of the "A"-parameter measuring method for 1Cr½Mo(4).