

A review of the present state of the art of assessing remanent life of pressure vessels and pressurized systems designed for high temperature service

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Foreword

This Published Document has been prepared under the direction of the Pressure Vessel Standards Committee.

The committee wishes to acknowledge the valuable contributions to this work from the expert members of the panel responsible for the detailed drafting of the document which was chaired by Mr. C.H.A. Townley (Research Department, CEGB Berkeley Nuclear Laboratories).

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 26, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. The background to remanent life assessment

The document has been prepared in response to the interest which is now being shown in demonstrating the continuing fitness for purpose of high temperature pressurized systems. High temperature systems, in this context, are defined as those where the design stress is determined by time-dependent materials properties.

It was appreciated from the outset that it would be impossible to provide a recommended code of practice applicable to all pressurized systems. So many factors influence the scope of a fitness for purpose investigation, and the time in the life of the plant that it should be undertaken, that no attempt is made to lay down specific rules. Rather, the document provides a review of the techniques which are available. This will enable those who are responsible for the operation of high temperature plant to select those portions which are most appropriate for their own purpose. For the time being, the nature of the investigations which are needed and their timing in relation to the design life will have to rest with the owner of the plant and the inspection authority. However, with the knowledge now available it should be feasible to draw-up guidelines for specific types of plant (e.g. steam boilers).

For new plant, it will usually be worthwhile to plan, from the beginning, for remanent life investigations and fitness for purpose reviews. Where this is to be done, the designer/manufacturer will need to be consulted at an early stage, so that proper provision can be made. The designer can also often assist with the reviews of older plant, which has been in service for some time.

The type of investigation to be carried out will be influenced by three factors: the nature of the plant, the economic consequences of a plant failure or an unplanned shut-down, and the safety hazards involved. Different criteria may apply to different components in a single plant. For example, in a large steam boiler different procedures may be justified for the tubes, the headers and the piping.

At one extreme, there may be a strong economic incentive to keep the plant in operation well beyond nominal design life. It is therefore important to know about the condition of the high temperature components.

Are they approaching the end of their life, but can they be kept in service for a year or two until a replacement has been obtained?

Are they only part way through their life, and can a prediction be made with reasonable certainty about their remaining life?

Are they so near to failure that some remedial action needs to be taken immediately, by way of reduction of operating temperature or operating pressure?

At the other extreme, where there is no economic incentive to keep the plant operating beyond the nominal design life, a fitness for purpose physical examination coupled with an analysis of the operating conditions may be sufficient to check that all is well and that the plant can continue in operation. Even in these circumstances, it is usually worthwhile to make at least a rough estimate of the life which remains.

Where the timing of the investigation is not dictated by the vessel design code, it is clearly desirable to estimate the fraction of useful working life so far expended before undertaking what could be a detailed and expensive exercise. As described in section 2, this is normally obtained from an analysis of the operating history of the plant. In addition, the analysis may assist in identifying those regions of the plant which require detailed consideration. As is pointed out later, the more accurate the estimate, the less will be the time and money spent on unnecessary follow-up investigations.

For plant constructed from well established materials using well established procedures, it may be appropriate to defer the detailed investigation until a relatively large fraction of the life has been used. With less well established materials, particularly if there are doubts about the long-term ductility of the materials, it may be appropriate to initiate the work at half design life.

An early investigation may be necessary if the plant has been subjected to an abnormal occurrence such as would take pressures and temperatures beyond those specified in the design. It will also be necessary if there is any reason to suspect that the plant is deteriorating at an unexpectedly rapid rate.

Proper records of previous operating history are an essential input to the analysis of fractional life usage. In the absence of life fraction calculations, the assessment should be no later than two-thirds design life.

For vessels designed and manufactured to BS 5500 and to BS 1113, special considerations apply. Vessels designed for finite life are subjected to a review at the end of design life. Components designed using the criteria permitted by footnote 7 to Table 2.3 of BS 5500:1982 and footnotes 5, 6 and 7 to Table 1 of BS 1113:1969 require a review at two-thirds design life. Experience has demonstrated that components designed according to these rules can be expected to exceed their full design life. A full remanent life analysis may, therefore, not be required. A simple fitness for purpose examination may be all that is necessary.

The timing of subsequent investigations will depend on what is discovered about the state of the plant, taking into account the future operating regime. When there is no detectable deterioration, and supporting studies confirm a large remanent life, the next investigation may be deferred for an extended period. Where there is evidence of deterioration, the period between investigations will be determined from estimates of the rate of deterioration.

A physical examination to determine the continuing fitness for purpose of the plant provides one of the main safeguards against plant failure and where replacement of components incurs little economic penalty, there is probably no need to do anything else. Guidelines as to what is required are given in section 3.

A thorough analysis of remanent life requires a much more extensive investigation, which can be very costly, and may involve metallurgical studies and tests to establish operational stress and temperature levels fairly precisely. The first step is usually a re-analysis of the operating history, with more precise estimates of temperatures and stresses in the critical regions of the plant, as outlined in section 2. Since no single method of remanent life assessment is likely to be complete in itself, there will need to be a number of back-up investigations. These are likely to include some, or all of the following:

- accelerated creep tests on serviced material to determine the fraction of life so far exhausted;
- metallurgical examination of serviced material to establish the current amount of damage;
- measurement of deformation (or lack of it) to estimate the permanent strains which have been accumulated to date.

These aspects are discussed further in sections 3, 4 and 5.

The majority of high temperature plants operate under relatively steady conditions, so that creep is the predominant cause of deterioration. Some equipment is subject to fatigue loading as well. This may range from high frequency oscillations superimposed on the steady state stresses due to pressure or external loads, through to relatively infrequent shocks and major changes in temperature and pressure. Special consideration is needed where significant fatigue is present, and the modifications which have to be made to the methods of assessment are discussed in section 6.

The safe working life of a plant may be influenced by the environment in which it operates. In some situations, environmental attack may merely lead to a loss of section. In other circumstances the environment may affect the material in other ways. For example, there may be inter-granular attack, or diffusion of alloying elements. Some general guidelines are given in section 7, although each case will need special consideration.

In some types of chemical and petrochemical plant, vessels are deliberately subjected, at infrequent intervals, to conditions different from those encountered in normal operation. This can happen, for example, during decarbonization and during catalyst regeneration. The effects of such planned periods of abnormal operation have to be taken into account when applying the procedures described in sections 2 and 3.

Of particular importance are metallurgical changes which may have been induced by temperatures higher than those which apply in normal operation.

Section 8 describes a simple procedure which is applicable in certain special circumstances and avoids the need for many of the investigations which are described earlier in the document. This procedure was developed in the first place for the analysis of reformer tubes in petrochemical plant. It has potential application in many similar situations, where the plant is made up of a large number of similar components, and where failure carries no safety implication, either to personnel or to adjacent plant. The allowable rate of failure of components is governed by financial considerations, and the object of the analysis is to decide how quickly replacement is necessary before the economics of the process are impaired.

Following the publication of this document the next logical step would be to provide guidelines for specific types of plant (e.g. steam boilers) based on the general principles in this document. The procedures to be adopted will depend on safety issues and economic considerations and will have to be nominated by those with specialist knowledge of the plant concerned.

Section 2. Operating history

The rate at which creep damage accumulates in a material depends on stress and temperature, and the useful working life is therefore strongly influenced by the conditions to which the plant is subjected in service. An analysis of past operating history can be used to provide information on stresses and temperatures. This information is then combined with creep rupture data for the materials of construction to evaluate the fraction of the useful working life which has so far been expended. An analysis of the maintenance history may give pointers to regions requiring special attention.

Estimates of the expired fraction of life made in this way are necessarily approximate, and often highly conservative. Nevertheless, they are an essential first step in the whole process of remanent life assessment. They serve to identify those parts of the plant which are most at risk, because of high temperatures and high stresses, and which have to be subjected to rigorous investigation by other procedures. They can give early warning that replacement of some parts of the plant has to be planned for. They may show that damage is accumulating so slowly that inspection and more detailed remanent life assessments can be deferred for a considerable time.

The depth to which the operating history is analysed will depend on economic and safety considerations. The procedure described in this section is that which would typically be employed for a pressurized system where premature failure or unplanned retirement from service would have significant economic and safety implications. For many high temperature systems, such a comprehensive procedure may not be justified economically. Simplified procedures based on the principles of this section will often be sufficient, provided records of operating history are adequate. The user and the inspection authority have the responsibility to decide what records it is necessary to keep. Such records as are kept should be in a form that can readily be analysed.

The analysis of operating history is generally carried out in two stages, a typical example being described by Bolton and Verrier (1). First there is a preliminary screening to identify those regions of the plant where creep damage accumulates at the fastest rate, and which are therefore critical from the point of view of plant retirement or replacement. This is then followed by a more detailed and rigorous analysis of these regions to establish the fraction of life which has been used up. The critical regions may not necessarily be those that operate at the highest temperatures or highest pressures.

In both stages of the assessment the basic method is the same. The records of operating history are used to evaluate the time that the material has been at stress and temperature. This information is compared with the creep rupture data of the material to estimate fractional life usage. The following text applies both to the preliminary screening and the subsequent analysis of the critical regions; the main difference is that preliminary survey need only be carried out with limited precision.

Care has to be exercised in establishing metal temperatures from the operating history. In general, the metal temperature will differ from the process fluid temperature. It may be higher or lower depending on the direction of heat flow. Equally important are the variations of metal temperature from region to region in the plant. These variations occur even in parts of the plant that are nominally at the same temperature. Measurement of actual metal temperatures during plant operation may be necessary to investigate this, although often temperature variations can be established by experience. Examples relevant to large steam boilers can be found in reference 7.

Stress levels also need careful consideration. In most instances, it is not sufficient to assume that only the nominal membrane stress is present. For example in piping systems, there are additional system stresses, including those due to cold pull. In vessels, there are many stress concentrating features, such as branch connections and support attachments. Finally, in a complex plant, there may be additional loads to be considered, which have not been fully taken into account at the design stage, and which arise from a variety of causes. Although, in high temperature plant, the stress levels to consider in assessing creep damage are lower than the elastically calculated values, an elastic stress analysis will generally identify the regions which need further investigation.

If a more detailed stress analysis is required, recourse has to be made either to time dependent finite element calculations, or to simplified methods, such as those described by Goodall et al in reference 2. Where the region of the structure under consideration contains materials with different creep deformation properties, it may be desirable to allow for these in the calculation. It is emphasized that such analyses are not normally undertaken during the initial design. There is usually no need, since the margins inherent in the design codes are intended to provide the specified life of the plant, despite such variations. However, such considerations can be of crucial importance in determining how long it is possible to operate plant beyond the end of design life. Even though in many cases relevant materials data are not available, it is usually possible to make an appropriate allowance. Further information may be obtained from papers by Goodall and Walters (3) and by Etienne van Rossum and Roode (4, 5).

Having established temperatures and stresses, the next stage is to decide what creep rupture data should be used for the life assessment. An accurate prediction of remanent life would require knowledge of the rupture properties of the material actually used in the construction of the plant. The cost of obtaining such information is only justified in very special circumstances, and it is likely to be inappropriate for a preliminary analysis of fractional life usage.

At this stage it is more important to assume that the material properties are those used for design purposes. There are two alternative ways of proceeding. In one, data given in the design codes, for example that given in Table 2.3 of BS 5500:1982, can be plotted to give curves which relate time to rupture with applied stress for a range of averages. In the other, use can be made of the ISO mean property curves, which form the basis of design stress tables of BS 5500 and similar standards. In the absence of other information, the ISO rupture strength is generally divided by 1.25¹⁾ to give a minimum of creep rupture data.

Some further allowance is needed if there is reason to suspect that the materials of construction exhibit low long-term ductility. There is no reason to do this when dealing with plants made from well established materials, using well established welding procedures. However, care is necessary when dealing with relatively new materials or new fabrication procedures, or where vessels operate in a hostile environment.

The information on stresses and temperatures is usually combined with the materials data using Robinson's life fraction rule (6), and it is this procedure which is described here. A logical route through the calculations will be found in the paper by Bolton and Verrier (1).

To use the life fraction rule a histogram is prepared from the operating records, to show the total time spent at discrete stress levels and discrete temperatures. For each of the selected stress levels and temperatures the time to rupture is established from the creep rupture data. The fractional life usage, f , due to this part of the operational history is given by

$$f = \frac{t}{t_r}$$

where

t is the period of time spent at this stress, and

t_r is the corresponding time to rupture.

This is repeated for all other periods of operating history. The total fractional life usage f_T for the region of the plant under investigation is then obtained by summing all the individual values of f , i.e.

$$f_T = \sum_{1}^n f_n$$

The total fractional life usage, f_T , obtained in this way is unlikely to be precise. However, it should be adequate for the purposes of an initial investigation. At the same time, before embarking on expensive supplementary investigations or considering replacement of plant items on the grounds that fractional life usage is high, consideration has to be given to the inaccuracies inherent in the calculations. More accurate estimates of fractional life usage may show that the financial penalties due to inspection costs and extended plant outages need not be incurred. As indicated below, improved accuracy implies a detailed knowledge of plant operating history; it may also involve tests on archive materials and the monitoring of selected temperatures and pressures on the plant. Provided the need for this is recognized when the plant is ordered, the savings achieved later in the life of the plant may justify the extra initial costs.

¹⁾ This is higher than the stress used for design purposes, which is generally the *mean* rupture strength at the appropriate design life, divided by a suitable factor.

There are four principal reasons for the inaccuracies in the estimating of f_T which are outlined in the following paragraphs. For an in-depth discussion reference should be made to the paper by Williams and Plastow (7). On balance the errors tend to lead to an over-conservative prediction of fractional life usage.

- 1) The life fraction rule, implicit in the procedure, may be in error, particularly if there are wide variations in operating temperature and stress which lead to the accumulation of creep damage by different microstructural mechanisms. There is extended discussion on this topic in section 4. Reference should also be made to the failure maps such as described by Ashby et al (8), which define the regions of stress and temperature where different mechanisms dominate.
- 2) The estimated temperatures and stresses will tend to be pessimistic to allow for the approximations and assumptions used in their calculation. This happens because investigators will usually allow additional margins to cover uncertainties. Similar pessimisms will tend to arise from incomplete operating records, although this will not be the case if excursions and abnormal occurrences have been removed.
- 3) The material used in the manufacture of the vessel is likely to have better creep rupture strength than that assumed in the calculations. This assumes that allowance has been made for any deleterious effects of a hostile environment, or for materials which exhibit unusual long-term behaviour.
- 4) The ISO mean property curves, used to derive the materials data, may themselves be in error, if a large amount of extrapolation has been necessary to obtain long-term data.

There are three steps which can be taken to improve the accuracy of estimates of fractional life usage, provided that the need to do so is recognized at an early stage.

The first concerns the keeping of operating records which are adequate for the purpose of life assessment. The extra cost of keeping proper records is generally small compared with the financial benefit to be gained later in life when unresolved questions about fitness for purpose may lead to expensive replacement or repairs which may not be necessary. The manner in which records are kept will depend on the nature of the plant, the use to which it is put, and the way in which it is operated. It is not appropriate to provide specific guidelines here, but the whole question of records should be considered by the operator at the time when the plant is ordered. The general aim should be to provide all the information which is needed for fitness for purpose investigations and, if appropriate, for remanent life analysis. The records should not be so voluminous and complex that they overwhelm the investigator. At the same time they should include all relevant information about abnormal occurrences and periods when the plant is being operated outside design limits. Consideration should be given to computerized methods of recording the data.

The other two steps to improve the accuracy of fractional life calculations are more costly. The expense involved may not be justified, except for plant of high capital cost or of high commercial value.

The first involves conserving off-cuts of material actually used in the construction of the plant, including samples of welds. These can be used to provide realistic creep rupture data in place of the pessimistically assumed lower bound values derived from ISO data. As will be shown in later sections, such archive material is also necessary if full value is to be gained from metallographic examination of serviced material and from post-exposure creep tests.

The second involves monitoring selected regions of the plant to obtain more accurate information on temperatures and stresses than can be deduced from the operating records. Direct monitoring of temperatures in these regions throughout the life of the plant may sometimes be possible. Where it is not, some characteristic temperature, such as that of the process fluid, should be monitored continuously and the metal temperatures in the critical regions estimated from this. It is unlikely that direct measurements can be made of the stresses. Instead other variables such as pressure and external forces should be monitored, from which stresses can be calculated. Even where such direct measurements are made, errors in thermocouples and pressure transducers may occur, and due allowance should be made in the analysis.

Section 3. Physical examination and interpretation of observations

The regular periodic inspection of high temperature plant includes a visual inspection and a non-destructive examination of such regions as are considered to be necessary. The intervals between such periodic inspections are in some cases determined by statutory requirements. In the remainder, they are determined by good practice and by the requirements of the inspection authority. The purpose of this section is to focus attention on the physical examination which will be carried out in the context of a fitness for purpose review. However, much of its content is also applicable to what is observed during a normal periodic inspection.

Physical examination in the context of a fitness for purpose review implies a thorough visual inspection of the critical parts of the plant, coupled with non-destructive examination to check whether cracks are present. Visual and non-destructive examination has to be as thorough as possible, to confirm that unexpected deterioration has not occurred. However, special attention will be devoted to those regions of the plant which the operating history and design analysis have shown to be most at risk.

Guidelines for physical examination, and the interpretation of the indications which are observed, are described in this section. They are written from the standpoint of plant which is designed for high temperature service.

However, many of the procedures, particularly those relating to the interpretation of observations, are equally applicable to plant which normally operates below the creep range, but has suffered overheating. In such circumstances, investigations should be undertaken which are sufficiently extensive to establish the cause of the problem with confidence. Where it is clear that an isolated temperature excursion has occurred, that the material has not deteriorated, and that all parts of the plant are normally operating well below creep temperatures, then no remedial action is needed. However, it is essential to record the nature of any distortion for comparison purposes in the future. If the investigations show that damage to the plant has occurred during normal operation, for example because of local areas of overheating or rogue material, then remanent life assessment is needed to determine if and when remedial action is necessary.

Visual examination and dimensional checks.

The purpose of the visual examination is to identify, at an early stage, whether deterioration is occurring. The plant should be examined and its general condition assessed in terms of defects, distortion, scale formation and anomalous metallurgical features. Investigations should be related to historical records of plant operation, including those providing information on deviation from design conditions. Information on material behaviour not available at the time of the design should be taken into account.

The visual examination should give emphasis to investigating the following:

- a) local areas of overheating, and other more general areas where the operating temperature is higher than allowed for in design;
- b) whether behaviour is consistent with the materials which have been specified;
- c) stress concentration regions;
- d) areas where repairs have been carried out;
- e) areas affected by failures of other components during operation;
- f) areas where cracks have been revealed in previous examinations.

Any visible distension of vessels, headers and tubes can be an indication of creep damage, and should be thoroughly investigated to determine whether or not localized or general creep is taking place. In the absence of dimensional changes, premature creep failures may be initiated in positions of stress concentration, for example a nozzle penetration or support region. Therefore, these sites should be specifically investigated. Care is needed if it is suspected that the materials have a low creep ductility.

Where it is decided to make dimensional checks, clear datum points need to be established so that later remeasurements can be taken, possibly by different personnel, at exactly the same positions. Care is needed to ensure that datum points, such as pips, do not deteriorate and are properly protected against accidental damage. It is important to record the temperature at which measurements are taken, so that the readings can be corrected; otherwise thermal expansion effects may mask the true creep distortion in the component.

When datum positions are established using external reference marks, such as inserts, pads and surface indentations, care should be exercised in their application.

They could produce injurious metallurgical features which might affect the serviceability of the plant.