DESIGN OF HIGH TEMPERATURE METALLIC COMPONENTS

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Preface

The successful operation of metallic alloys under conditions prevalent in high temperature plant such as gas turbines, heat exchangers, coal gasifiers, and chemical or petrochemical process units is completely determined by the information available to the designer in the form of material specifications, material properties and the available codes he has to work with. However, the plant operating conditions are so varied, and also often extremely aggressive including very high temperatures, corrosive elements, erosive particles, thermal cycling and high loads, that these are not systematically or even easily incorporated into design codes.

The purpose of the discussion seminar 'Design of High Temperature Metallic Components' organised by the Information Centre of the High Temperature Materials Programme of the European Commission Joint Research Centre, Petten Establishment, was both to guide scientists towards the information the high temperature designer requires and conversely to inform the design engineer of the present state of materials research in relation to high temperature component design.

The lectures were chosen so as firstly to review available knowledge concerning high temperature design codes and practices appertaining to two important industries: electrical generation and chemical/petrochemical production. Although the paper on the latter subject had somewhat less a review characteristic, many of the important problem areas were highlighted. Secondly, the methods and progress in metallurgical research aimed at producing more directly usable data and the possibilities for component lifetime prediction were thoroughly delineated in two successive lectures. These were followed by a detailed description of the engineer's contribution to the component design problem via exact finite element analysis methods. Finally, the complex situation was covered where property interactions, complex stresses and component testing require that a combined interdisciplinary materials/engineering knowledge be applied.

It is hoped that the papers presented during the discussion seminar, in book form, should satisfy both engineers and materials scientists making their individual contributions to improving high temperature metallic component design and, perhaps more importantly, bring them closer together so that they can synergistically reach their goal.

As scientific co-ordinator (R.C.H.) and Information Centre Head (M.M.) it is a pleasure for us to thank C. H. A. Townley, Ph. Holl, R. W. Evans, B. Wilshire, D. R. J. Owen, O. J. A. Gonçalves, and F. Schubert and his co-authors for their efforts in both presenting and preparing an evidently high-quality collection of papers and to the delegates at the seminar who contributed to its success through their active participation.

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Introduction

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The design of engineering components for service at elevated temperatures is a great deal more complicated than that for equivalent components operating at ambient temperature, because various degradation processes become active and are much accelerated by rise of temperature. The processes contributing to the progressive fall in serviceability of a component are of three main types: first, structural changes in the constitution of the alloys; second, deformation and crack growth under the influence of the imposed mechanical stresses; and third, chemical corrosion of the surface of the component by reaction with the environment. Further, to complicate the situation, these three processes interact with one another, so that while they may be studied separately under controlled laboratory conditions, the effects on components in service are less readily separated.

The design of a specific high temperature component has, therefore, to be made in the light of a body of property data which has, for the most part, been determined on idealised specimens tested under simplified conditions of temperature profile, stress cycle and environment. The component is then expected to perform satisfactorily in service when all the controlling factors referred to may differ significantly from those of the available data. The time of operation may also be different from that of the test data. Thus, to allow for the uncertainties involved, generous safety factors are normally applied, but while these may ensure safe operation, they can involve wasteful use of materials. There is therefore a clear incentive to combine safety in design with economical use of materials and, in essence, this forms the main theme of this seminar.

In addition to the interaction between the effects of imposed stress and corrosion, which can be studied reasonably satisfactorily on simple samples, there are other important factors which arise when considering the application of standard data to component design. These include the effects of size and geometry, and the problems of joining.

Most data are derived from samples with a ruling section of the order of 1 cm, while components may be much larger and may be produced by a significantly different process leading to differences in both macrostructures and microstructures.

Larger sizes also lead to increased internal stresses resulting from heat treatments, which, even if relieved by thermal relaxation in the early stages of service, cause redistribution of stress patterns. Thermal stresses generated during change of service condition are also dependent on the component geometry, and, of course, have to be allowed for in operating procedures.

Some high temperature components, such as turbine blades, are integral parts in which the critical areas are remote from attachment points, and are small enough to allow simulated service testing to confirm design. However, others, such as steam pipes or reformer tubes, require joints and fixtures within the critical zones, and here the effects of welding or mechanical joining have to be considered, including the influence of *in-situ* stress-relieving treatments.

While interpolation of the effects of temperature or of stress on time-dependent failure mechanisms such as creep and fatigue is usually reliable, extrapolation of data beyond the range of observation is notoriously risky. Many attempts have been made to derive fundamental or phenomenological formulae to aid the process, but fully reliable success has not been achieved. Not only does this imply that fully reliable designs for a 30 years life require full-time test data but also that, even if these data are available, the material is 30 years old. Almost certainly it is not representative of that from modern production processes.

The influence of these and other factors demanding close attention to the insurance of safety in operation, combined with economy in construction, points to the need for the testing of more advanced types of specimen or model component under conditions simulating as closely as possible those anticipated in service. With their increasing complexity and size such facilities are expensive and it seems necessary that co-operative action to provide them is required.

At this seminar, we have the benefit of presentations from the representatives of major industries involved in large-scale high temperature plant and of those concerned with basic studies of materials property data and their application to design. It is hoped that the lectures presented and the ensuing discussion will prove helpful and stimulating to those engaged in this field.

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Design Methods for High Temperature Power Plant Structures

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1. INTRODUCTION

As an introduction to the seminar, I have been asked to provide a review of the design methods and design criteria currently in use for both nuclear and fossil fuelled power plant.

It would be an impossible task to compare and contrast the very many national design codes which are available, especially for conventional power plant and pressure vessels. Instead, I have chosen to examine two examples—BS 1113,[1] which is representative of the design codes employed for power station boiler plant, and ASME Code Case N47,[2] which is being developed for high temperature nuclear reactors, especially the liquid metal fast breeder reactor. The first derives from an industry with many years of operating experience behind it; the second ventures into a relatively unknown field, where procedures must necessarily be derived from first principles.

In accordance with the theme of the seminar, I have been asked to draw attention to the topics which, as an engineer, I believe should be of interest to metallurgists. However, the materials issues cannot be divorced from the design procedures which are adopted. The designer of a pressure vessel or a nuclear component is faced with a structure of complex geometries, containing stress concentrations and stress gradients. Often it will be subject to multiaxial stresses, and the loading may be far from constant. This is in contrast to the simple uniaxial tests which are employed to derive the materials data which the designer must use. The art of successful design is to ensure that stress concentration features, the welds used in fabricating the component, the loadings applied in service and so on do not lead to premature failure.

TABLE 1
TYPICAL UK POWER PLANT MATERIALS

Power plant	*Component*	*Material*	*Approximate operating temperature (°C)*
500 MW power station boiler	Superheater tubes	Mild steel, 1Cr1Mo, $2\frac{1}{4}$Cr1	370 min
		Eshette, AISI 347, 316, 304	620 max
	Reheater tubes	Mild steel, 1Cr1Mo, $2\frac{1}{4}$Cr1 Eshette, AISI 347, 316, 304	400–620 max
	Superheater headers	AISI 316 or 347	370–580
Advanced gas cooled reactors	Evaporator/ superheater tubes	C Steel, 9Cr1Mo Austenitic AISI 316	250–565
	Reheater tubes	AISI 316	400–565
	Superheater headers	AISI 316	150–565
	Primary circuit	AISI 304, 347, 316	150–565
Fast reactor (proposed design)	Primary circuit	AISI 316	400–575
	Secondary circuit	9Cr1Mo	350–525

I have therefore provided, for both examples, a brief introduction to the design principles which they employ. I cannot, in the short space available, discuss the finer points of the design procedures. To do so would only be justified in a conference of engineering specialists. However, I believe that what I have to say should be sufficient to illustrate the way in which the materials data are used, and will promote discussion on what further information on materials behaviour the designer needs.

One important point must be kept in mind. No design code provides a fully comprehensive procedure which, followed through step by step by a newcomer, would enable a satisfactory pressure vessel to be designed and manufactured. That is not what is intended. The codes essentially provide base-line methods and criteria, which are to be used by specialist organisations with relevant experience in the field.

Many factors which contribute to a successful design, which will give trouble-free service throughout its specified life, are not discussed at all in the codes, or at least receive scant attention. Some, such as the performance of welds at high temperature, will be considered in this paper. Others, such as corrosion, erosion, and environmental cracking are judged to be outside the scope of the present seminar, but nonetheless are of crucial importance.

Table 1 provides a summary of the materials most commonly used in high temperature power plant, and the temperatures at which they operate. I have drawn on UK experience for this table, and I should mention that alternative materials are used for similar duties in other countries.

2. DESIGN CODES FOR POWER STATION BOILERS

Design rules for chemical vessels and steam generating plant are based, to a large extent, on previous practice. There is a considerable background of information on what has given satisfactory performance in the past, and what is to be avoided in the future. At the same time, the codes are being continually updated in a way which takes advantage of improved knowledge in the fields of structural analysis, materials properties and failure criteria.

In the UK BS 5500[3] is the master code for unfired pressure vessels, BS 806[4] is used for power station pipework and BS 1113[1] for large steam boilers. There is a strong similarity in all three codes with regard to their basic principles, resulting from an integrated approach to the preparation of pressure vessel design rules in the British Standards Institution. I have chosen BS 1113 for discussion in the present paper.

This code provides a design route which avoids extensive stress analysis, although there is nothing to prevent the designer doing this if he so wishes. The basic membrane thickness of the vessel is fixed by a simple mandatory formula. Charts and formulae are provided to estimate the additional thickness needed in stress concentration regions. Design procedures are the same for components operating at relatively low temperatures and those operating where creep is important.

The minimum thickness for a component, such as a header, in the regions away from geometrical discontinuities is obtained from the formula

$$t = \frac{pD_i}{2f - p} \qquad \text{or} \qquad t = \frac{pD_o}{2f + p} \tag{1}$$

where t = is the minimum thickness of shell, p is calculation pressure, D_i is the inside diameter of the shell, D_o = is the outside diameter of the shell, and f is the design stress of the metal at the appropriate temperature. A joint efficiency factor may be required if the component contains welds.

Similar formulae are used to obtain the minimum thickness of straight tubes and integral pipework. Here the code requires an additional provision to be made for surface corrosion which may occur during the life of the plant. Allowance is also made for thinning which may occur at pipe and tube bends.

The design stresses to be used in these formulae are tabulated in the code. At high temperature, the design stress is the minimum stress to cause rupture in the required design life, divided by 1·3. In general, the rupture stresses are those agreed by the International Standards Organisation for the classes of steel permitted by the code. In some instances, where long-term UK experience shows that the ISO values are conservative, higher design stresses are permitted.

Materials are restricted to those which have given satisfactory performance in service. Chemical and physical properties are tightly specified.

As stated earlier, detailed stress analysis is not required for the various stress-raising features, such as branch connections, end closures, vessel supports and ligament regions. Instead, the code provides a set of simple rules to estimate the amount of thickening required in these regions to reduce the stress concentration to an acceptable level.

A full discussion on how each of the stress concentration regions is dealt with is outside the scope of the seminar. To illustrate the procedure, I have chosen as a typical example the information provided to the designer about the reinforcement needed in branch connections. A series of charts is provided, an example relating to protruding nozzles being shown in Fig. 1. T is the thickness of the main shell away from the discontinuity. T_r is the local thickness of the main shell to provide the reinforcement, and t_r is the local thickness of the branch pipe required to provide the reinforcement. ρ is the geometrical factor $d/D.\sqrt{(D/2T_r)}$. C is a factor, tabulated in the code, which takes account of any external loads which are applied to the connection.

Within certain specified limits the designer is permitted to put the reinforcement either in the main shell or in the branch pipe, or in a combination of both. It is a simple matter to read off from the chart what local thickening is required in the branch pipe and the main shell.

At first sight, it is perhaps surprising that the identical reinforcement rules can be applied to branch connections in high temperature plant as well as at lower temperatures. The explanation is provided from considerations of the way in which the design charts were derived.[5]

The starting point was a large amount of data, obtained both

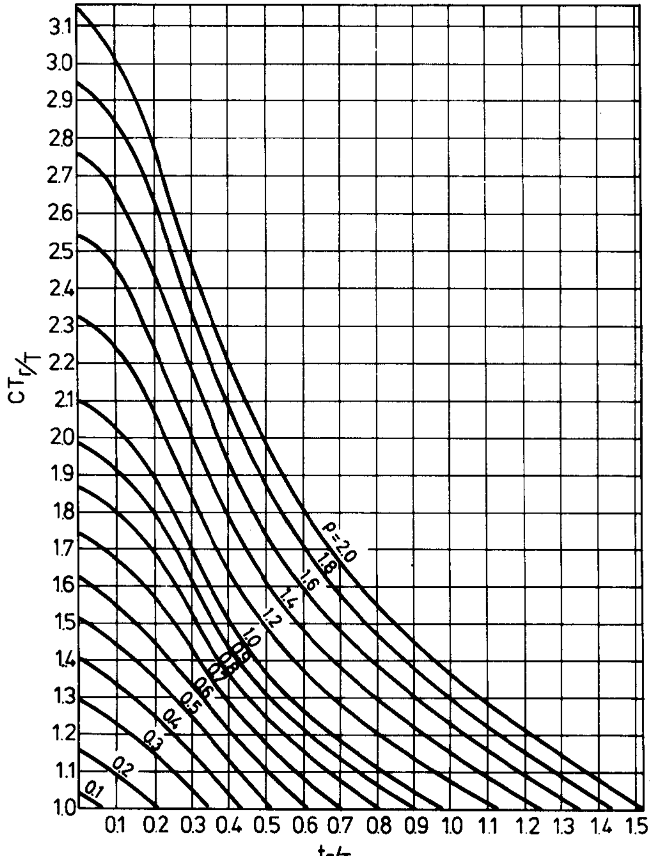

FIG. 1. Design curve for protruding nozzles. (From BS 1113: 1983[1].)

theoretically and experimentally, which provided information on elastic stress concentration factors and limit loads for nozzle intersections. From this information, the design charts were drawn up to indicate the minimum reinforcement required to achieve shakedown in service and prevent excessive plastic deformation during the proof test.

The first requirement, transposed into the more familiar ASME notation (see Section 3.1), is

$$P_L + P_B + Q \leq 2{\cdot}25S_m \tag{2}$$

The value of 2·25 was used when the UK rules were drawn up, in place of the more usual value of 3·0, to provide additional margins of safety.

The second requirement can be expressed as

$$\frac{(P_{\text{lim}})_{\text{intersection}}}{(P_{\text{lim}})_{\text{plain shell}}} \simeq 1 \tag{3}$$

where the numerator and denominator refer, respectively, to the limit pressure of the intersection and plain unreinforced shell.

Leckie and Ponter[6,7] have shown that, in the creep regime, shakedown is still an important concept. Using the ASME notation, their work shows that plastic deformation can be neglected in the creep range, provided

$$P_L + P_B + Q \leq \frac{2n}{n+1} S_y \tag{4}$$

where n is the creep index of the material and S_y is the instantaneous yield stress.

Goodall *et al.*[8,9] have shown that, provided the material has adequate creep-rupture ductility, a conservative estimate of the creep life of a component of complex shape can be obtained by reading the stress to rupture/time to rupture curve of the material at the reference stress level.

Taking into account the relationships between S_m, which for high temperature components is based on creep rupture, and S_y, the instantaneous yield stress, and inserting realistic values of n, it is apparent that a high temperature component designed to satisfy inequality (2) will also satisfy inequality (4), and will therefore achieve shakedown.

Inequality (3) ensures that the reference stress for the nozzle intersection is numerically equal to the hoop stress in the plain membrane portion of the vessel. The intersection will thus have the same margins of safety against creep rupture as the main body of the vessel, subject to the requirement that the creep-rupture ductility of the material at the end of life is adequate.

BS 1113 does not give specific design methods for dealing with thermal stresses, for the simple reason that it is unusual to find high thermal stresses, of sufficient magnitude to cause thermal fatigue, in boilers of established construction, installed and operated in accordance with the manufacturer's instructions. The code requires that special consideration be given to the design of pressure parts when, *inter alia*, abnormally rapid or frequent changes of pressure or temperature are likely to occur.

BS 1113 has little to say on the subject of strength of welds at high temperature. It is assumed that, provided the creep-rupture strength of the weld metal is similar to that of the parent material, the 'joint efficiency factor' can be taken as unity. In general, this assumption is borne out by the good performance which has been obtained in service with vessels designed to BS 1113. However, it must be remembered that this would probably not have been achieved in the absence of development work carried out by fabricators on high temperature performance of weld metals, research carried out by plant owners such as the CEGB, and collaborative investigations which have been undertaken, for example, by the ERA. The more recent research, such as is discussed in Ref. 10, and illustrated in Fig. 2, casts doubt on the adoption of matching strength as the most important criterion. It appears that ductility of all the parts of the complete weldment, including the heat affected zone (HAZ), is an important factor as is the relationship between the creep deformations of the various parts.

Welded transition joints occur in most modern power station boilers, between austenitic and ferritic tubes and pipes. No specific design rules are provided in BS 1113 for such joints between dissimilar metals. Again, satisfactory performance has been assured through research and development programmes carried out jointly between the manufacturers and large customers, such as the CEGB.

Experience with boilers designed to BS 1113 suggests that there are few, if any, deficiencies in the design procedures, or in the choice of material design stresses. In general, vessels designed for a nominal life of 100 000 h have achieved that life, and, as will be discussed below, attention is now focussed on demonstrating that these are capable of continuing in operation well beyond that time.

Where difficulties have been experienced with boiler plant in service, and these have been relatively few, the causes have usually been found elsewhere: temperatures actually higher than those allowed for in the design; extraneous system stresses in interconnecting pipework; and occasional deficiencies in quality control during manufacture.

It would thus appear that there is no pressing need for major alterations to BS 1113 and associated codes. However, it would be wrong to imply that no further improvements are required. For example, more precise guidance is desirable on thermal fatigue and, more generally, on the fatigue of attachment welds; design criteria for very thick cylindrical shells at high temperature could also be improved. Additional design charts for stress concentrating features will be provided as more results become available from theoretical and experimental stress analyses.

As far as high temperature data on the parent materials are concerned, some long-term tests remain to be completed to obtain creep rupture properties for times upwards of 100 000 h. The general impression is that present design stresses are over-conservative. It is pertinent to ask whether design values could be increased, without compromising safety, in view of

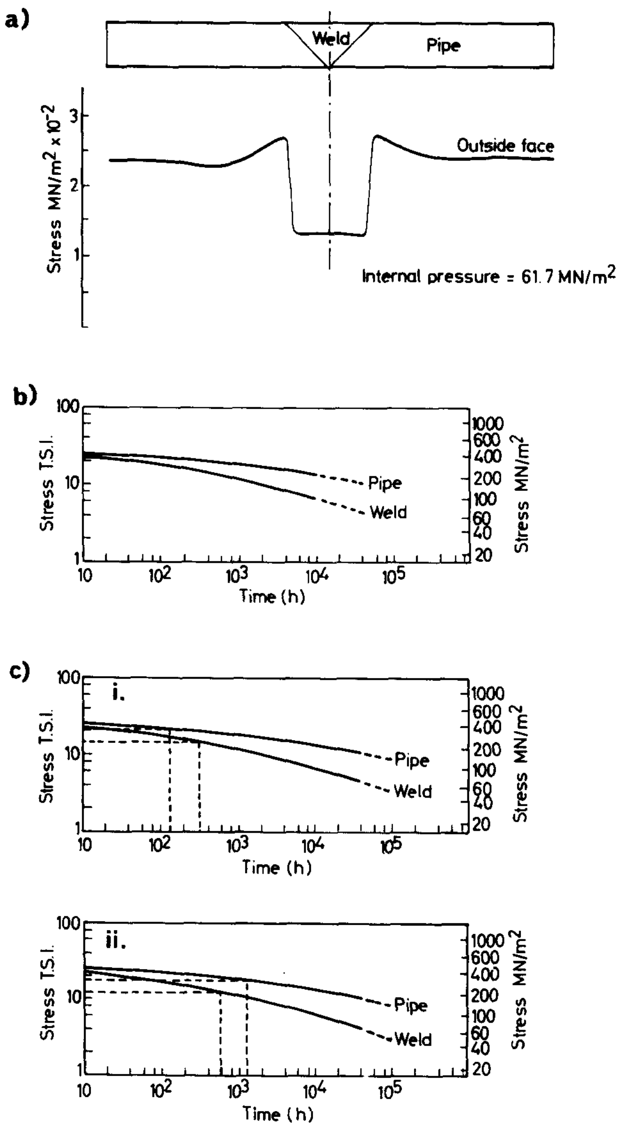

FIG. 2. Redistribution of stress in weld due to creep, and its effect on rupture life. (a) Off-loading of the tangential stress in the weld. (b) The stress–rupture properties of weld and parent material. (c) Effect of diverging stress–rupture curves on location of failure: (i) failure in pipe; (ii) failure in weld.