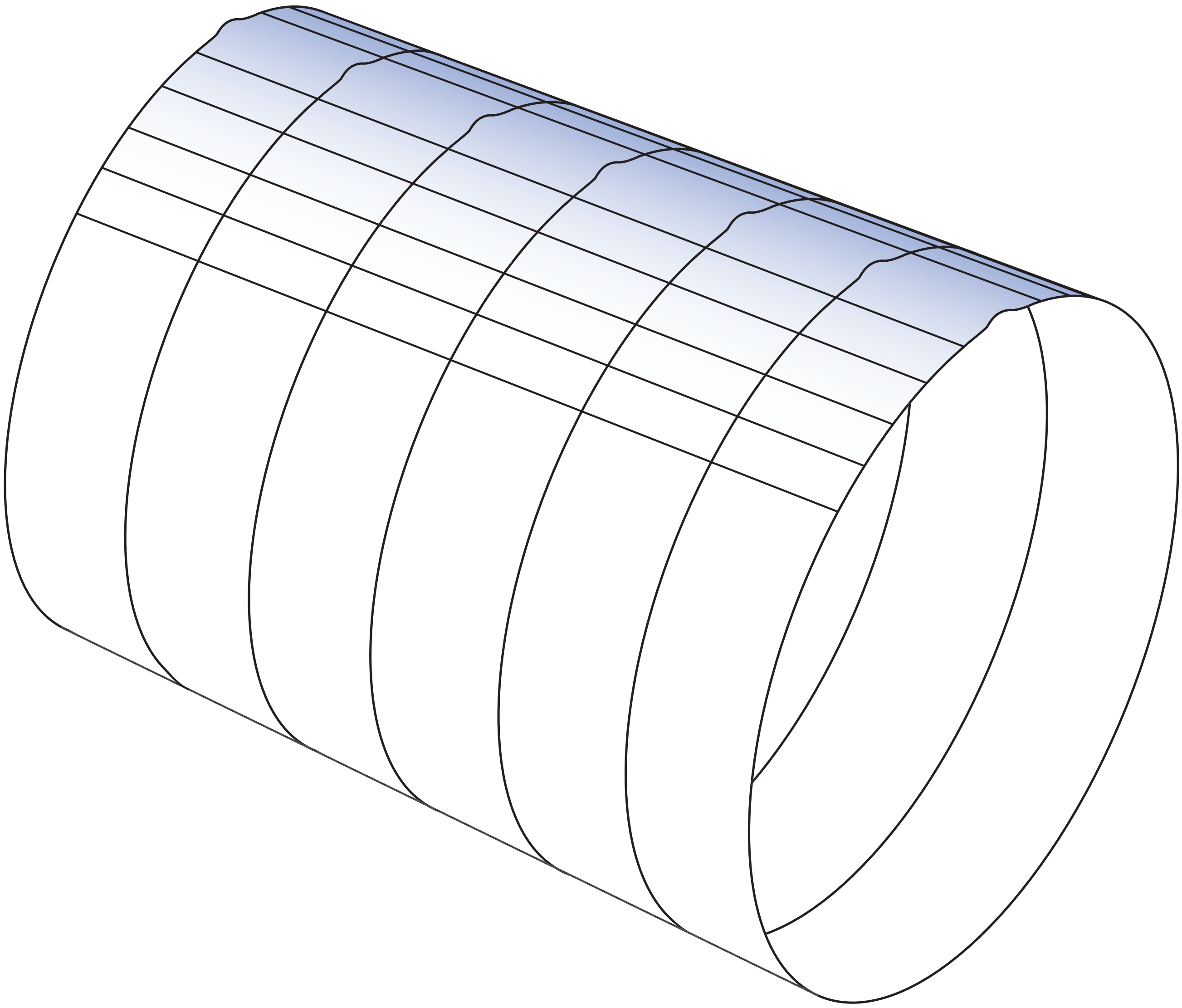
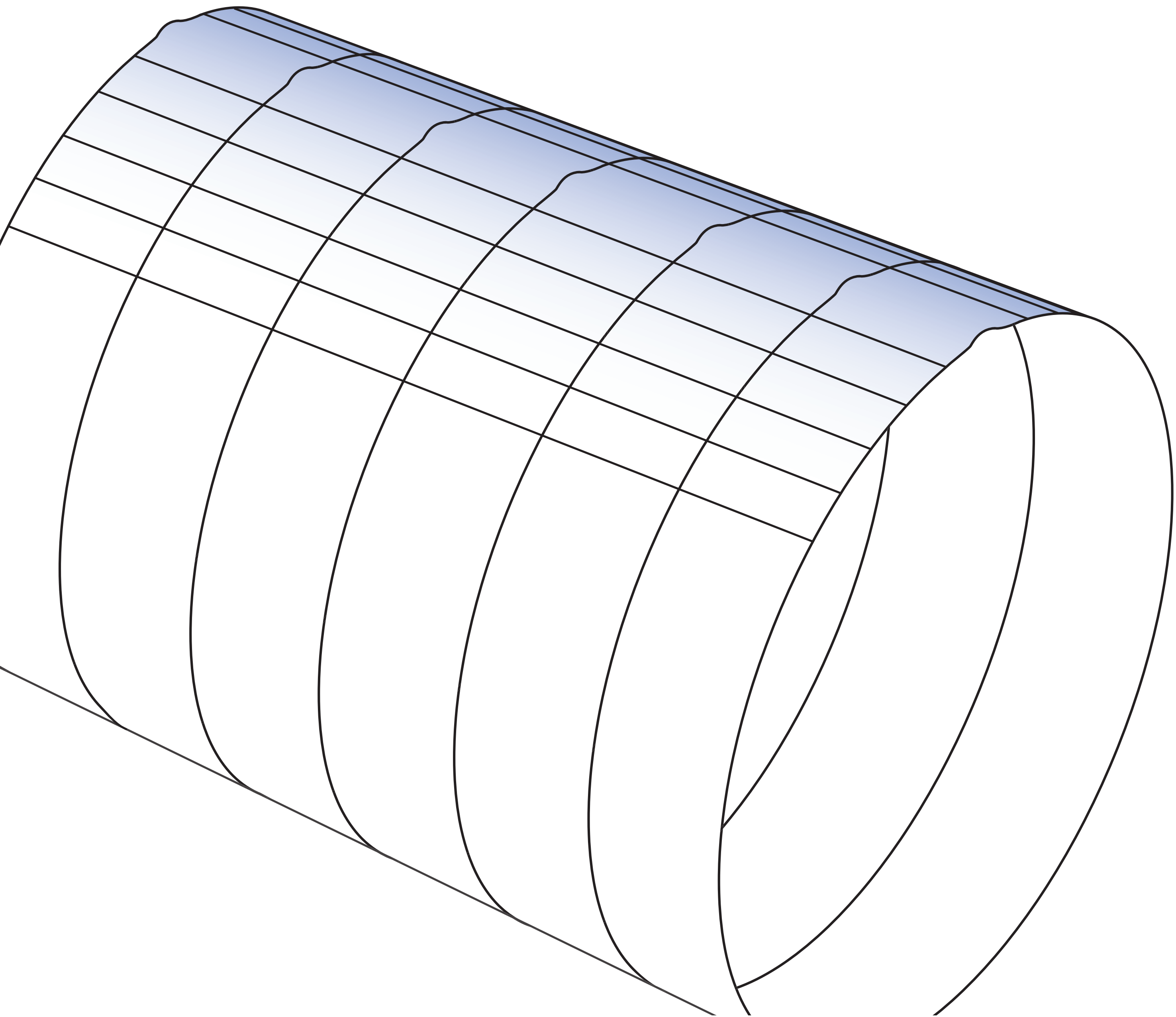
SHELL BOILERS

Guidelines for the examination of longitudinal seams of shell boilers (SBG2)





Foreword

A revised edition of the Associated Offices Technical Committee (AOTC) Guidance Booklet (GN3) was prepared by a working group comprising: representatives from the Safety Assessment Federation (SAFed), the Health and Safety Executive (HSE) and other interested parties.

This edition was revised in 2012 by SAFed to update references to standards and regulations where appropriate and to incorporate some changes made by SAFed since its initial publication.

The guidance addresses a particular aspect of boiler examination and is primarily aimed at those with duties under The Pressure Systems Safety Regulations (SI 2000 No. 128) - including owners, users and Competent Persons.

The procedures described in this document represent what is considered to be good practice and incorporate experience gained over many years in assessing defects at peaked longitudinal seams in shell boilers.

The Safety Assessment Federation - SAFed - represents the interests of companies engaged in independent inspection and safety assessment of engineering and manufacturing plant, systems and machinery.

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1 INTRODUCTION

These guidelines have been produced by SAFed to provide up-to-date information to users and Competent Persons on examination requirements for longitudinal seams of shell boilers. Previous guidance issued by the Associated Offices Technical Committee (AOTC) in 1988 has been updated to take account of developments in stress analysis of deviations from a true cylindrical shape, additional corrosion fatigue data, and the results of strain gauge measurements of boilers with peaked longitudinal seams. (The main changes from the previous document are listed below for reference purposes.)

MAIN CHANGES FROM AOTC DOCUMENT

- Various methods of measuring local peaking are included as an alternative to providing an accurate profile gauge for each size of boiler to be examined.
- To allow for various factors that have not been taken into account in this simplified procedure, a maximum period between ultrasonic tests of 5 years has been specified.
- The time taken to raise steam pressure from either hot or cold shutdown conditions can have a marked effect on corrosion fatigue crack growth rate. A minimum time to be taken when raising steam is therefore included. The use of firing rates that raise steam pressure faster than the time specified may require that the ultrasonic inspection interval be reduced.
- Where excessive peaking leads to a calculated peak stress in excess of 330 N/mm^2 it may be necessary to carry out strain gauge measurement of the longitudinal seam. Guidance is given on a suitable procedure for carrying out such measurement and an alternative fatigue design curve is included so that the safety factor for strain gauged boilers is similar to that of boilers with calculated stresses.
- Detailed guidance on the ultrasonic testing procedure and report content are included. Previously, a magnetic particle crack test has been used internally as an alternative to external ultrasonic testing, but experience has shown that this should only be used to supplement the ultrasonic test.

MAIN CHANGES IN THIS REVISION

- References to British and European Standards have been updated to reflect 2012 publications.
- References to The Pressure Systems and Transportable Gas Containers Regulations 1989 have been changed to Pressure Systems Safety Regulations (SI 2000 No. 128)
- SAFed Guidance PEC 6 and PEC 7 have been incorporated into this document.

When a written scheme of examination is produced in accordance with Regulation 8 of *The Pressure Systems Safety Regulations (SI 2000 No 128)* it should include any additional testing considered necessary. It is intended that these recommendations will assist Competent Persons drawing up or certifying written schemes for shell boilers.

2 BACKGROUND

Following the failure, in 1988, of two steam boilers, *Guidelines for Measurement of Peaking and Calculation of Ultrasonic Inspection Intervals (GN3)* was produced by a joint working group comprising representatives of the Associated Offices Technical Committee (AOTC), the Independent Engineering Insurers Committee (IEIC) and the Health and Safety Executive (HSE). This publication contained recommendations for the measurement of peaking at the longitudinal seam, the calculation of peak stress and a method of establishing suitable ultrasonic examination intervals. It also offered guidance on nondestructive testing (NDT) techniques to be used in the examination of longitudinal seams.

However, since the publication of GN3, experience has shown that a number of cracks discovered in the longitudinal seams of boilers cannot be explained merely by considering peak stresses or the corrosion fatigue data used for assessment. It is thought that cyclic conditions may be much more onerous than those previously assumed for assessment, and that certain other factors could also influence stresses in the area of longitudinal seams. Such concerns have been addressed in this re-evaluation of the guidance previously offered in GN3 in order that the risk of boiler cracking and subsequent explosions may be further reduced.

By 1998, approximately 10,000 steam boilers had been examined in the UK to establish the degree of peaking at longitudinal seams. These boilers had continued to be examined, using appropriate NDT techniques, at the intervals recommended in GN3. Such assessments had shown that a number of boilers had calculated stress levels exceeding those permitted in GN3 and more than 20 of these boilers had had their actual stress levels determined using a strain gauge measurement technique. (Comparisons between strain gauge results and calculated stresses are presented in Appendix I).

Testing had revealed a significant number of boilers with cracks at the longitudinal seams. Some of these boilers were repaired and others withdrawn from service. Had the cracks not been detected, these boilers could have failed with catastrophic results.

Moreover, in order to measure peaking on many thousands of boilers at diverse locations, the Inspection Organisations have developed additional methods of measurement. These produce successful results and are considered easier to use and more accurate than profile gauges. (Information on these methods is presented in Chapter 4.)

The guidance on preparation, ultrasonic examination and repair has been based on the collective experience of the Inspecting Organisations participating in the preparation of this document and is not intended to be definitive.

Since 1998 UK boiler manufacturers have addressed the issue of peaking at longitudinal seams of shell boilers and introduced manufacturing checks to ensure that code tolerances are not exceeded. This has led to a great reduction in incidences of cracked longitudinal seams but a small number have still occurred. It is important that the measurement, assessment and testing of the longitudinal seams of boilers is continued in future for the following reasons:

- The increasing numbers of shell boilers being imported from overseas where specific peaking checks may not be required.
- Variations in cyclic duty that may exceed those taken into account in the assessment.
- Deviations in shape and alignment in addition to peaking that can cause excessive peak stresses.

3 SCOPE

This guidance is specifically intended for horizontal multi-tubular shell-type boilers with the following characteristics:

operating pressure	> 2 bar g	***and***
nominal diameter	> 650 mm	***and***
operating temperature	> 134°C	***and***
membrane hoop stress*	≥ 39 N/mm^2	

*As calculated for σm_l

Vertical boilers are excluded due to size and geometry limitations, i.e. only a small proportion of the longitudinal seam is in the steam space. Pressurised and unpressurised hot water boilers are excluded due to their low pressure fluctuations and minimal water contamination as a result of operation in a fully flooded closed system.

4 INITIAL ASSESSMENT

Most existing boilers will have undergone peaking measurement prior to the publication of this document. Section 4.1 only applies to boilers with no record of peaking measurement, those where the accuracy of the peaking measurement is in doubt, or new boilers.

4.1 TIMING OF INITIAL PEAKING SURVEY AND ULTRASONIC TEST

The extent of any peaking should be determined at the following times and an ultrasonic test carried out at the same time.

4.1.1 For boilers constructed to BS 2790 or other standards where the peaking is measured during construction and is within BS 2790 tolerances.

For all boilers where the peaking has been measured during construction and confirmed to be equal to or less than the smaller of e/4+0.5mm or e/20+3mm (where e is the nominal shell thickness in mm) the initial peaking survey and ultrasonic test should be carried out before the boiler is 10 years old (See also 4.1.2 b).

4.1.2 For other boilers

a) In all other cases except b) below the initial peaking survey and ultrasonic test should be carried out before the boiler is 5 years old. (Where applicable this work can be carried out at the same time as the preparation and testing required for the shell and furnace to endplate seams).

b) If operating conditions are unduly severe with excessive cyclic operations or lack of control of water treatment consideration should be given to carrying out the initial peaking survey and ultrasonic test at an earlier period.

Note 1
An assessment of the ultrasonic inspection interval is required in SBG 2 to ensure that the 5 yearly ultrasonic test requirement is suitable for the actual operating conditions and measured peaking. In practice the assessment would only give a reduced interval for excessive cyclic operation with peaking in excess of BS 2790 requirements.

The maximum allowable peaking to BS 2790 can be used in this assessment for boilers manufactured to that standard prior to the actual peaking measurement being carried out. For boilers manufactured to BS EN 12953 the maximum permitted peaking is as follows:

Wall thickness e (mm)	Maximum permitted peaking (mm)
$e < 3$	1.5
$3 \leq e < 6$	2.5
$6 \leq e < 9$	3.0
$9 \leq e$	e/3

These figures can be used for an assessment for boilers manufactured to BS EN 12953.

4.2 METHOD OF PEAKING MEASUREMENT

There are various ways to measure peaking. Whichever is used, it is essential that measurements are taken accurately. Variations of ±1mm can lead to a significant variation in the calculated ultrasonic inspection interval(s).

Experience has shown that a **bridge gauge** offers a convenient way to measure peaking, either internally or externally, with acceptable accuracy. The position of maximum peaking can be determined simply by moving the gauge along the shell; the same gauge can be used for a wide range of boiler diameters. The limitations of a bridge gauge are that it does not measure or record the extent of any flats adjacent to the seam and that a correction factor for the weld width is required.

A **needle gauge** of suitable size has most of the benefits of a bridge gauge and also produces a record of the actual profile of the shell at the location of the longitudinal seam. It is, however, less easy to use than a bridge gauge and the need to draw out the profile and compare it with an arc of the correct diameter can lead to a loss of accuracy.

A **profile gauge** based on the diameter of the actual boiler shell may be used to measure peaking although care is necessary to ensure accuracy.

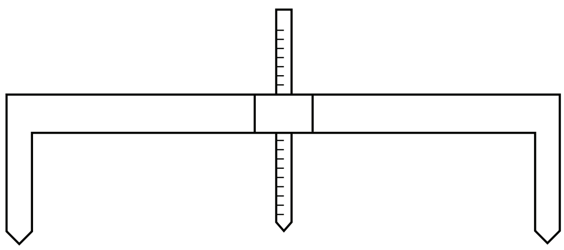
Plaster casts are one way of taking a permanent record of peaking but, in practice, they are difficult to use, cannot give multiple readings and offer no advantages over needle gauges.

4.2.1 Use of gauges

The location of the longitudinal seam(s) should be ascertained. This may require the removal of casings, insulation or smokebox covers. For external measurement, casings and insulation should be removed for the full length of the longitudinal seam(s) and for a width which will permit access with the gauge. Any scale or corrosion product should be removed from the internal or external surfaces adjacent to the seam(s) to be measured. Readings should be taken at 250mm intervals along the longitudinal seam(s) and a detailed survey carried out in the region(s) of maximum peaking.

4.2.2 Bridge gauge

Figure 1: Typical Bridge Gauge (the span of the gauge should be sufficient to clear any flats adjacent to the seam)

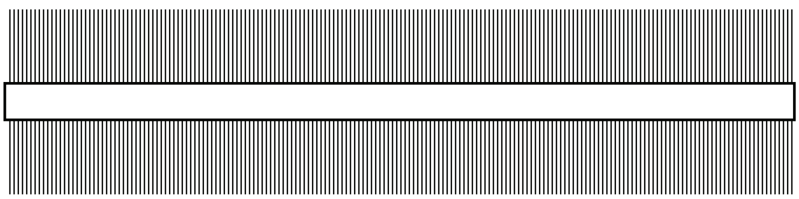


Whether the measurement is to be made internally or externally, the principle is simply to hold the gauge at right angles and perpendicular to the seam with the legs of the gauge in contact with the plate on either side of the seam. The graduated rule is then adjusted until the point is in contact with the shell at the edge of the seam (taking care to avoid any undercut or weld reinforcement). The measurement should then be repeated on the other edge of the seam and the maximum value used. To determine the amount of peaking, the reading from the gauge should be added to or subtracted from a reading taken on a flat surface. This can then be compared with the theoretical depth of curvature for an arc of the external diameter of the boiler and the span of the gauge (See Notes 2 and 3).

4.2.3 Needle gauge

Whether the measurement is to be made internally or externally, the principle is simply to hold the gauge at right angles and perpendicular to the seam. The gauge is then pressed against the surface straddling the weld until each of the needles is in contact with it. It should then be moved along the seam until the point with most peaking is determined. The profile can then be drawn on to a piece of paper and the height of the arc compared with the theoretical depth of curvature for an arc of the internal or external diameter of the boiler and the span of the gauge. (For large boilers it may be necessary to overlap profile measurements to ensure that 20° of the arc is gauged.) (See Notes 2 and 3).

Figure 2: Typical Needle Gauge (the span of the gauge should be sufficient to clear any flats adjacent to the seam and would normally be a minimum of 300mm)



Note 2

For both bridge and needle gauges: due to variations of shape around a boiler shell remote from the seam, comparisons with other parts of the boiler to determine the extent of peaking may lead to inaccuracies.

Note 3

The theoretical depth of curvature of an arc of a cylindrical shell (see Figure 3) can be calculated using the following formula:

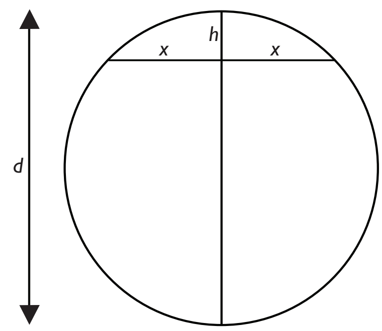
$$h(d - h) = x^2$$

or

$$h = \frac{d - \sqrt{d^2 - 4x^2}}{2}$$

Where:
h = depth of curvature
d = internal/external diameter of the shell
x = half the span of the gauge being used

Figure 3: Theoretical depth of curvature



4.2.4 Profile Gauge

To enable peaking to be measured externally a profile gauge should be made for each size of boiler to be examined. (Details of the gauge are presented in Figure 4). The minimum arc length should be 0.175 Do (20° of arc), where Do is the external diameter of the boiler. This diameter should be checked by measurement of the actual boiler shell.

However, for some boilers the calculated arc length may not extend beyond the flats. Because of this, the minimum arc length of the gauge should be sufficient to clear the flats. Where the gauge is prepared off-site the recommended width of the weld cut-out is 28mm (this may need to be increased on-site to ensure that the cutout is clear of the weld - see Figure 4a). It is necessary to note any cut-outs greater than 28mm so that a correction factor may be applied. When the approximate zone of maximum peaking has been found, maximum peaking should be determined by accurate measurement of L_1 and L_2 (see Figures 4b and 4c). Care should be taken to ensure that the gauge makes contact with the boiler shell at the points indicated in the notation to Figure 4. It may be beneficial to make a taper gauge, as shown in Figure 5 for checking L_1 and L_2.

Figure 4: Profile Gauge used for external measurement

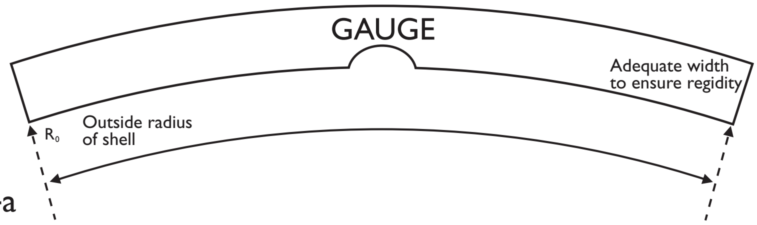


Figure 4a

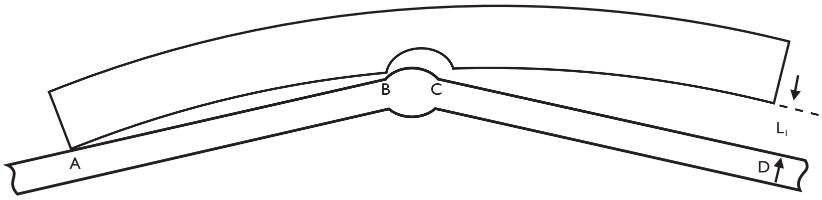


Figure 4b

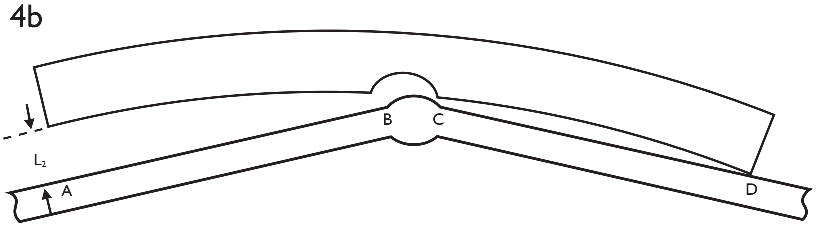


Figure 4c

Maximum Peaking = 0.25 (L_1 + L_2)

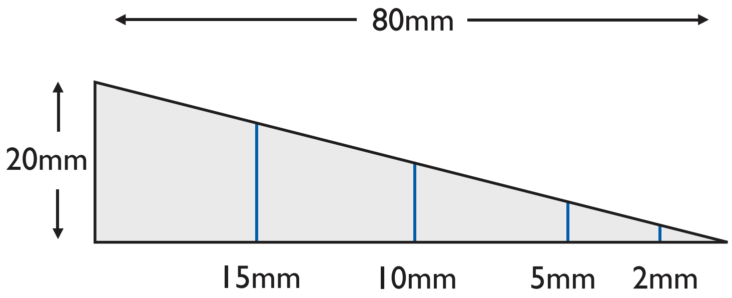
Notation for Figure 4

Figure 4b: the gauge should touch the shell at point A and as near as possible to point B

Figure 4c: the gauge should touch the shell at point D and as near as possible to point C

If there is a significant high spot between point A and B in Figure 4b or between points D and C in Figure 4c then this method may overestimate peaking and an alternative method of measurement should be used. Also note that points A and D must be clear of any flats.

Figure 5: Taper Gauge



4.2.5 Boiler details

When peaking is measured or an assessment is to be carried out, other factors in connection with the boiler operation need to be established and recorded to enable the interval between ultrasonic inspections to be determined. The following details should be recorded and retained with the examination reports:

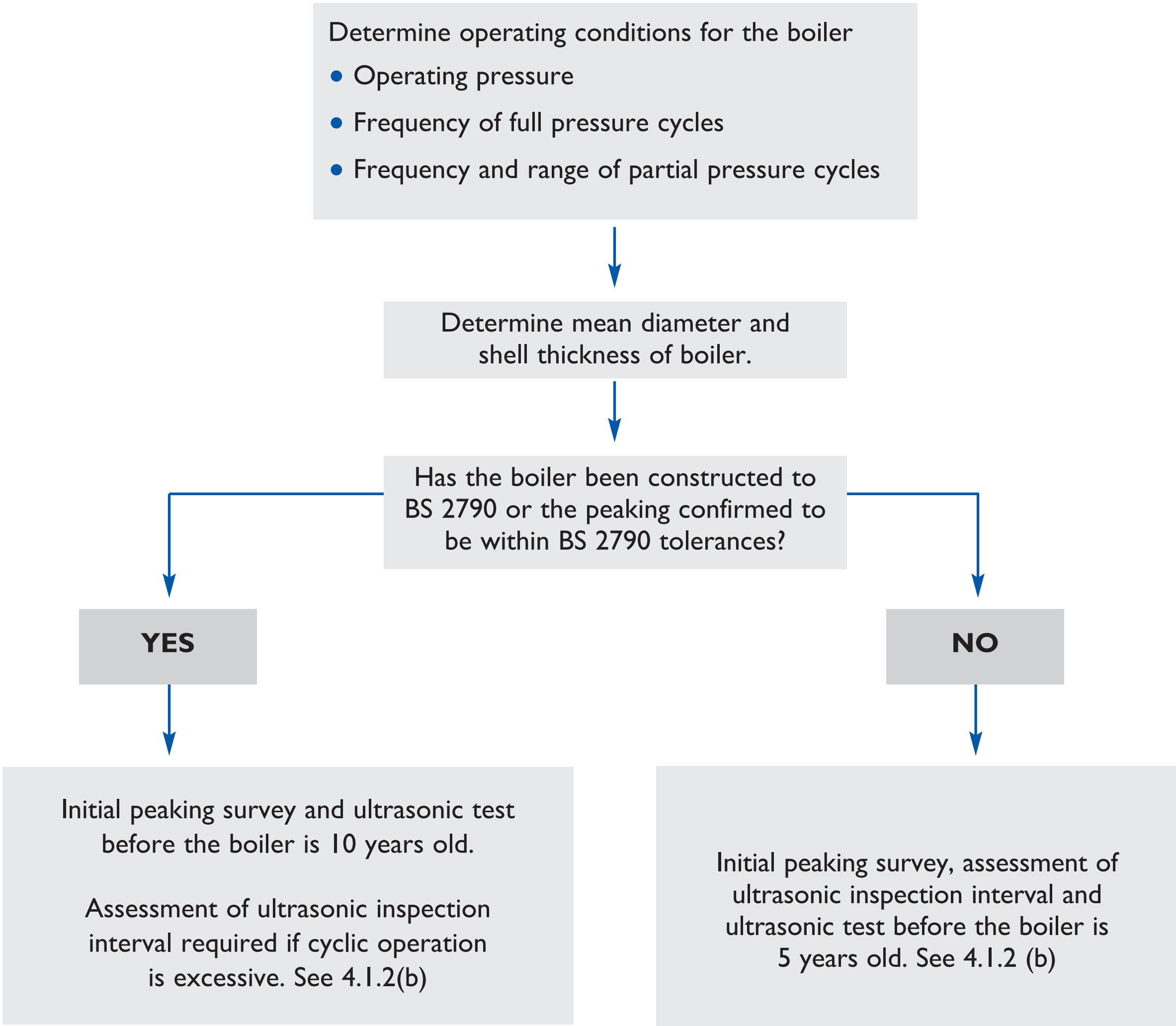
- boiler manufacturer, type and serial number
- date of manufacture
- outside diameter and minimum shell thickness
- design and normal operating pressures (see Note 4)
- maximum peaking measured
- location of maximum peaking on the longitudinal seam
- details of the gauge used to measure peaking
- number of full pressure cycles per day/week/year (see Note 5)
- number of partial pressure cycles per day/week/year and pressure range (see Note 5)
- effectiveness of water treatment, with special regard to oxygen treatment; any history of adverse experience
- any repairs, adverse operating conditions or past history of cracking
- any discernible internal corrosion/grooving of the shell at, or adjacent to, the longitudinal seam(s)
- the extent of internal examination carried out.

Note 4
It is essential that normal operating pressure be positively ascertained for use in the calculations. It should be confirmed with the user that this is typical of normal operation and that there are no regular excursions beyond this pressure.

Note 5
There is a wide variation in the cyclic operation of steam boilers depending on the duty of the boiler and its capacity in relation to steam demand. In many cases it may not be conservative to assume typical values for numbers of cycles and it will be necessary for the user to take positive steps to determine the number and range of pressure cycles. This can be achieved by reviewing chart recorder results for operation during representative periods or by recording pressure gauge variations.

Generally, partial pressure variations are considered significant when they are equal to or exceed 20% of the maximum operating pressure. Where there are many cycles between 10 and 20% of maximum operating pressure (i.e. $> 2 \times 10^5$ cycles per year) these may become significant.

Initial peaking survey and ultrasonic test



5 CALCULATION OF ULTRASONIC INSPECTION INTERVALS

The following calculation procedure is recommended; however, it does not preclude the Competent Person from making other assessments based on corrosion fatigue and fracture mechanics analyses.

5.1 DEFINITIONS

$\sigma m_{1,2}$	=	membrane hoop stress (N/mm^2)
$\sigma \rho_{1,2}$	=	peak stress (N/mm^2)
$Kt_{1,2}$	=	Stress Concentration Factor (SCF) due to peaking
D	=	mean diameter of boiler (mm)
δ	=	inward or outward peaking determined in accordance with Section 5.2, (mm)
t	=	boiler shell thickness (mm) (Note: use the minimum measured shell thickness)
P_1	=	normal operating pressure range (N/mm^2) (See Note 6)
P_2	=	partial pressure range (N/mm^2) (See Note 7)
N_1	=	allowable number of fatigue cycles due to pressure range P_1
N_2	=	allowable number of fatigue cycles due to pressure range P_2
$C_{1,2}$	=	pressure cycles
Subscripts 1 and 2 refer to P_1 and P_2 respectively		

Note 6
This pressure range is zero to normal operating pressure; i.e. for P_1, use the pressure at which the automatic pressure control cuts out the burner. If the normal pressure range is not known, use the safety valve set pressure.

Note 7
The partial pressure range is the difference between the pressure at which the automatic pressure control cuts the burner in and out.

5.2 PEAKING

When an appropriate-length needle gauge or a plaster cast has been used to measure peaking, then the effective value of peaking (δ) can be measured directly from the trace without applying a correction factor. When peaking has been measured using a 20° gauge or bridge gauge, the effective peaking (δ) should be the **maximum** value from (a) or (b) below.

(a)	δ	=	measured peaking + 1mm
or			
(b)	δ	=	measured peaking + 10% of measured peaking

The 1mm or 10% correction is to allow for the effect of the weld width and gauge cut out. Where the gauge cut out for the weld is greater than 30mm, use the graph in Figure 7 (page 19) to determine the effective peaking δ. A correction factor for the boiler diameter can be determined from Figure 6 but in practice this has little effect.

5.3 MEMBRANE HOOP STRESS

Calculate the membrane hoop stress as follows:

$$\sigma m_1 = \frac{P_1 D}{2t}$$

$$\sigma m_2 = \frac{P_2 D}{2t}$$

5.4 CALCULATION OF THE STRESS CONCENTRATION FACTOR (Kt_1)

Calculate the value of β_1 as follows:

$$\beta_1 = 0.0075\sqrt{\frac{D\delta\sigma m_1}{t^2}}$$

Determine $\tanh(\beta_1)/\beta_1$ either by calculation or using Figure 8. The stress concentration factor (Kt_1) may then be calculated as follows:

$$Kt_1 = 1 + \frac{6\delta}{t}\,\frac{\tanh(\beta_1)}{\beta_1}$$ **but not less than 2.5**

5.5 CALCULATION OF THE PEAK STRESS FOR P_1

Calculate peak stress due to the pressure range P_1 as follows:

$$\sigma\rho_1 = Kt_1\,\sigma m_1$$

If the pressure range P_2 is less than 20% of P_1 then ignore sections 5.6 and 5.7 below. If $\sigma\rho_1$ is greater than 330N/mm^2 see Section 5.11.

5.6 CALCULATION OF THE STRESS CONCENTRATION FACTOR (Kt_2)

Calculate the value of β_2 as follows:

$$\beta_2 = 0.0075\sqrt{\frac{D\delta\sigma m_2}{t^2}}$$

Determine tanh $(\beta_2)/\beta_2$ either by calculation or using Figure 8. The stress concentration factor (Kt_2) may then be calculated as follows:

$$Kt_2 = 1 + \frac{6\delta}{t}\,\frac{\tanh(\beta_2)}{\beta_2}$$ **but not less than 2.5**

5.7 CALCULATION OF PEAK STRESS FOR P_2

Calculate the peak stress due to the pressure range P_2 as follows:

$$\sigma\rho_2 = Kt_2\,\sigma m_2$$

If $\sigma\rho_2$ is greater than 330 N/mm$_2$, see Section 5.11.

5.8 CALCULATION OF FATIGUE LIFE (N)

5.8.1 For the stress value $\sigma\rho_1$ use the assessment line in Figure 9a (page 21) or the formula given for N to determine the allowable number of fatigue cycles N_1.

5.8.2 For the stress value $\sigma\rho_2$ use the assessment line in Figure 9a or the formula given for N to determine the allowable number of fatigue cycles N_2.

5.8.3 Where the actual number of fatigues cycles per year is known, the values of C_1 and C_2 should be specified as follows:

C_1 = number of pressure cycles per year with full pressure range P_1

C_2 = number of pressure cycles per year with partial pressure range P_2 (if P_2 is less than 20% of P_1 then set $C_2 = 0$)

If the actual value of C_1 and C_2 are not known, the experience of the Competent Person assessing the results should be used to estimate values; however, the following typical values may be used:

C_1 = 365 (i.e. 1 full pressure cycle per day)

C_2 = 17500 (i.e. 2 partial pressure cycles per hour throughout the year or 6 partial pressure cycles per hour over an 8-hour day)

or

C_1 = 52 (i.e. 1 full pressure cycle per week)

C_2 = 50000 (i.e. 6 partial pressure cycles per hour throughout the year)

5.9 CALCULATION OF ULTRASONIC INSPECTION INTERVAL

The inspection interval should be the minimum value from (i) or (ii) below.

(i) Inspection interval in years = $\dfrac{1}{\dfrac{C_1}{N_1} + \dfrac{C_2}{N_2}}$

or

(ii) 5 years

Note 8

Worked examples of the above procedure (5.1 - 5.9) are presented in Appendix II.

5.10 ADDITIONAL REQUIREMENTS

If the boiler is operated so that full pressure is reached from zero in less than 2000 seconds (approximately 30 minutes) or sudden changes in load occur, then the assessment line in Figure 9b (page 22) should be used.

5.11 CALCULATED PEAK STRESSES IN EXCESS OF 330 N/mm^2

Boilers with calculated peak stress greater than 330 N/mm^2 are outside the scope of this assessment procedure. If the peak stress is greater than 330 N/mm^2 then the threshold stress intensity factor of 25 MPa$\sqrt{m}$ could be exceeded for a surface defect 1.5mm deep. This factor forms the basis of the assessment curve in Figure 9a and is dependent on the cyclic loading rate (see also 5.10).

Where the frequency of examination using this procedure is not considered acceptable or the peak stress exceeds 330 N/mm^2, one or more of the following options should be considered:-

- Reduce boiler operating pressure to reduce peak stress to below 330 N/mm^2.
- Determine the stresses more accurately using strain gauges, and use the assessment line in Figure 9b (substituting the appropriate values in Sections 5.8 and 5.9; see also Appendix III).
- Where internal access is possible carry out both: 100% Magnetic Particle Inspection (MPI) of the longitudinal weld from the internal surface after it has first been ground flush and 100% ultrasonic examination of the longitudinal weld from the outer surface. (These NDT inspections should be undertaken annually.)
- Repair the peaking by removing a section of shell from the boiler and welding a new section in place (see Section 6).

5.12 REPORTING

Following assessment of the boiler for ultrasonic inspection intervals it is recommended that the following statement should be included in the report:

The ultrasonic examination of the longitudinal seam(s) on.......................... [date] revealed no discernible defects. Based on the operating conditions shown below being maintained, a further ultrasonic examination of the seam(s) should be carried out on or before ....[date].

Operating conditions:

- boiler operating pressure range 0 -
- partial pressure range
- full pressure cycles per year
- partial pressure cycles per year

Should the operating conditions change, a reassessment will be required.

Should a future reassessment be required following, for example, a change of operating regime or ownership it is useful to have additional information recorded on the boiler examination report. It is recommended that the following information should be included:

- Shell outside diameter
- Shell thickness
- Peaking (δ)

Figure 6: Correction factor for boiler diameter.

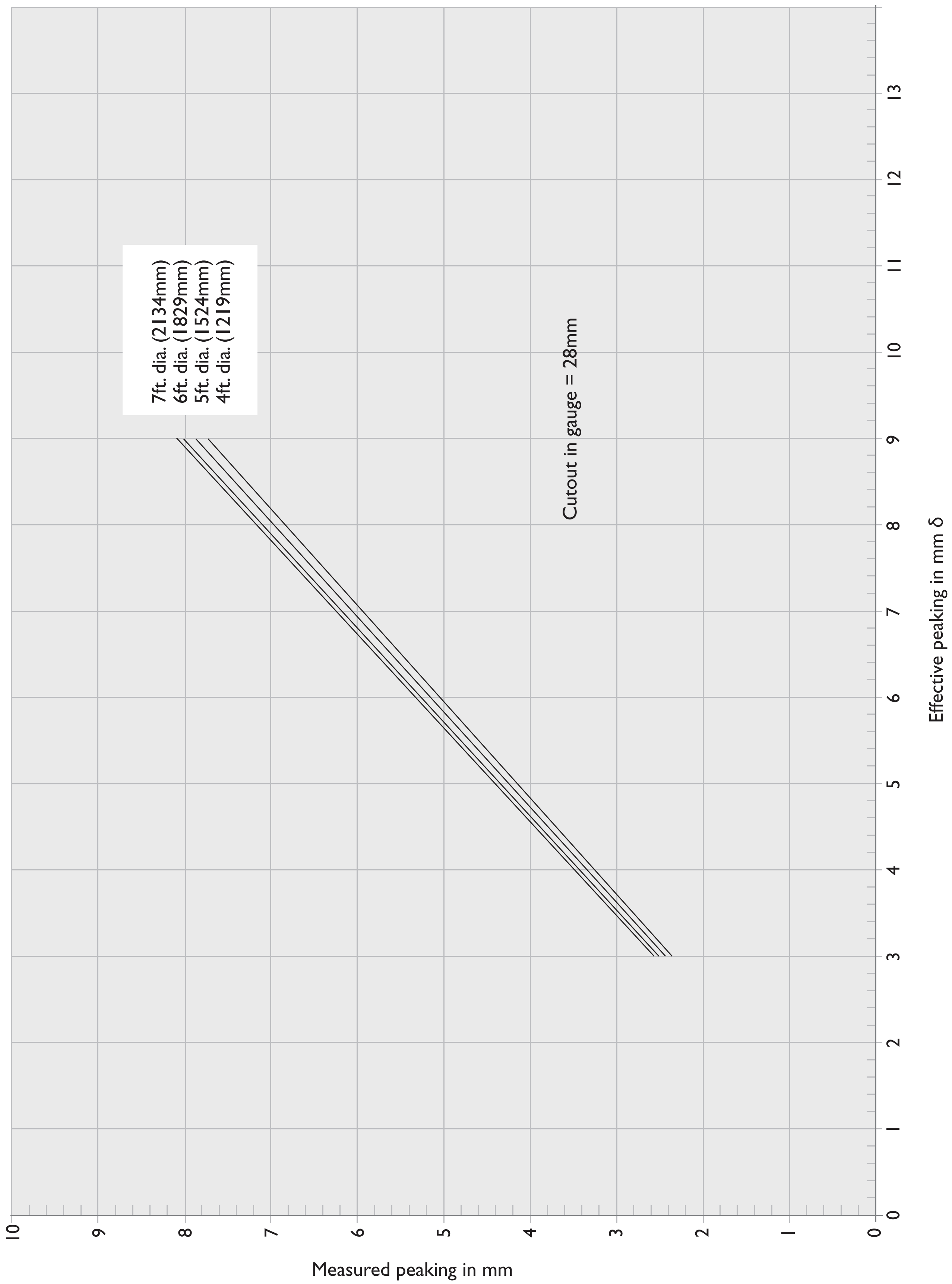


Figure 7: Effect of gauge cut-out on peaking measurement.

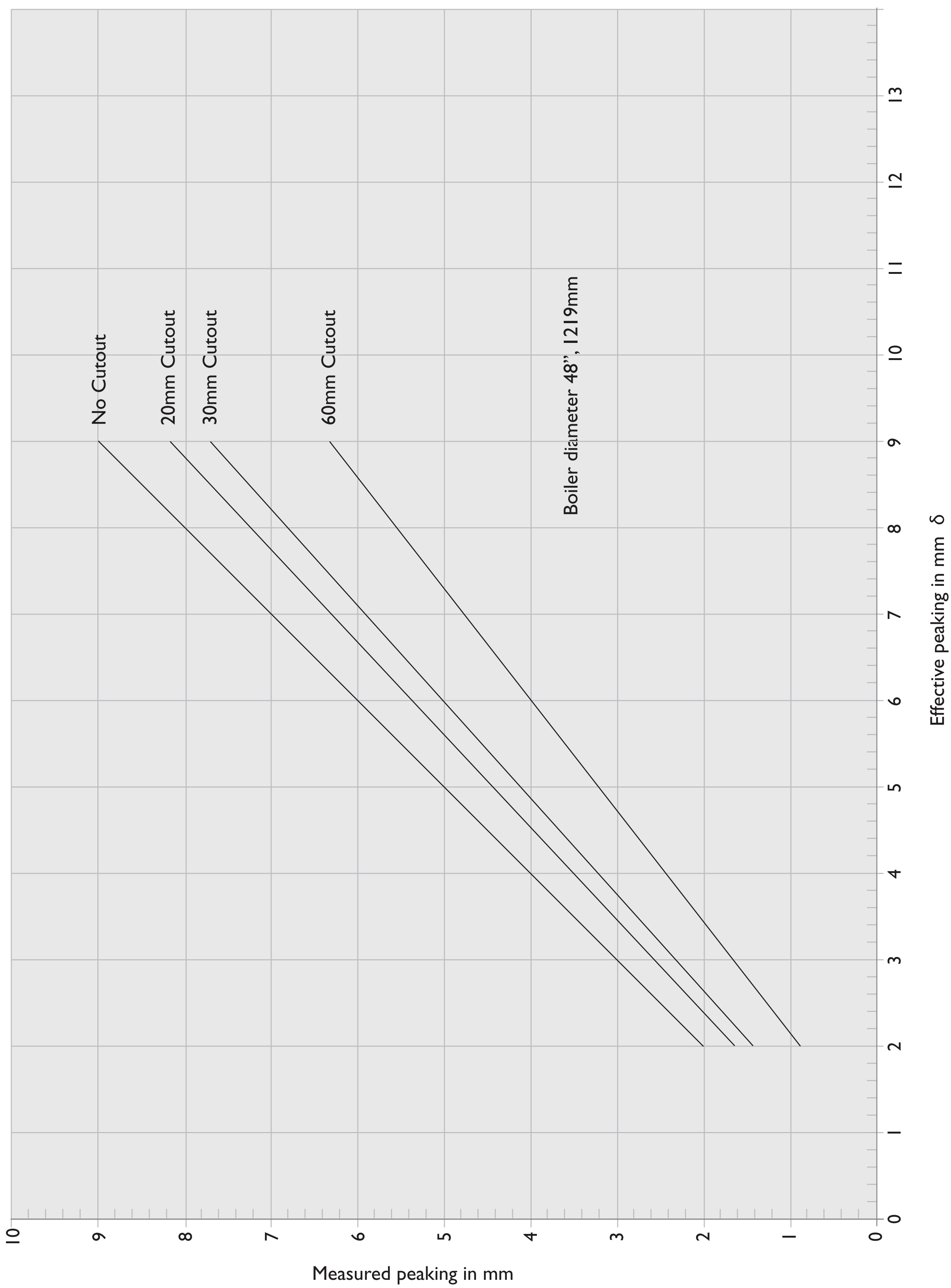


Figure 8: Tanh β/β curve

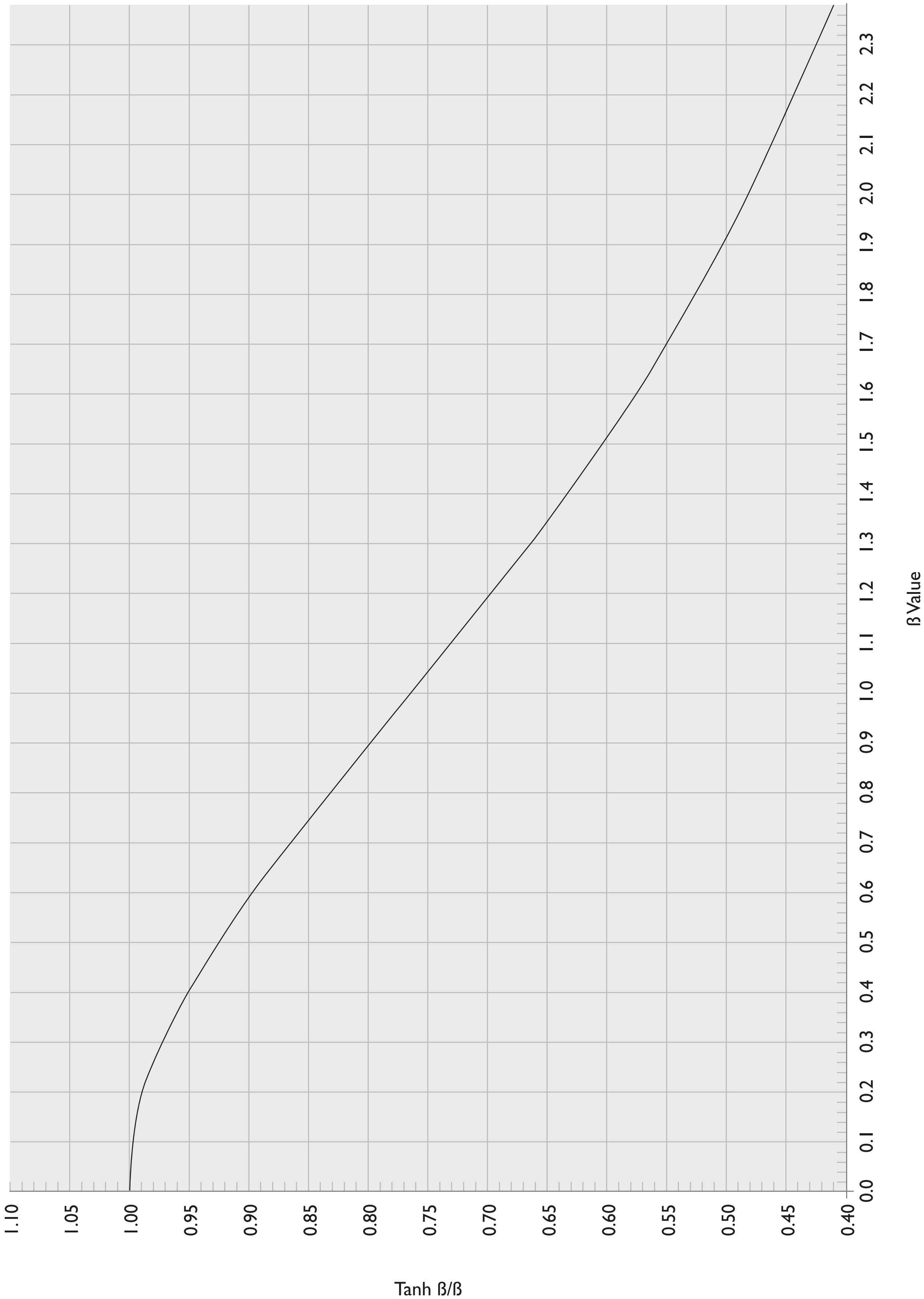


Figure 9a: Fatigue design curve

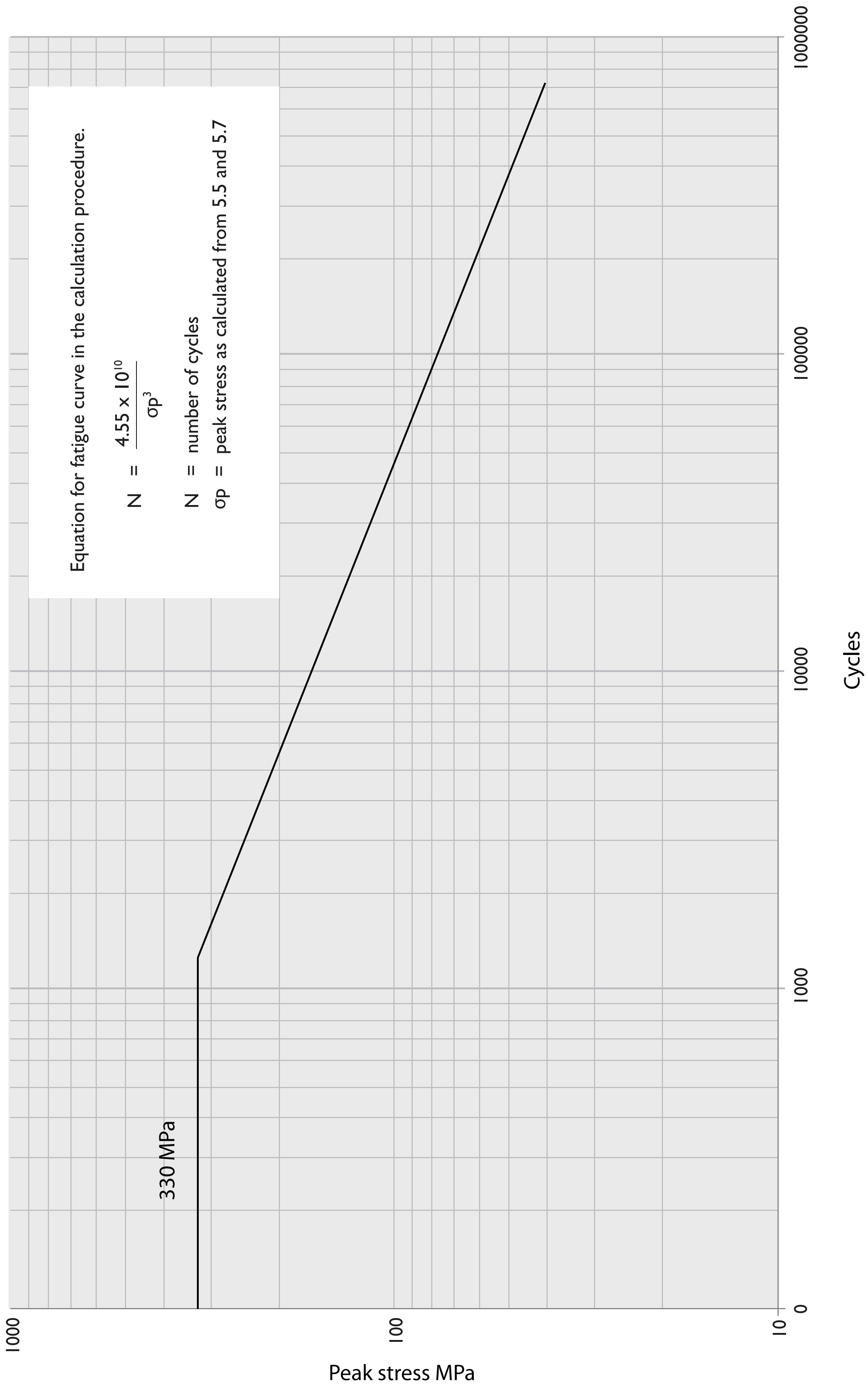
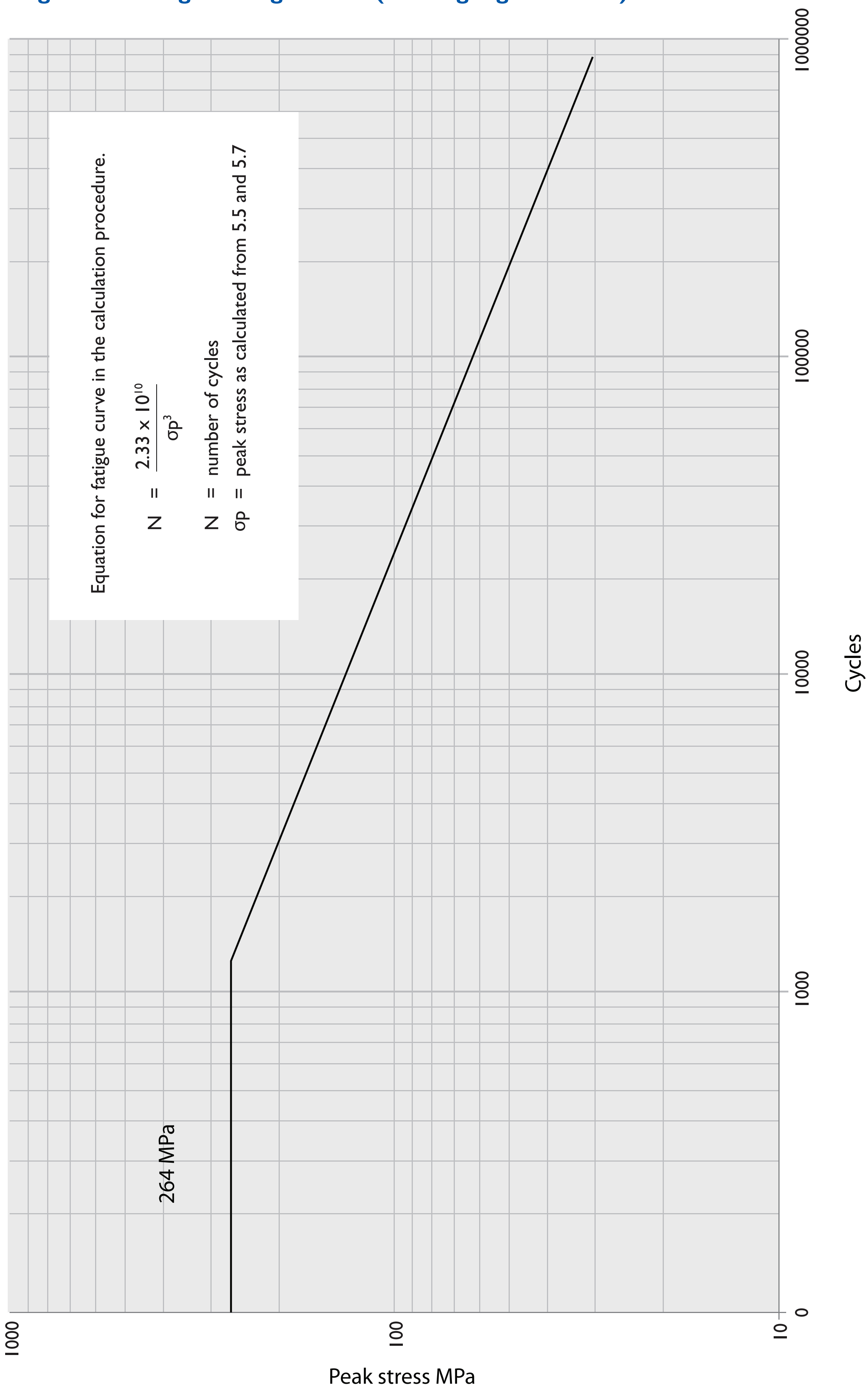


Figure 9b: Fatigue design curve (strain gauged boilers)



6 REPAIRS

6.1 GENERAL

All repairs, including subsequent NDT, should be carried out to the requirements of the Competent Person certifying the boiler. Workmanship and materials, inspection and testing should be to a standard at least equivalent to the original code of construction. For further information on repairs see SAfed Guidance PSG 15, 'Repairs or modifications to pressure systems'.

Departures from design code requirements may be necessary because of:

- the construction of the boiler and/or
- the nature of the repair

e.g. lack of access for double-sided welds or impracticability of local stress relief.

In such cases deviations should be agreed by the Competent Person and any additional testing to ensure integrity should be specified.

6.2 WELDING

Welder performance and welding procedure qualifications should be certified, to a recognised standard, as satisfactory for the type of weld concerned; appropriate standards include:

- BS EN 287 Part 1
- BS EN ISO 15614-1
- ASME IX.

Further information on welded repairs is provided in SAFed document PSG 15.

6.3 PREFERRED TYPES OF REPAIR

The preferred type of repair for a peaked boiler shell is to remove the section containing the peaked longitudinal seam and to weld a new section in place. Care should be taken that the removed section is of sufficient width to ensure that all flats and local departures from circularity beyond code requirements are removed. The completed boiler shell with the replacement section should meet all code requirements for local departure from circularity and peaking and a reassessment of future ultrasonic inspection intervals should be carried out in accordance with Section 5.

Note
In practice it has been found a very difficult to achieve code tolerances for local departure from circularity and peaking when welding a replacement patch in place of the existing longitudinal seams.

7 NON-DESTRUCTIVE TESTING

7.1 PREPARATION

The owner/user should prepare the boiler for examination in advance of the attendance of the NDT operator/technician.

7.1.1 Areas to be prepared

The full length of shell longitudinal seam(s) require to be tested from the outside surface(s). This necessitates the removal of parts of the external cladding and insulation to expose seams and adjacent areas of the shell plate.

On small boilers the shell may be fabricated from one plate with only one longitudinal seam, usually (but not always) located at the 10 o'clock or 2 o'clock position when looking at the end of the boiler. Larger boilers are usually fabricated from two (or more) plates in which case the seams are staggered and are usually at the 11 o'clock and 1 o'clock positions.

The seam position can usually be located visually from inside the boiler; alternatively it can be located by examining the end of the shell or removing a small area of insulation in the areas where the seam is thought to be.

7.1.2 Cleaning

The weld surfaces, together with the adjacent plate material, should be exposed and cleaned to bare metal with a surface finish of 3.2 µm Ra or better for a minimum of 250mm either side of the seam; this is best achieved using a sanding-type flapper disc. (If any attachments are welded to the shell within this area these welds should also be cleaned.) In cases where there has been excessive corrosion, a light surface grinding may be necessary but care should be taken to remove as little of the parent material as possible. **Chipping hammers and needle guns should not be used.**

Clients/owners should ensure that adequate safe access and lighting is provided to the area in question and that all applicable legal requirements, eg The Health and Safety at Work Act 1974 and current Asbestos Regulations, are adhered to.

7.1.3 Special Requirements

In certain circumstances the Competent Person may require magnetic particle surface crack-detection tests to be carried out (to comply with para. 5.11). In this case, additional preparation by grinding may be required.

7.2 RESPONSIBILITY FOR NDT TESTING

Non-destructive tests covered in this document will normally be carried out as part of an examination under The Pressure Systems Safety Regulations (SI 2000 No 128). These Regulations place duties on Competent Persons and require them to ensure that proper procedures and precautions are followed -even when some aspects of the work are carried out by other organisations.

In many instances the tests will be undertaken by a Competent Person with the necessary experience and expertise to perform them; in cases where the NDT is carried out by another organisation, the Competent Person will be responsible for determining the acceptability of:

- the NDT organisation and the operator contracted to do the work
- the procedure employed
- the reports produced
- the results

The recommendations outlined in the following sections are designed to assist the Competent Person in making the above decisions and are regarded as the minimum criteria for such examinations.

7.3 NDT ORGANISATION

Suitable organisations would hold a recognised quality accreditation eg UKAS accreditation to BS EN ISO 17020 and/or a recognised quality certification eg to BS EN ISO 9001.

7.4 NDT OPERATORS

Suitability of operators would be indicated by:

7.4.1 Qualifications

Appropriate level II qualifications eg PCN or ASNT with full supporting Documentation.

7.4.2 Training

Documented evidence of training in non-destructive testing and the detection of in-service defects in shell boilers.

7.4.3 Experience

Documented evidence of carrying out successful non-destructive testing of shell boilers under the supervision of a fully qualified and experienced level II operator who has previously met these requirements.

7.4.4 Certification

A current SAFed/BINDT qualification for NDT of shell boilers ensures that the above requirements are met and should satisfy the Competent Person's obligations to ensure that proper procedures and precautions are followed.

7.5 PROCEDURE

Testing should be carried out in accordance with formal controlled documentation specific to the boiler(s) to be examined; these documents should be produced by a level III qualified person who meets the training and experience guidelines in 7.4.2 and 7.4.3 above.

7.6 NDT CARRIED OUT BY ORGANISATIONS OTHER THAN THE COMPETENT PERSON

Where an organisation other than the Competent Person is carrying out the tests, it is the owner's/user's responsibility to provide to the Competent Person the documentation in support of Sections 7.3, 7.4 and 7.5. This documentation should be supplied at least two weeks prior to the examination and should include:

- the name(s) of the operator(s) who will be performing the tests
- copies of the SAFed/BINDT qualifications

The Competent Person should review the documentation against the recommended guidelines and may also require to witness/audit the tests as they are performed; in such cases, NDT testing should be arranged to coincide with the Competent Person's visit.

7.7 REPORTS OF ULTRASONIC TESTS

On completion of the ultrasonic tests a full written report should be submitted which should comprise as a minimum:

a) Full boiler details including:

- boiler manufacturer
- date of manufacture
- serial number
- shell diameter
- shell thickness

b) Areas of longitudinal seam tested including:

- details of any areas not tested and the reasons why
- type of tests carried out
- surface from which the tests were carried out

c) Identification of test procedure

d) Identity and certification status of ultrasonic operator

e) Date of test

f) Type and serial number of flaw detector used

g) Details of probes used including:

- make
- type
- frequency
- serial number

h) Calibration blocks used

i) Test sensitivity
This should be related to a common reference eg 3mm DAC to BS 3923 Appendix K

j) Report of parent metal examination

k) Details of any cracks detected or a statement that no cracks were detected.

7.8 Reports of Magnetic Particle Inspection (MPI) (where applicable)

On completion of the MPI a full written report should be submitted which should comprise as a minimum:

a) Full boiler details including:

- boiler manufacturer
- date of manufacture
- serial number
- shell diameter
- shell thickness

b) Areas of longitudinal seam tested including:

- details of any areas not tested and the reasons why

c) Identification of test procedure/technique sheets used

d) Identity and certification status of MPI operator

e) Date of test

f) Full details of equipment used, including serial numbers

g) Details of all consumables used, including make and reference

h) Viewing conditions

i) Method of flux generation

j) AC/DC/half wave rectified etc as applicable

k) Amps applied where relevant

1) Spacing of magnet poles/prods as applicable

m) Details of any defects located, including their position n relation to an easily identified datum.

7.9 NDT METHODS

Checks for cracking originating from the toes of the shell longitudinal seam welds at the inside surface should be carried out using ultrasonic methods from the outside surface of the shell. MPI from the inside surface is not an acceptable alternative.

Where negative peaking has been identified an MPI should also be carried out on the external surface to check for external cracking.

REFERENCES

1 BS 2790, *Specification for design and manufacture of shell boilers of welded construction*. British Standards Institution, London.

2 PD 5500, *Unfired Fusion Welded Pressure Vessels*. British Standards Institution, London.

3 BS EN 287-1, *Qualification test of welders - fusion welding*. British Standards Institution, London.

4 BS EN ISO 15614-1, *Specification and qualification of welding procedures for metallic materials*. British Standards Institution, London.

5 BS EN 1714, *Non destructive testing of welded joints*. *Ultrasonic testing of welded joints*. British Standards Institution, London.

6 BS EN ISO 9001, *Quality Systems, Model for quality assurance in design,development. production, installation and servicing*. British Standards Institution, London.

7 *TWI report* 279/1985, Dr S J Maddox.

8 Prater and Coffin, *Crack growth studies on a carbon steel in oxygenated high pressure water at elevated temperatures*. NUREG/CP-0044 1983.

9 *Safety of pressure systems, pressure systems safety regulations* (SI 2000 No 128). Health and Safety Commission Approved Code of Practice L122, HSE books

10 T P O'Donnell and W J O'Donnell, *Cyclic rate-dependant fatigue life in reactor water.* Pressure Vessels and Piping Vol. 306. ASME 1995.

11 Makoto Higuchi and Kunihiro Iida, *Effects of strength and sulfur content on fatigue strength of carbon steel weldments in oxygenated high temperature water.* International Conference on Pressure Vessel Technology, Vol. 1. ASME 1996.

12 J L Zeman, *On the problem of angular misalignment of longitudinal weld joints of cylindrical shells*. International Journal of Pressure Vessels and Piping. Vol. 58 1994.

13 N Bock and J L Zeman, *On bending stresses at longitudinal weld joints of cylindrical shells due to peaking*. International Journal of Pressure Vessels and Piping. Vol. 60 1994.

14 Norton, White and Hawkins, F*inite element stress analysis on peaked shell boilers.* preliminary report. Health and Safety Laboratories 1997.

BIBLIOGRAPHY

American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section IX, *Welding and brazing qualifications,* ASME, New York, USA.

American Society for Non-Destructive Testing, *Recommended practice SNT-TC-1A, Personnel Qualification in NDE,* ASNT, Columbus, Ohio, USA.

BS EN ISO 9934-1, Non destructive testing. *Magnetic particle testing*. General principles, British Standards Institution, London.

L S Ong and K H Hoon, *Bending stresses at longitudinal weld joints of pressurised cylindrical shells due to angular distortion.* Journal of Pressure Vessel Technology. Vol. 118 August 1996.

Personnel certification in non-destructive testing, PCN GEN 92. PCN, Northampton, 1992.

D A Savage, *Peaking in shell type steam boilers*. Engineering Council Examination Project Report.

A S Tooth and O Lin-Seng, *The derivation of the stresses in a pressurised pipe or cylindrical vessel with initial geometric imperfections*.

APPENDIX I: DISCUSSION

From the information available regarding two explosions of shell-type steam boilers in 1988 and cracking of a longitudinal seam recorded in 1982, it was determined that the failure was due to a corrosion fatigue mechanism resulting from a combination of several factors:

- corrosive environment due mainly to the ingress of oxygen during the daily shutdown of the boiler
- cyclic operation of the boiler with significant pressure fluctuations
- high stress at the toe of the weld of the longitudinal seam (the working group's brief restricted its consideration to stress concentration due to peaking).

The first two conditions may be common to a considerable number of shell boilers. Hence if peaking of the longitudinal seam (or the presence of any other stress raiser) of a shell boiler is found, a more detailed investigation into the operating conditions of the boiler is recommended. High-oxygen conditions can also result from incorrect water treatment; this means that even boilers that are depressurised infrequently should be assessed.

In order to evaluate an appropriate interval between ultrasonic examinations it was necessary to develop a simplified calculation procedure to estimate the stresses local to the weld seams for use in corrosion fatigue analysis. The first step in this procedure involves measurement of peaking. Various alternative methods of measurement are detailed in Section 4 of this document.

The calculation procedure is presented in Section 5 and has been formulated to cover conditions considered likely to occur in shell boilers. It has been assumed that oxygen-saturated conditions could occur for periods after a shutdown, resulting in greater potential crack growth rates as a result of this more aggressive corrosion fatigue environment.

Due to the limitations of the ultrasonic examination techniques available, it is possible that small defects could escape detection and therefore, even where the ultrasonic examination gives no indications, the fatigue analysis assumes that a long defect, 1.5mm deep, exists at the water side surface at the toe of the weld. In calculating the stresses at the seam a simplified formula has been used - this has been compared with finite element calculations and strain gauge results carried out by working group members. (A graph of calculated stress and strain results is presented in Figure 10).

In comparison with the strain gauge results the simplified formula tends to overestimate the stresses, as shown in Figure 10. However, as there are other factors that can affect peaking stress (eg weld profile, orientation of the weld to any ovality, misalignment of the plates, etc) this margin of safety was considered to be acceptable.

The formula given for the stress concentration factor (SCF) Kt was taken from Welding Institute Research Report 279/1985 by Dr S J Maddox (Ref. 7). However, a minimum value of a stress concentration factor of 2.5 was introduced to take account of situations where there is little peaking and the stress at the weld seam could be due to a combination of ovality, plate misalignment or weld profile, and to cater for the possibility of other factors affecting stress at the weld (eg attachments and nozzles local to the seam).

Various methods of analysis were evaluated to derive the fatigue curves. In particular, the time-based corrosion fatigue method currently being evaluated by the American Society of Mechanical Engineers (ASME) for inclusion in future editions of the ASME Codes was considered. This gives crack growth rates lower than those finally selected where the stress was below 330 N/mm^2. However, the information used to develop this procedure came mainly from the nuclear industry and most of the data related to water conditions with low oxygen concentrations.

Some limited test data for corrosion fatigue for steel grade SA333 Grade 6 in air saturated water at 288°C from Prater and Coffin (Ref. 8) were also considered.

As a result of the review of this work, it was considered that the most likely stress intensity factor for the onset of environmentally assisted cracking (at slow strain rates) was 25 MPa√m. For a limiting value of stress intensity of 25 MPa√m at the onset of environmentally assisted cracking, the time-based method essentially results in a cut-off at 330 Nmm^2 in peak stress based on an assumed initial defect 1.5mm deep.

At the same time, the working group investigated the effects of the rate of application of stress. This review indicated that, where pressure is raised quickly, this would have an adverse effect on crack growth rates. In particular, Cyclic Rate Dependent Fatigue Life in Reactor Water by T O'Donnell and W O'Donnell, PVP Volume 306 (Ref. 10), indicates that where the rise time is less than 30 minutes this would reduce the threshold stress intensity to approximately 20 MPa√m (thus reducing the allowable maximum peak stress to approximately 264 N/mm^2 based on a 1.5mm-deep crack).

The working group also considered research presented by Makoto Higuchi and Kunihiro Iida, Effects of Strength and Sulfur Content on Fatigue Strength of Carbon Steel Weldments in Oxygenated High Temperature Water (Ref. 11) which considered corrosion fatigue in oxygenated water. However, this only applies to test samples without initial defects and does not consider crack growth rates from a pre-cracked specimen.

Conventional corrosion fatigue methods were also reviewed but there appeared to be little specific data for this type of environment. Corrosion fatigue data in sea water was found to be more conservative than the time-based method for stresses up to 330 N/mm^2. This was not, however, adopted as it was not considered appropriate for a shell boiler environment.

A fatigue curve based on BS 5500 (Enquiry case 5500/79 - Assessment of Vessels Subjected to Fatigue; Alternative Approach to Method in Appendix C) for a Class-E butt weld with the reinforcement left on and with the design life reduced by a factor of 20, was eventually adopted to take account of the assumed initial defect and the environmental conditions. This curve produced results comparable with the sea-water corrosion fatigue data and which was more conservative than the time-based method for stress levels up to 330 N/mm^2. This additional conservatism was felt to be appropriate in view of the consequences of failure. The method also had the added advantage of simplicity.

However, when reviewing the failures reported following the publication and use of the original AOTC Guidance Booklet GN3, it was noted that there had been a number of failures that had not been predicted by the method utilised therein. In view of this, it was felt that it was appropriate to introduce a 5-year maximum inspection interval to guard against the unexpected development of cracks.

In the method adopted in this document it should be noted that there is a maximum stress of 330 N/mm^2. This maximum stress level is based on an assumed surface defect 1.5mm deep (which has failed to be detected by ultrasonic examination) and a calculated stress intensity of 25 MPa√m. From examination of the limited corrosion fatigue data available for oxygen-saturated water it has been concluded that, above this threshold stress intensity, there could be a rapid increase in crack growth rate. Hence operation in these instances can only be accepted under controlled conditions. The simple fatigue formula contained in this document should not be used above this stress limit.

Assumptions made in the calculation procedure may be summarised as follows:

- oxygen-saturated conditions may exist within the boiler for a short period of time after shutdown
- a 1.5mm-deep infinitely long crack at the inside surface could fail to be detected by ultrasonic examination
- the lower-bound fracture toughness would be 120 MPa√m (at normal operating temperature)
- a threshold stress intensity of 25 MPa√m for the onset of environmentally assisted cracking
- the time to raise steam will exceed 30 minutes.

Where boilers are found with peak stress levels exceeding 330 N/mm^2, rapid corrosion fatigue is possible and one of the alternatives presented in Section 5.11 should be implemented to monitor the operation of the boiler.

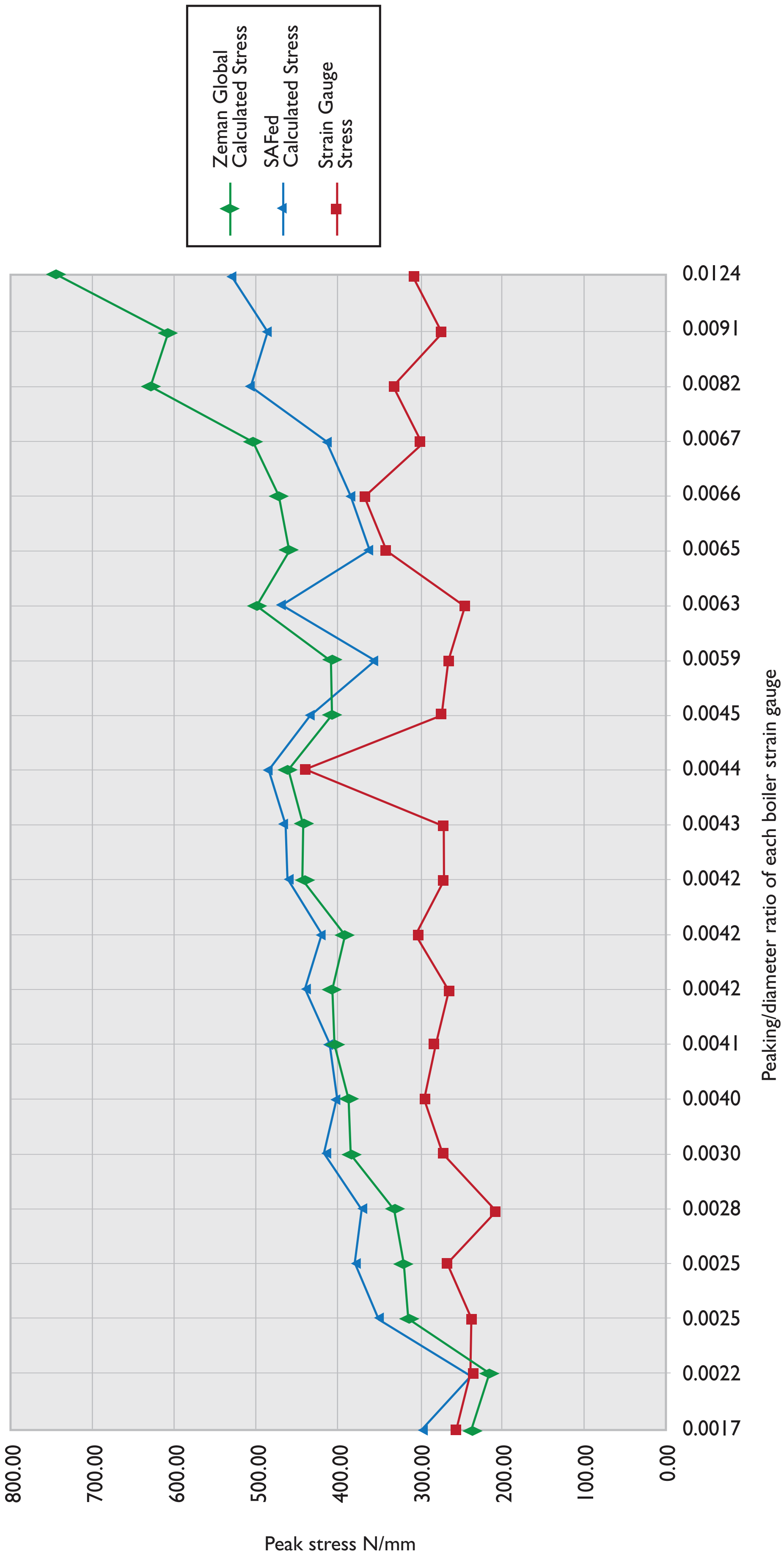
Research by Professor Zeman (Refs 12 and 13) was also reviewed by the working group. It suggests that stresses of up to 200% of those calculated by the peaking formula in Section 5 may be present in boilers with peaking at the longitudinal seam. This is where global peaking due to residual bending moments at the longitudinal seam from the welding process is present as opposed to local peaking due to plate-rolling imperfections.

It is not practical to measure global peaking on an existing boiler because of the internal tubes and furnace(s), and to assume that all measured peaking on a boiler shell is of a global nature would lead to calculated stresses in excess of 330 N/mm^2 for many boilers, even with moderate peaking.

A substantial number of strain gauge tests have been carried out on peaked boilers and the results are included in Figure 10. These show that the higher stresses predicted by Zeman for larger peaking-over-diameter ratios (in excess of about 0.0059) are not found in practice. In addition, extensive finite element stress analysis work of various sizes of boilers with both local peaking and out of roundness has been carried out by the Health and Safety Laboratory. The results show that, for relatively short length-over-diameter ratios (<3) - as in shell boilers where the ends are restrained by welded endplates - the SAFed formula is conservative. The manufacturing process of shell boilers where the shell must effectively be cylindrical at the ends so that the tubeplates can be set in would, in any case, limit the amount of global peaking that could occur in practice.

Finite element analysis of a typical boiler geometry demonstrates that the global peaking calculations proposed by Professor Zeman are too pessimistic for typical shell boiler designs and, therefore, the SAFed formula will generally give a conservative level of calculated stress. The working group considers that the maximum ultrasonic examination period of 5 years is justified to take account of the uncertainties in stress analyses for the range of boiler geometries, stress concentration features and loading conditions possible.

Figure 10: Comparison of peak stress calculations and strain gauge results



APPENDIX II: WORKED EXAMPLES

This appendix contains *worked examples* to illustrate the calculation procedure covered in Section 5.

Section 5.1 Boiler specification

- external diameter = 1800mm
- shell thickness = 10.6mm
- safety valve setting = 150 psi (1.034 N/mm^2)
- measured peaking using a bridge gauge = 6mm

Burner cuts in at 90 psi (0.62 N/mm^2) and cuts out at 120 psi (0.83 N/mm). The boiler operates 12 hours/day and cycles twice per hour as partial pressure cycles, it operates for 5 days/week and the factory is shut down for 2 weeks per year.

The boiler has one full pressure cycle per working day.

D = 1789.4mm

t = 10.6mm

P_1 = 0.83 N/mm^2

P_2 = 0.21 N/mm^2

C_1 = 250 cycles

C_2 = 6000 cycles

Section 5.2 Peaking

$\delta = 6 + 1\text{mm} = 7\text{mm}$

or $\delta = 6 + 0.6\text{mm} = 6.6\text{mm}$

Use $\delta = 7\text{mm}$

Section 5.3 Membrane hoop stress

Membrane hoop stress σm_1

$$\sigma m_1 = \frac{0.83 \times 1789.4}{2 \times 10.6} = 70 \text{ N/mm}^2$$

Membrane hoop stress σm_2

$$\sigma m_2 = \frac{0.21 \times 1789.4}{2 \times 10.6} = 17.7 \text{ N/mm}^2$$

Section 5.4 Calculation of the stress concentration factor (Kt_1)

$$\beta_1 = 0.0075\sqrt{\frac{1789.4 \times 7 \times 70}{10.6^2}}$$

$\beta_1 = 0.66$

From Figure 8. $\tanh \beta_1 / \beta_1 = 0.875$

$$Kt_1 = 1 + \frac{6 \times 7}{10.6} \times 0.875 = 4.47$$

Section 5.5 Calculation of peak stress for P_1

$\sigma \rho_1 = 4.47 \times 70 = 312.9\ N/mm^2$

20% of $P_1 = 0.166\ N/mm^2$. Therefore $P_2 > 0.2\ P1$

Section 5.6 Calculation of the stress concentration factor (Kt_2)

$$\beta_2 = 0.0075 \sqrt{\frac{1789.4 \times 7 \times 17.7}{10.6^2}}$$

$\beta_2 = 0.33$

From Figure 8. $\tanh \beta_2 / \beta_2 = 0.965$

$$Kt_2 = 1 + \frac{6 \times 7}{10.6} \times 0.965 = 4.82$$

Section 5.7 Calculation of peak stress for P_2

$\sigma \rho_2 = 4.82 \times 17.7 = 85.3 N/mm^2$

Section 5.8.1 Calculation of fatigue life (N)

From Figure 9a

N1 = 1500 cycles (measured from graph)

N1 = 1485 cycles (calculated)

Section 5.8.2 Calculation of fatigue life (N)

From Figure 9a

N2 = 74000 cycles (measured from graph)

N2 = 73310 cycles (calculated)

Section 5.9 Calculation of ultrasonic inspection interval

$$\text{Inspection interval} = \frac{1}{\frac{C_1}{N_1} + \frac{C_2}{N_2}} = 3.99 \text{ years}$$

Hence this boiler should be subjected to NDT at 4-yearly intervals.

If the same boiler has measured peaking of 4mm and is under the same peaking and operating conditions the calculation would be as follows:

Section 5.2 Peaking

$\delta = 4 + 1mm = 5mm$

or $\delta = 4 + 0.4mm = 4.4mm$

Use $\delta = 5mm$

Section 5.3 Membrane hoop stress

Membrane hoop stress σm_1

$$\sigma m_1 = \frac{0.83 \times 1789.4}{2 \times 10.6} = 70 \text{ N/mm}^2$$

Membrane hoop stress σm_2

$$\sigma m_2 = \frac{0.21 \times 1789.4}{2 \times 10.6} = 17.7 \text{ N/mm}^2$$

Section 5.4 Calculation of the stress concentration factor (Kt_1)

$$\beta_1 = 0.0075\sqrt{\frac{1789.4 \times 5 \times 70}{10.6^2}}$$

$\beta_1 = 0.56$

From Figure 8. tanh $\beta_1 / \beta_1 = 0.91$

$$Kt_1 = 1 + \frac{6 \times 5}{10.6} \times 0.91 = 3.58$$

Section 5.5 Calculation of peak stress for P_1

$\sigma\rho_1 = 3.587 \times 70 = 250.6$ N/mm^2

20% of $P_1 = 0.166$ N/mm^2. Therefore $P_2 > 0.2 P_1$

Section 5.6 Calculation of the stress concentration factor (Kt_2)

$$\beta_2 = 0.0075\sqrt{\frac{1789.4 \times 5 \times 17.7}{10.6^2}}$$

$\beta_2 = 0.28$

From Figure 8. tanh $\beta_2 / \beta_2 = 0.97$

$$Kt_2 = 1 + \frac{6 \times 5}{10.6} \times 0.97 = 3.75$$

Section 5.7 Calculation of peak stress for P_2

$\sigma\rho_2 = 3.75 \times 17.7 = 66.4$ N/mm2

Section 5.8.1 Calculation of fatigue life (N)

From Figure 9a

N1 = 3000 cycles (measured from graph)

N1 = 2891 cycles (calculated)

Section 5.8.2 Calculation of fatigue life (N)

From Figure 9a

N2 = 162000 cycles (measured from graph)

N2 = 155420 cycles (calculated)

Section 5.9 Calculation of ultrasonic inspection interval

$$\text{Inspection interval} = \frac{1}{\frac{250}{2891} + \frac{6000}{155420}} = 7.99 \text{ years}$$

Hence as the maximum inspection intervals is 5 years this boiler should be subjected to NDT at 5-yearly intervals.

A further example using the following boiler specification

- external diameter = 2000mm
- shell thickness = 14mm
- design pressure = 1.38 N/mm^2
- maximum working pressure = 1.31 N/mm^2

Measured peaking using a needle gauge = 10mm

Burner cuts in at 1.1 N/mm^2 and cuts out at 1.31 N/mm^2. The boiler operates 24 hours/day for 5 days each week and cycles twice per hour as partial pressure cycles.

The boiler has one full pressure cycle per working day.

D	=	1986mm
T	=	14mm
P_1	=	1.31 N/mm^2
P_2	=	0.2 N/mm^2
C_1	=	52 cycles
C_2	=	17500 cycles

Section 5.2 Peaking

As the peaking was measured using a needle gauge there is no need to use a correction factor. δ = 10mm

Section 5.3 Membrane hoop stress

Membrane hoop stress σm_1

$$\sigma m1 = \frac{1.31 \times 1986}{2 \times 14} = 92.9 \ N/mm^2$$

Membrane hoop stress σm^2

$$\sigma m_2 = \frac{0.2 \times 1986}{2 \times 14} = 14.2 \ N/mm^2$$

Section 5.4 Calculation of the stress concentration factor (Kt_1)

$$\beta_1 = 0.0075\sqrt{\frac{1986 \times 10 \times 92.9}{14^2}}$$

$$\beta_1 = 0.73$$

From Figure 8. $\tanh \beta_1 / \beta_1 = 0.86$

$$Kt_1 = 1 + \frac{6 \times 10}{14} \times 0.86 = 4.69$$

Section 5.5 Calculation of peak stress for P_1

$$\sigma\rho_1 = 4.69 \times 92.9 = 435.7 \text{ N/mm}^2$$

This peak stress is greater than 330 N/mm^2 so the ultrasonic interval cannot be determined and the boiler should not be operated until one of the options in 5.11 has been implemented.

APPENDIX III: STRAIN GAUGE MEASUREMENT TECHNIQUE

The guidelines stipulate that, where the calculated maximum local stresses are in excess of 330 N/mm^2, a strain gauge measurement technique may be used to determine such stresses more accurately.

Appendix III presents details on how and where to apply appropriate strain gauges in order to ensure that a unified and consistent approach is adopted and that the maximum overall local peak stress values along the longitudinal seam are determined with an acceptable degree of accuracy (preferably within ±5% or better).

To achieve the desired level of accuracy following the general survey of peaking measurement carried out at 250mm intervals, a more precise local survey should be carried out to ensure that the location(s) of maximum peaking are established, marked and recorded.

It is important to bear in mind that local peak stresses, whose actual values we are trying to determine, are governed not only by the amount of peaking but also by such factors as misalignment, ovality or general distortion of the shell as well as by the presence of other discontinuities such as manways, fittings and other attachments in the vicinity of the longitudinal seam. Some, or a combination, of these discontinuities/features will lead to rotation of the weld junction. This rotation can occur in either direction - clockwise or anticlockwise when viewed from a datum point - when internal pressure is applied to the boiler shell.

It is necessary to apply strain gauges on both sides of the longitudinal seam as stress levels may not be the same on each side.

Figure 11: Strain gauge location

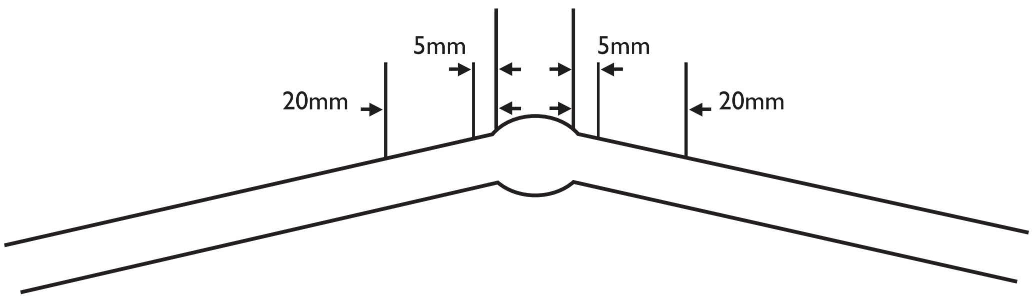


Figure 12 shows a typical strain gauge extrapolation technique. It is readily apparent that, for reliable extrapolation of peak strain/stress levels at the toe line of the weld, it is necessary to apply strain gauges at not less than two locations (such as positions A and B). Furthermore, to ensure that positions A and B are on a relatively straight portion of the strain plot, the recommended distances 'a' and 'b' should nominally be 5 and 20mm respectively, both measured from the toe line to the centre line of each gauge.

Note that these distances are not critical as such, but both 'a' and 'b' should be measured to within ±0.5mm to ensure overall accuracy in the subsequent extrapolation technique. Should the distance 'b' exceed, say, 30mm additional errors may be introduced into the extrapolation technique due to the change in the slope of the line A-B and the corresponding reduction in the intercept on the strain axis (the ordinate).

It must be borne in mind that actual strain plots will not be available unless multiple strain gauge techniques are adopted to obtain such results. Larger errors than those shown can be introduced into the extrapolation technique if the deviation from linearity in the strain plot itself is more pronounced. Strain gauge measurements should be carried out at suitable increments up to the maximum boiler operating pressure.

A3.1 Assessment of peak strain/stress levels

The method of extrapolation and estimation of stress levels is illustrated in the following example.

For a specific shell boiler, the following information has been established:

Strain gauge tests have been carried out at maximum operating pressure using a 'two strain gauge' technique where the gauges were applied to both sides of the longitudinal seam. Strain gauges were attached at 5 and 20mm from the respective toe lines. Due to the size of the boiler, strain gauges could only be applied on the external surfaces of the weld junction. The nominal hoop stress was calculated as 71 N/mm^2 based on actual boiler geometry and measured shell thickness.

The maximum recorded strain levels on one side of the weld at positions A (5mm) and B (20mm) were -608 and -332 microstrain (x10^{-6}), compressive, with the longitudinal strain at position A recorded as +60 microstrain, tension (each relating to the maximum boiler operating pressure); see Figure 12 for strain plot.

A3.1.1 In order to determine the maximum peak stress level on the inside surface of the boiler shell the following procedure should be carried out:

i) Establish the maximum peak strain level, on the external surface of the shell, using the appropriate extrapolation technique.

$$\Delta E = EA - EB = 608 - (-332) = 276\mu$$

$$\Delta E = \frac{b}{b-a} = -276 \times \frac{20}{15} = -368\mu$$

and hence the peak strain, E_h at the toe of the external weld is given by:

$$E_h = -368 + (-332) = 700\mu$$

The units of strain are in microstrain or x 10^{-6}.

ii) Establish the peak stress value on the external surface of the shell using the following relationship:

$$\sigma_h = \frac{E}{1 - \mu^2} (E_h + \mu E_L)$$

When the Young's Modulus (E) and the Poisson's ration (μ) are assumed to be 207,000 N/mm^2 and 0.3 respectively then equation [1] simplifies to:

$$\sigma_h = 227500\ (E_h + 0.3\ E_l)$$

since the (10^6) and 10^{-6}) factors cancel each other out and only the 'plain numbers' remain.

Substituting the corresponding values for the two strain levels (E_h = -700μ, E_l = 60μ) we get:

$$\sigma_{ext} = 0.2275\ (-700 + 0.3 \times 60)$$

$$= 0.2275\ (-682) = 155 \text{ N/mm}^2 \text{ compression}$$

iii) Determine the maximum peak stress value on the inside surface of the boiler shell - i.e. at the toe line of the inner weld. This can be achieved in the following manner.

The total stress, local to the peaked longitudinal seam, is made up of two basic stress components. First, there will be the usual membrane (hoop) stress (σm) which will be uniformly distributed across the shell thickness (T).

In addition there will be a bending stress (σb) imposed at the junction (seam) due to the deflection of the peaked shell when subjected to an internal pressure (P). For an outwardly peaked shell this deflection will be inwards, causing a slight reduction in the amount of local peaking whilst under load. Under such conditions the maximum stress on the outer surface will be equal to:

$\sigma_{ext} = -\sigma_b + \sigma_m = -155\ Nmm^2$

Hence the local bending stress, σ_b cabn be stated as:

$\sigma_b = \sigma_m + 155\ Nmm^2$

Also the combined stress on the inside surface of the shell will be equal to the sum of the two components:

$\sigma_{int} = \sigma_b + \sigma_m$

Combining equations (2a) and (3) we obtain:

$\sigma_{int} = -\sigma_m + 155\ Nmm^2 + \sigma_m = 2\sigma_m + 155\ N/mm^2$

or, in more general terms, the above equation can be written as:

$\sigma_{int} = 2\sigma_m - \sigma_{ext}$

See Figure 13 for a graphic illustration of stress distribution across the shell thickness at the toe line.

Thus, for an outwardly peaked boiler, the maximum peak stress level occurring on the inside surface of the boiler shell is equal to the sum of twice the nominal calculated membrane hoop stress ($2\sigma_m = PD/T$) and the absolute value of the peak stress measured on the external surface (σ_{ext}). In the specific case considered herein:

$\sigma_{int} = 2 \times 71 + 155 = 297\ N/mm^2$.

Where strain gauges are fitted to the inside surface of the boiler shell, the simple extrapolation technique will provide the peak strain levels at the toe of the inner weld. Equation (1a) can then be used to calculate maximum peak stress levels directly.

This is the appropriate stress level that should be used, in conjunction with Figure 9b and the relevant cycling conditions, to calculate ultrasonic inspection intervals.

Had a single-gauge technique been used, with strain gauges attached at 5mm positions only, the peak external stress would have been computed as -134 N/mm^2 and the corresponding maximum peak stress as 276 N/mm^2 only (2 x 71 + 134), resulting in 7.6% error. Had the single gauges been placed further away from the toe line this 'in-built error' would increase still further, becoming approximately 12% with gauges fixed at 7.5mm from the toe line.

A3.2 Modified fatigue design curve

In Section 5 it is considered that there is sufficient conservatism in the formulae used to determine peak stress levels to overcome any uncertainties regarding the number of fatigue cycles. However, if the 'built-in' conservatism is removed by recourse to a strain gauge technique to determine more accurately the actual values of maximum peak stress levels, the working party considered it prudent to refine the original procedure and to propose a modified version of the fatigue design curve (Figure 9b).

The modified fatigue design curve should now be used when maximum peak stresses are measured using strain gauge technique in the manner described. The new plot contains a cut-off stress level of 264 N/mm^2 (0.80 x 330) and the sloping line is now given by the following equation:

$$N = \frac{2.33 \times 10^{10}}{\sigma_p^{3}}$$

If this procedure gives an unacceptable inspection interval, Figure 9a may be used for the revised calculation but the following steps should be taken:

- the operating conditions should be determined to ensure that water treatment is satisfactory and that rise times when raising pressure are > 30 minutes
- the number of actual pressure cycles should be determined and monitored using a chart recorder
- the cyclic duty should be kept under review by the Competent Person.

A3.3 The effects of local weld geometry

For most practical situations, the following factors can be disregarded as far as the strain gauge test procedure is concerned:

- local variations in weld geometry
- weld profile
- height of weld reinforcement
- differences in weld cap widths between inner and outer weld runs
- overlap
- lateral shift between inner and outer weld runs.

The effects of such features on the assessment and measurement of local peak stress levels have been evaluated and found to be either negligible or beneficial, resulting in conservatism if such effects are ignored in the procedure and subsequent analysis.

A3.4 Type of strain gauges

Strain gauges of 2, 3 and 5mm nominal gauge length may be used. Stacked rosettes or individual gauges may be applied at specified locations. In the case of the 'side by side' layout of individual gauges, it is important that the positions of the hoop elements are measured accurately to within ±0.5mm.

Strain recording instruments should be properly calibrated prior to the commencement of the tests. For instruments with a built-in calibration facility calibration should be carried out for each channel (gauge element) prior to the start of the pressurisation stages.

A3.5 Strain gauge test report

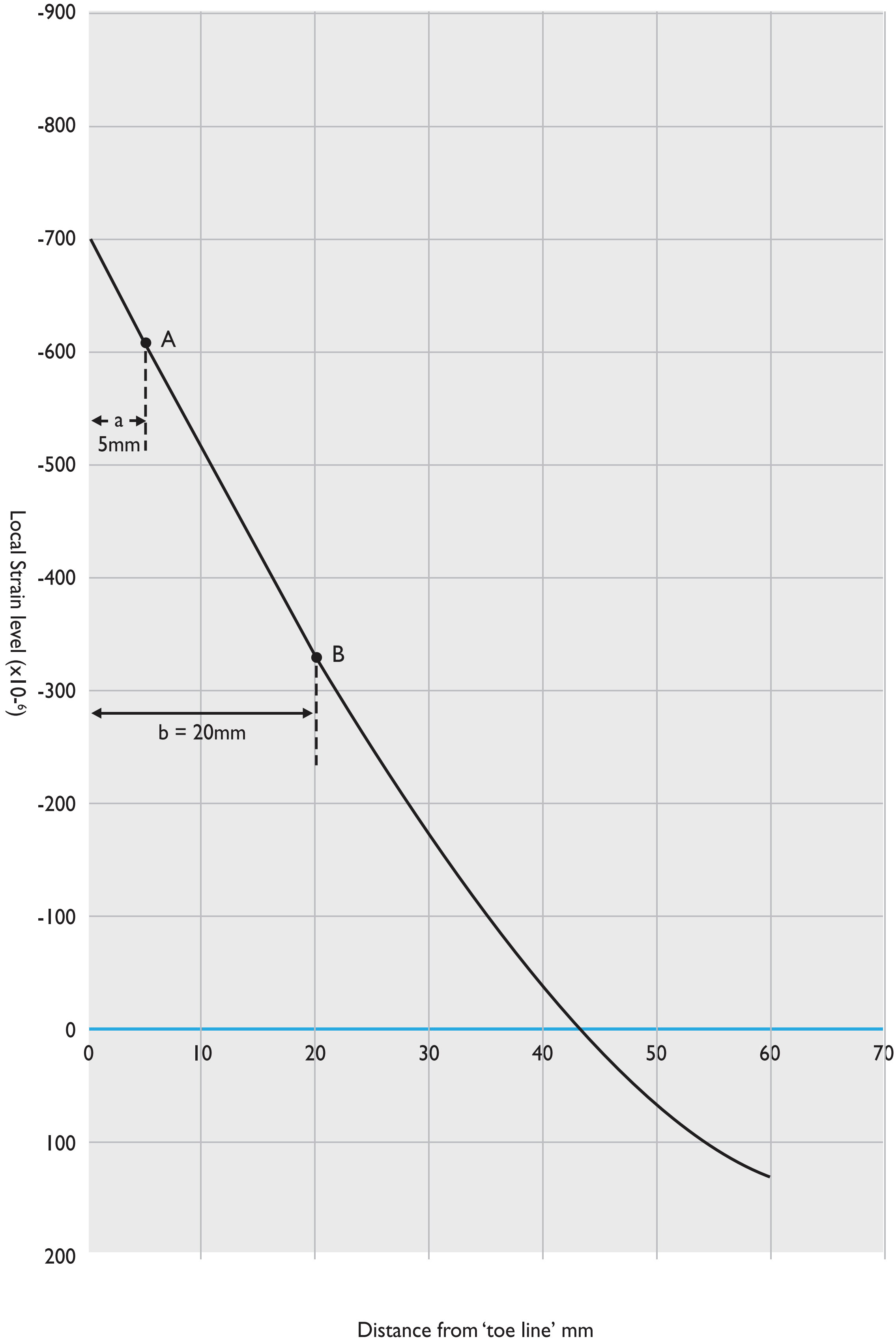
The report should specify:

- the organisation performing the tests
- the organisation supervising the tests (if different from above)
- type of instruments used for recording strain levels
- type and size of strain gauges
- precise location (to within ±0.5mm) of hoop elements
- calibration constants (or provide corrected strain readings)
- details of pressure gauge (size, graduation, range) and, if recently calibrated, date of calibration
- equations and constants used to convert strains to stresses.
- pressures applied and strains recorded.

A3.6 Boiler geometry

Diameter, nominal, outer, etc.	-	specify
Shell thickness	-	nominal, measured
Maximum peaking	-	preferably provide plot/trace

Figure 12: Strain gauge positions and extrapolation of results



Notation for Figure 12

a) The two important gauge locations are at points A and B. These distances should nominally be at 5 and 20mm from the toe line of the weld.

b) The distances 'a' and 'b' should be measured to within ±0.5mm. These distances refer to the hoop elements of the side-by-side gauge pairs.

c) Strain gauges of nominal length of 2, 3, or 5mm may be used. Stacked tees, rectangular pairs, or side-by-side pairs may be used. Gauges should be compatible with the shell material and self-temperature compensated.

d) Gauges should be attached to both sides of the longitudinal seams (above and below the weld). It is permissible to attach gauges at position A and to carry out a preliminary pressure test. Gauges at position B can then be attached either above or below the seam depending on where the strains are highest.

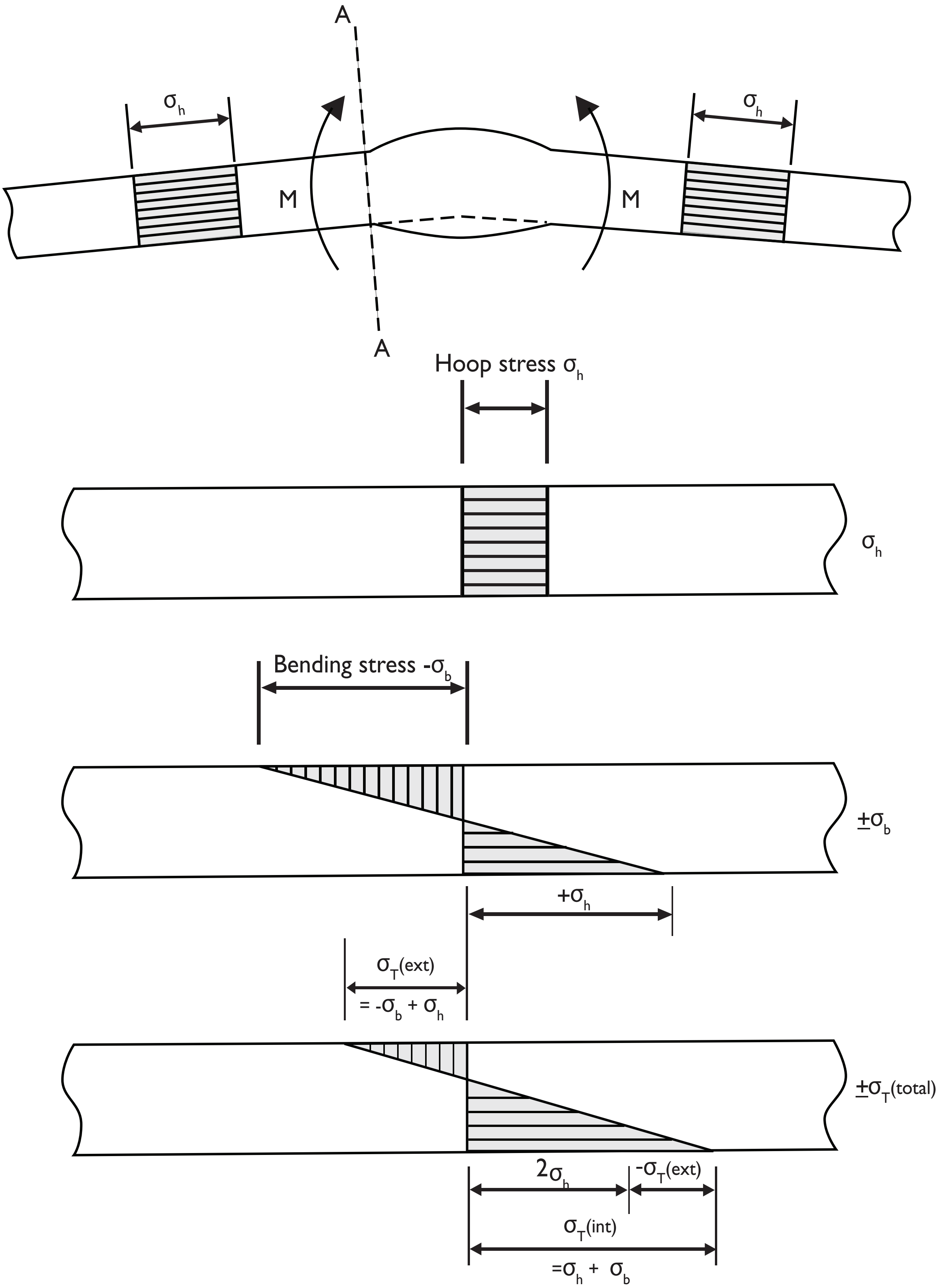
e) It must be borne in mind that actual strain gauge plots will be unknown unless multiple strain gauge techniques are used to obtain them.

f) Obtain peak strain values by extrapolation

$E_P = (EA - EB) \times \frac{b}{b\text{-}a} + EB$, where EA, EB are the strain levels recorded at positions A and B respectively.

g) Calculate the 'principle strains' and 'peak stresses' using formulae contained in the text.

Figure 13: Stress distribution across the shell thickness



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