ONGOING PRACTICAL ACTIVITIES WITH REGARD TO CREEP

L.B. Dufour*

This paper describes activities with regard to creep and remanent life expectancies of components operating at high temperatures.
Research and regulating work are discussed based on failure analyses and operational practice.

1 INTRODUCTION

In the Netherlands components employed under creep conditions are subject to design criteria which define an allowable stress for a specified design temperature. This stress is obtained from standard creep rupture data (DIN, ISO) by applying a safety factor to the mean stress of 1.5 (or a safety factor to the minimum stress of 1.2) to cause rupture after a specified time, normally of the order 100,000 h. The safety factor is incorporated to accomodate material property variability and operational fluctuations. Uncertainties often exist in these areas and consequently doubt exists regarding the true life expectancy of components.

The electricity supply companies need to assess the remaining life of components which have operated for extensive periods at high temperatures and of components approaching their design lives. These requirements arise from three main considerations:

- to prevent high temperature failures and thus to avoid costly unscheduled outages.
- to predict when component replacement is necessary and thus allow extension of life.

*L.B. Dufour,
N.V. KEMA, Joint Laboratories and Consulting Services of the Dutch Electricity Supply Companies,
Arnhem, Netherlands

- to meet safety reflections as formulated by the Dutch Government Authority "Dienst voor het Stoomwezen".

2 COMPONENTS AND MATERIALS

In developing a methodology for remanent creep life determination, in first instance consideration should be given to the types of components and materials most likely to require such determination. Several criteria can be used to determine application areas which could most benefit from developing accurate life prediction capability. In general these are:
plant design, operational practice, failure statistics, difficulties and uncertainties of repair, cost of associated outages and identification of failure cause.
An electricity supply plant availability study performed in 1981 by the Working Group Remanent Life of the Dutch Welding Institute "Nederlands Instituut voor Lastechniek" indicate, for example, for the period 1967 through 1981 a high frequency of failure in boiler tubes, see figure 1. From the 139 failures investigated, approximately 75 % referred to boiler tubing.
Running through the failure analysis reports a classification of failure causes was made into errors introduced during design, material manufacture (e.g. wrong heat treatment), erection (e.g. wrong welding procedure) and operation .

An accurate means of life assessment seems a priori unlikely in view of the wide variation in operating conditions, and thus in life controlling mechanisms, for tubing in different locations within the boiler. Therefore, it is often preferred to treat this problem for an individual boiler by means of an analysis of the tube failures themselves. Besides, boiler tubing can be replaced relatively easily and the outage time for an individual failure is low, with correspondingly modest costs.
In contrast, assessing the life expectancy of large components such as steam headers and steam pipes is extremely worthwhile. They are very expensive and difficult to replace, requiring extensive outage times. Replacements must be ordered timely before the eventual failure event.

Traditionally, the materials used in older fossile fired plants up to temperatures of approx. 570°C have been the low-alloy ferritic steels 1Cr½Mo (13CrMo4.4), 2¼Cr1Mo (10CrMo9.10) and ½CrMoV (14MoV6.3).
An accurate means of life assessment is therefore urgently needed for these materials, more urgently than for austenitic steels and higher alloyed ferritics (12Cr, X20CrMoV12.1) which have been increasingly applied in recent years.

3 SOME FAILURE EXAMPLES

A short description of some failure examples from Dutch power plants may illustrate difficulties and uncertainties encountered during remanent life investigations.

The first example refers to a 2¼Cr1Mo steam header with crack-like indications detected by magnetic particle testing in the welds between the outlet nozzles and the header, on the outside of the header. The component had been approximately 85,000 h in service at a temperature of 530°C. Although calculations showed that the header did not yet suffer from significant creep damage, the header was replaced and afterwards investigated in the KEMA metallurgical laboratory.
It became clear that the cracks, several mm deep, were oriented in longitudinal direction of the header on each side of the nozzles and were located in the weld material itself and to a much lesser extent in the coarsely grained heat-affected zone, not in the finely grained heat-affected zones from the base materials. This fact and the observation that internal oxidation near the cracks had taken place, led to the conclusion that the cracks had been formed by solidification cracking during welding and possibly some minor cracks by reheat cracking during stress relief heat treatment.
In other words, the cracks were present the first day of operation and grinding out these cracks after 85,000 h of operation would have saved the header.

Normally, creep damage near welds is located between the finely grained heat-affected zone and the unaffected base material, see figure 2. This is demonstrated by a single crack detected in a ½CrMoV steam pipe system after 98,000 h of operation at a temperature of approximately 540°C*).
The crack was located on the outside of a pipe adjacent to a weld to one leg of a forged Y-piece. A sample of material was removed and studied in the laboratory. The crack was several mm deep and oriented in the region between the finely grained heat affected zone and the unaffected base material as shown on figure 3, and is regarded as typical of a macro creep crack: partially distributed single creep voids (less clear due to etching of the metallurgical structure) and micro cracking formed by coalescence of voids step by step.
The fact that the crack was located only in one pipe leg and only covered a small percentage of the circumference of the pipe, did presume that external bending loads contributed to the developing of the creep crack. Additional stresses could have been caused by the fact that the crack was located in a wall thickness transition region from pipe to (thicker) Y-piece leg. Finally, the creep strength from the heat-affected zone might have been lower than from the original unaffected base material.
The expansion behaviour of the pipe system was verified, corrected and the pit caused by the sample removal was (temperarily?) repaired by welding.

*) Remanent life calculations based on internal pressure and creep rupture data from ½CrMoV base material demonstrated no significant creep damage had occurred.

A third and last example refers to creep cams welded on a straight 12Cr steam pipe during manufacture of the pipe system. These cams were intended as helps for measuring periodically a possible increase in the creep strain during operation of the pipe. No increase in strain was observed after 60,000 h of operation at a temperature of approximately 540°C.
Inspection by magnetic particle testing, however, revealed indications on the pipe directly adjacent to the welds. A metallurgical analysis of a removed sample showed that the indications were caused by a preferential corrosive attack, approximately 0.2 mm deep, of the ferritic pipe material, also found in tubular dissimilar austenitic/ ferritic welded joints. And indeed, the weld was found to have an austenitic metallurgical structure.
The cams and the austenitic material were removed and the corrosive attack was grinded out smoothly.

4 REGULATIONS

Together with Dutch suppliers and users of high-temperature equipment, KEMA and the "Dienst voor het Stoomwezen" are preparing rules regarding the life expectancy of components. These rules are, to some extent, based on the German "Technische Regel für Dampfkessel 508".
The philosophy is that when, at a certain calculated stress due to internal pressure in the component, operation will be continued beyond a minimum life fraction of 0.6, additional inspections are required, see figure 4. In the first instance, conservative input data, like design temperature, pressure and minimum creep rupture data, are used. A minimum of three additional inspections is required when operation is continued beyond a life fraction of 0.6 to a minimum life fraction of 1.0.
In consultation with the Authorities further operation is possible even beyond a minimum life fraction of 1.0. The inspection frequency, however, will be enhanced considerably.
The choice of inspection locations is, on the other hand, governed by inspection experiences and failure analyses, from which several examples were described in the previous chapter.
The inspection techniques which can be used are:

- magnetic particle and dye-penetrant testing.
- microscopic metallurgical testing directly on the component surface.
- ultrasonic testing of the interior of welds.
- removal of a micro sample material for optical investigation in the metallurgical laboratory, even for Scanning Electron Microscope (SEM) studies.
- removal of material to perform short duration creep rupture tests at elevated temperatures.
- acetate replicas on the component surface, which can be viewed by SEM or optically in the laboratory.

The integrity of weldments is an important consideration in life assessment methodology as failure analyses do suggest. In addition, damage accumulation at welds can give an indication of the life usage of base material regions remote from the welds, even if creep damage in the base material may not be directly detectable. In other words, initial signs of distress in components and systems are often associated with weld deterioration.
Fatigue is considered as having no influence on life usage as long as the number of start-ups of the installation remain less than 1,000.

5 PRACTICAL RESEARCH

The practical research activities are based on experience with failure analyses and on general problems encountered during remanent life determinations.
The work is partly performed in own house and partly contracted out to the Electrical Research Association Technology Ltd. (ERA, Leatherhead, UK) and the Dutch Welding Institute.

5.1 KEMA PROGRAMME

The KEMA programme consists of work on:

- verification of the merits of uniaxial short-duration creep rupture tests at elevated temperatures.
- the effect of test-piece oxidation during uniaxial creep rupture testing at elevated temperatures.
- creep rupture behaviour of welded ½CrMoV (Ø 72x6 mm) pipe under internal pressure and external bending load and uniaxial creep rupture testing of test-pieces simulating the various heat-affected zones in welded ½CrMoV.
- creep rupture testing of welded Esshete 1250/310 (Ø 33x9 mm) pipe under internal pressure and external bending load, and uniaxial creep rupture testing of the coextruded material.
- quantitative assessment of structural metallurgical parameters for predicting the remanent life.

Uniaxial short-duration creep rupture tests refer to tests at elevated temperatures under constant load conditions, initially at the nominal service or hoop stress (isostress tests).
At least five elevated temperature rupture data are used, for a fast test result in the range of 100 to 1,000 h. Then linear extrapolation in the coordinate system log t_R over $1/T$ or log t_R over T gives the time-to-rupture t_R (remanent life) at the service temperature T_S. The

method has been proposed as a preferred route to stress extrapolation by many workers*).

The programme for experimental verification of this method is shown schematically on figure 6. The main programme part B consists of loading 1Cr½Mo and 2¼Cr1Mo (Ø 60x5 mm) tubes under internal pressure and higher temperatures. Periodically material will be removed from the tubes and tested uniaxially at elevated temperatures to determine the remanent life RLD. At the end, the final rupture event of the last remaining tube section should have been predicted by the uniaxial elevated temperature test method.
Because the design of high-temperature equipment is still based on the use of uniaxial creep data, programme B is repeated to a large extent on uniaxially loaded strips. The outcome of this programme A can be of use for quality assurance work during erection of a plant.
Programme C consists of the same materials as used in the other programmes, however in unstressed conditions. This probably makes it possible to discriminate between temperature- and stress- induced changes in the metallurgical structure. Finally, to study the merits of the short-duration elevated temperature test method in combination with the life-fraction-rule

$$\frac{t_1}{t_{R1}} + \frac{t_2}{t_{R2}} + \frac{t_3}{t_{R3}} + \ldots\ldots\ldots = 1$$ for rupture, two tubes

2¼Cr1Mo are loaded in programme D under constant internal pressure and under varying temperature conditions, such as during actual operation does occur. The tubes are exposed for a certain time t_1 to a certain temperature giving a time-to-rupture t_{R1}, etc.
By the time this paper was written, the first material test-pieces in programmes A through D were removed after 12,500 h of accumulated service.

Oxidation during creep and rupture testing of low-alloy steels in air can significantly reduce the time-to-rupture. The effect is demonstrated in figure 7, which shows a comparison between isostress tests in air and nitrogen with 5 % of hydrogen on Ø 3 mm test-pieces removed from the steam header described in chapter 3. By testing in air, the life expectancy of the header is reduced by a factor of 2. Of course, this is of great importance since design and remanent life appreciation are based on tests in air. Any unnecessary (over)conservatism should be avoided.

In trying to simulate failures in welded ½CrMoV, as shown on figure 3, welded tubes Ø 72x6 mm are loaded in a set-up under an internal pressure of 70 bar at temperatures 550, 570 and 590°C and with an external dead weight

*) Figure 5 shows an example which refers to 30 tests on material removed from a 1Cr½Mo steam pipe after 115,000 h of operation at a temperature of approximately 535°C and a hoop stress of 42 MPa. In addition, an excellent reproducibility of the test method is demonstrated.

causing an axial bending stress of 109 MPa, see figure 8. Then the intention is to repair the tubes by removing cracks that have formed, followed by welding and re-testing in the set-up.

There are reasons to believe that the various heat-affected zones in welded ½CrMoV do have creep properties inferior to those of the unaffected base material. This is why test-pieces will be loaded uniaxially under constant load at elevated temperatures after the heat-affected zones have been simulated in the test-pieces in a weld simulator. The plan is under consideration to test also the various heat affected zones from a weld which has been in operation for 80,000 h.

Since 1969 coextruded Esshete 1250/310, developed by T.I. Chesterfield, has been used and studied in coal-fired units in the UK. The material consists of 3.5 mm austenitic AISI 310 on the outside for protection against corrosive attack, the inside is made from an austenitic 15Cr, 10Ni, 6Mn material with additions of Mo, Nb and V. The coextruded material should be able to withstand temperatures up to and even beyond 700°C.
For possible use in Dutch boilers isostress tests at elevated temperatures are performed and the welded material will be tested in the set-up from figure 8. General corrosive attack on the AISI 310, together with AISI 347 and 12Cr steels, is studied in the KEMA test boiler unit.

Structural degradation (e.g. precipitate coarsening, dislocation mesh growth) and creep cavitation or void formation, associated with grain boundaries, are the two distinct creep damage processes. In base materials remote from welds structural degradation might be the predominant mode of damage accumulation, in heat-affected zones from welds creep cavitation leading to cracking is the predominant mode of damage accumulation.
The main objective of the investigation at the KEMA metallurgical laboratory will be to quantify cavitation phenomena by several parameters (e.g. amount of voids, voids volume, voids orientation) in relation to the degree of creep damage and the remanent life expectancy.
Figure 9 shows an example of typically oriented voids and carbides on grain boundaries.
Figure 10 shows an amount of voids presented as function of the angle between the longest void axis and the direction of the principal stress.
For quantitative assessments in early stages of creep cavitation a SEM image is necessary. For further quantitative analysis the SEM recently has been interfaced with a computerized image analysing system. With this equipment it is possible to study and quantify structural metallurgical parameters in several stages of creep damage.
The quantitative analysis will be related to and compared with remanent life expectations determined by short and longer duration creep rupture tests at elevated temperatures, stress analyses and component rupture tests (e.g. tubes or pipes under internal pressure at high temperatures).

5.2 ERA PROGRAMME

KEMA, together with other companies from the UK, Denmark, Canada, Japan, the USA, Italy and India, sponsors a project mainly aimed at the verification of the isostress test method. This project consists of three parts.
The first part is similar to part B of the KEMA programme. The same tube material (2¼Cr1Mo) is tested, however under different temperature and internal pressure conditions.
The second part is comparable with part A (loading of strips) of the KEMA programme. Instead of 1Cr½Mo and 2¼Cr1Mo, however, a ½CrMoV steam pipe material and a CrMoV (GS-17MoV5.3) turbine house casting are tested.
The third programme consists of loading Ø 38.1x6.4 mm 2¼Cr1Mo tubes with internal pressure (hoop stress 116 MPa) at 525°C. The failure moment of the tubes is already known under these conditions. After a life fraction of 0.8 the tubes will be rupture tested under the same internal pressure but at elevated temperatures. By extrapolating the test results to 525°C a remanent life fraction of 0.2 should be predicted.
This ERA programme started in 1979 and will probably continue till 1988.

KEMA also sponsors an ERA project which deals with the effect of oxidation on creep rupture strength. Test-pieces*) up to thicknesses of 50 mm are tested in air and argon.
This ERA programme started in 1983 and will continue to 1993.

5.3 NETHERLANDS WELDING INSTITUTE PROGRAMME

The programme of the Netherlands Welding Institute with regard to remanent life mainly consists in loading six new 1Cr½Mo components with outside diameters of 270 mm with and without stress concentrations (e.g. nozzles and wall thickness transitions) under internal pressure at 525°C. They have been designed to give 1 % strain and rupture after 40,000 h. The intention is to load the components for 25,000 h.
Two 1Cr½Mo pipe sections from steam pipe systems of an electricity supply plant and a chemical plant, with 85,000 and 4,380 service hours respectively, are also loaded under internal pressure at 525°C.
Finite element calculations are being performed for predicting the strain behaviour of some components. Destructive and non-destructive metallurgical examinations are periodically carried out for (quantitative) remanent life determinations. The whole programme is accompanied by literature studies.

*) of 1Cr½Mo and 2¼Cr1Mo

KEMA, together with other companies, sponsors and participates in this Welding Institute programme. The interest of KEMA goes particularly to the quantitative metallurgical examinations, including the merits of isostress tests.
The programme will probably be terminated in 1985.

6 FINAL REMARKS

KEMA is in a fortunate position to base research activities directly on operational practice in power plants, as demonstrated in this paper.
Not yet mentioned is the use of fracture mechanics techniques for predicting the remanent life of components containing defects or cracks. This use can be of interest when a quick start-up of the plant is required once cracks have been detected during inspection. Besides, a weld repair introduces additional uncertainties.
A case is known in which linear elastic fracture mechanics (in accordance with Appendix A of the ASME-Code, Section XI) was used to determine possible crack extension of solidification cracking in a weld from a ½CrMoV steam pipe system, which had been in service for approximately 100,000 h. The system went into operation again without removal of the cracks.

7 ACKNOWLEDGEMENTS

The author wishes to thank especially all his co-workers at the KEMA metallurgical laboratory for their dedication in performing and managing the work described in this paper.

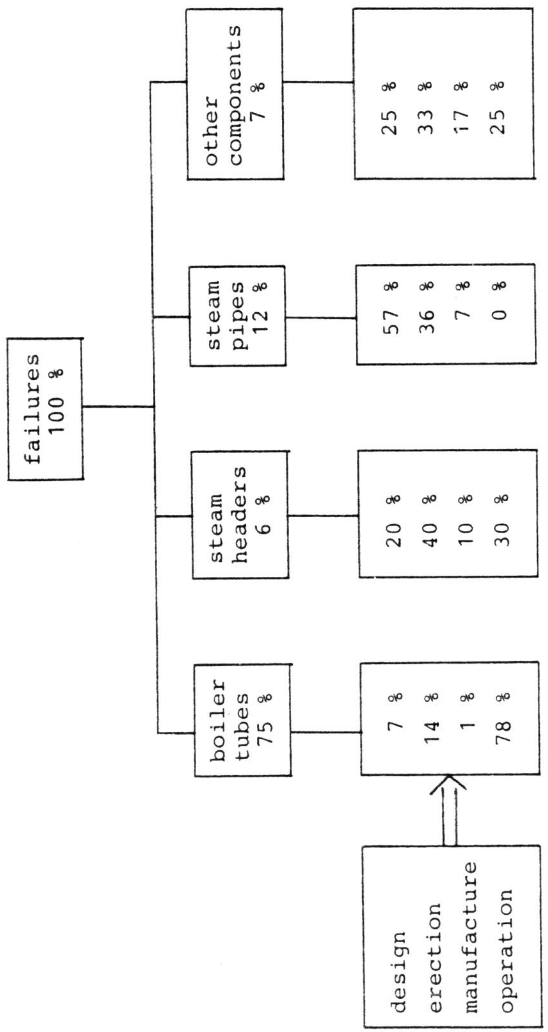

Figure 1

Failure statistic of Dutch power plants from 1967 through 1981 (from: Working Group report 81-33).

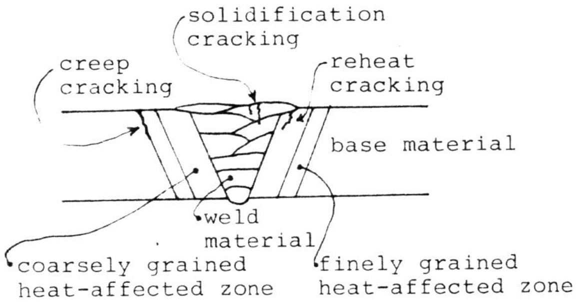

Figure 2

Crack types in low-alloy ferritics used under creep conditions.

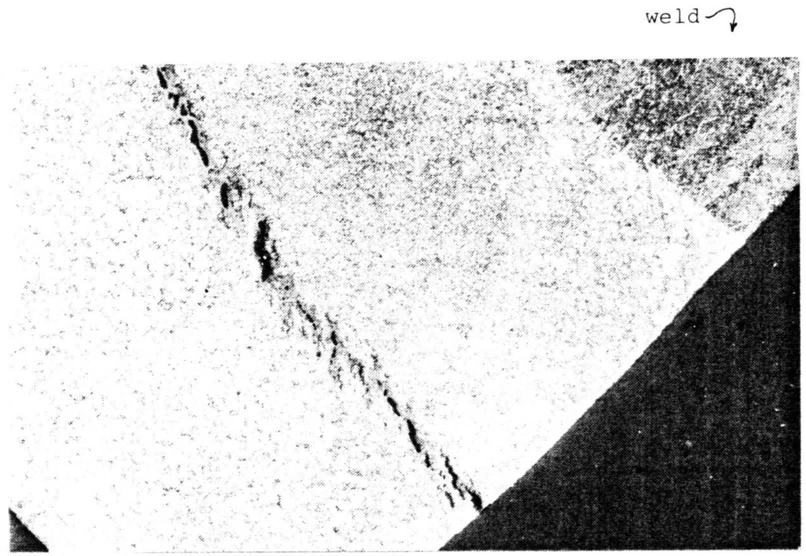

Figure 3

Creep crack in a ½CrMoV steam pipe system, magnification factor of 50.

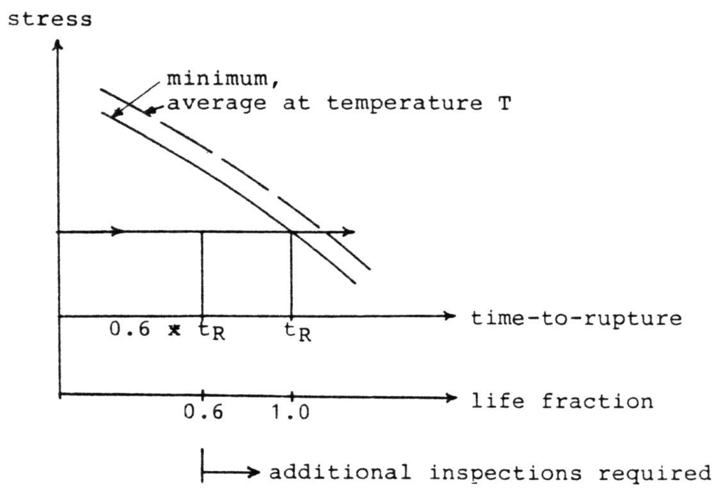

Figure 4

Philosophy of regulation.

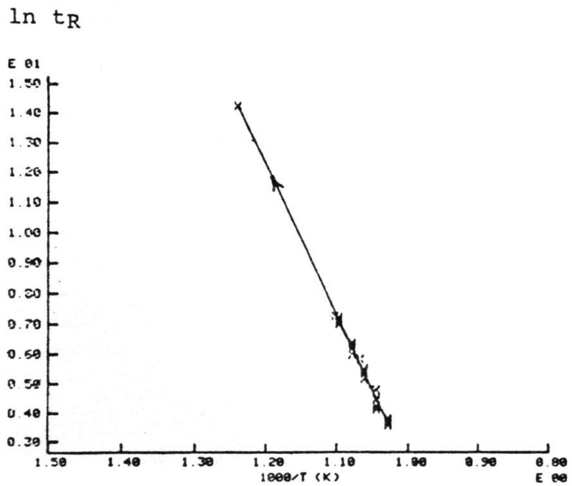

Figure 5

Linear extrapolation of 30 iso-stress tests.

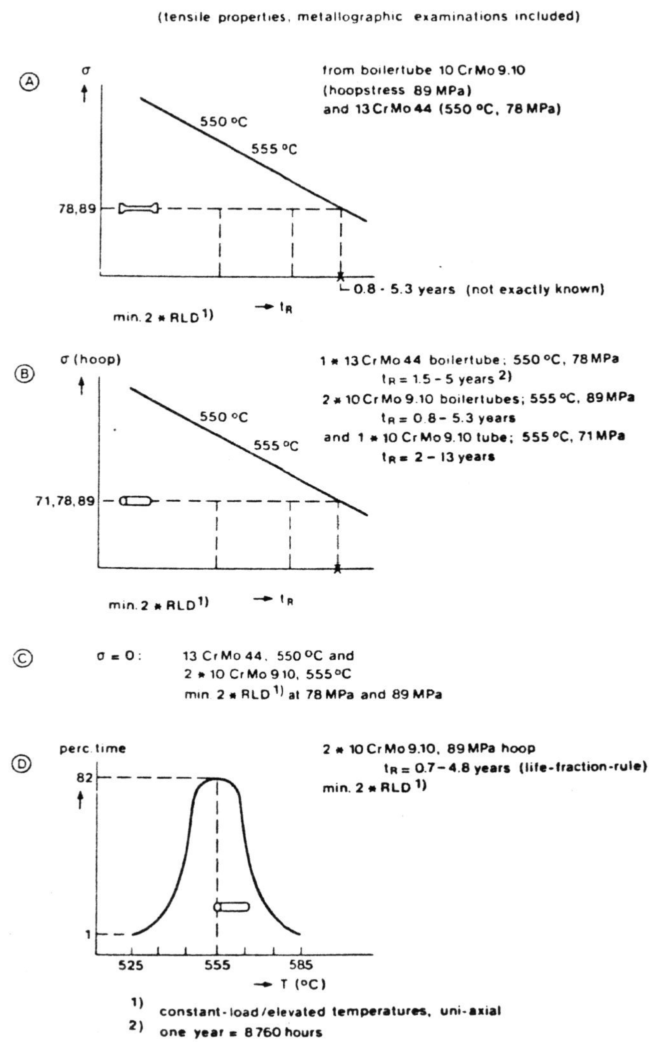

Figure 6

KEMA programme for verification of the isostress test method.

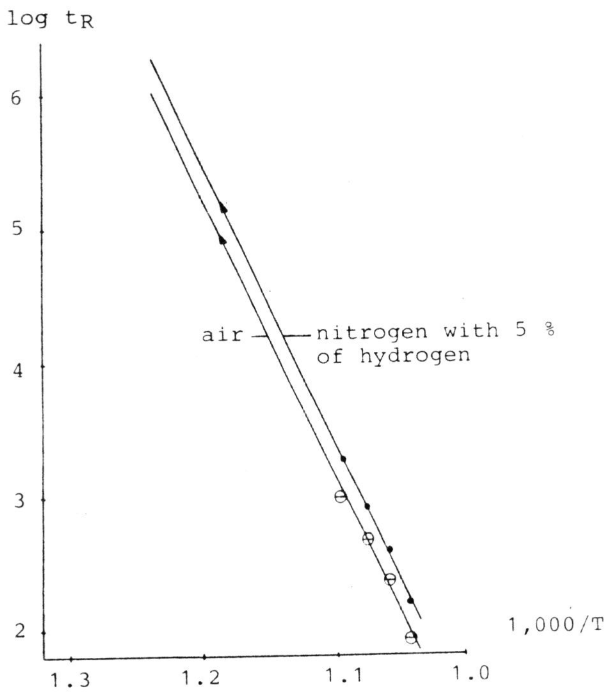

Figure 7

Comparison of isostress tests in air and nitrogen with 5 % of hydrogen.

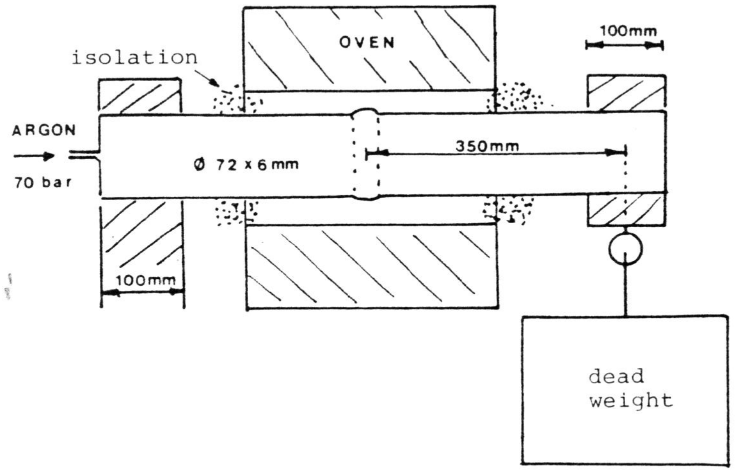

Figure 8

Set-up for tube testing with internal pressure and bending load at high temperatures.

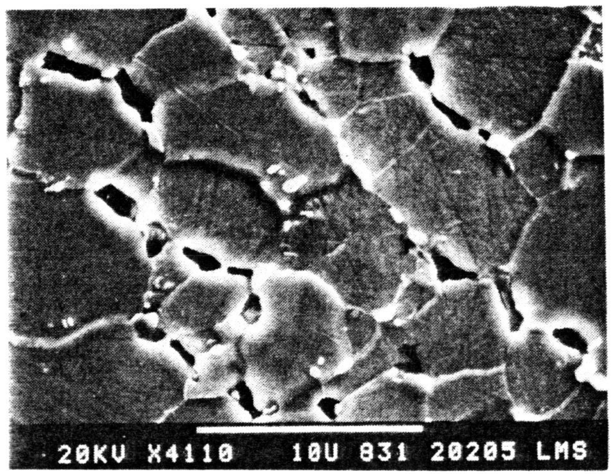

Figure 9

SEM image of creep damaged 1Cr½Mo with typically oriented voids on grain boundaries and carbides, magnification factor of 4,110.

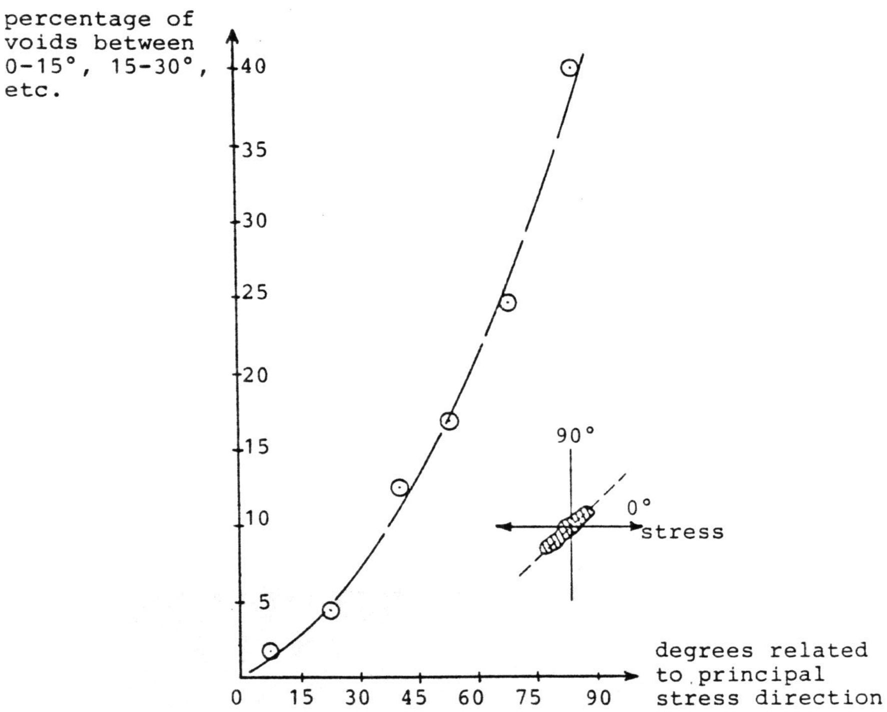

Figure 10

Example of quantitative assessment of creep cavitation damage.