The assessment of pressure vessels operating at low temperature

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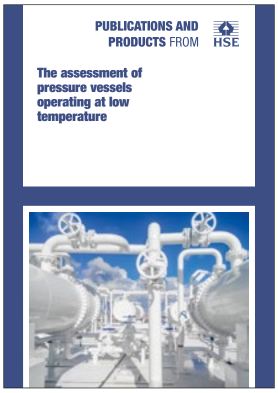

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This guidance is aimed at users of pressure vessels in low temperature duty and the competent persons who carry out periodic inspection and integrity assessment of these vessels.

Low temperatures can adversely affect the tensile toughness of commonly-used materials; including certain steels used in pressure vessel manufacture. These materials experience a shift, from ductile to brittle behaviour, if the temperature is reduced below their transition point.

Loss of material ductility at low temperature can contribute to an increased risk of catastrophic brittle failure, of process equipment.

The purpose of this guidance is to help users of pressure systems, and their competent persons, to establish procedures that can be used for assessing whether an operational pressure vessel is safe to operate at low temperatures.

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PURPOSE

1 The purpose of this guidance is to help users of pressure systems and their competent persons establish procedures that can be used for assessing whether an operational pressure vessel is safe to operate at a specified low temperature, or range of low temperatures. The methods of assessment recommended in this publication are based either upon the requirements of a recognised pressure vessel design code, or upon 'fitness for service' use of a fracture mechanics based approach. The appropriate assessment routes in Figures 2, 3, and 4 should be used to confirm the safe low temperature operating limits of a pressure system. This should provide an adequate means of demonstrating compliance with the legal requirements.

2 This guidance makes reference to pressure vessel design codes and uses extracts for illustrative purposes. The guidance should not be used as an alternative to these codes. It is essential that anyone involved in the assessment procedures has a thorough knowledge of the codes and fitness for service techniques and is competent to carry out these activities. The guidance is aimed predominantly at pressure vessels, but some limited reference is made to similar approaches that can be applied to piping.

LEGAL REQUIREMENTS

3 Establishing an acceptable method of assessing pressure vessels for low temperature duty may present a problem, particularly when relevant information about the vessel is inadequate or not available. Users of pressure systems and competent persons who carry out the periodic in-service inspection of these vessels are required to comply with the general duties of the Health and Safety at Work etc. Act 1974 [1] and more specifically with the Pressure Systems Safety Regulations (PSSR) 2000 [2]. Regulation 7 requires that the user of an installed system or the owner of a mobile system which contains a relevant fluid shall not allow that pressure system to be operated until the safe operating limits of the system have been established. Under Regulation 9(5) of the above Regulations a competent person on completing the thorough examination, is required to confirm to the user that the safe operating limits remain valid, and, if not, must advise the user of the system of any changes necessary before it can go back into service. This responsibility may create difficulties for the competent person when the minimum operating temperature is low and when the material documentation is not specific about material suitability for this low temperature, or where such documentation does not exist.

4 Other legislation such as Control of Major Accident Hazards (COMAH) 2015 [3] require duty holders to demonstrate that equipment is suitable for its intended purpose and that risks are reduced as low as reasonably practicable (ALARP). The HSE Guidance [3] explains this requirement in detail and includes the requirement that in Major Accident Hazard Scenarios good practice should be adopted as a minimum. The codes standards and guidance referenced in this document are recognised as sources the duty holders may use in demonstrating adoption of good practice.

5 The Provision and Use of Work Equipment Regulations (PUWER) 1998 [4] Regulation 5 requires employers to ensure that work equipment is maintained in an efficient state, in efficient working order and in good repair. In addition, PUWER 1998 Regulation 6 requires that every employer shall ensure that work equipment exposed to conditions causing deterioration which is liable to result in dangerous situations, is inspected at suitable intervals and each time exceptional circumstances occur. This is to ensure that health and safety conditions are maintained, and that any deterioration can be remedied and detected in good time.

INTRODUCTION

6 Many pressure vessels are manufactured from carbon and carbon-manganese steels because these materials have good mechanical properties which combine strength and ductility with ease of fabrication. The materials do however have one adverse characteristic that requires special consideration when vessels are operated at low temperatures. Ferritic steels are subject to a temperature related transition in which the material changes from a notch ductile to a notch brittle condition as the temperature is reduced. A typical relationship is shown in Figure 1. This adverse property can be modified by means of alloying and control of heat treatment in the steel making and fabrication process to make the steel suitable for applications where low temperatures are involved. For even lower temperatures, alternative materials such as austenitic stainless steel or aluminium are used because they do not exhibit the characteristic ductile-to-brittle transition shown in Figure 1.

7 The design of pressure vessels and the selection of steels suitable for pressure vessel applications are covered by well-known national and international standards. Many pressure vessels operating in the United Kingdom were designed and fabricated to one of three British Standards: BS 1500 [5], BS 1515 [6] and BS 5500 [7]. The steels used generally meet the requirements of the BS 1501 series of standards. BS 1501-6 [8] offers a selection of ferritic steels which are suitable for a wide range of operating temperatures including low temperatures. The low temperature property of the steel is defined from a quality control point of view by means of the Charpy-V notch impact test which will determine the notch ductility of a steel at a given test temperature. Toughness properties of the steel are more accurately demonstrated by other means such as the Crack Tip Opening Displacement (CTOD) method, J-integral or the critical stress intensity factor, (K_{IC}), derived from fracture mechanics principles. Where toughness values are not readily available then a correlation between the Charpy toughness value, C_V, and K_{IC} can be used for assessment purposes.

8 The current UK and European pressure vessel standard, BS EN 13445-2: 2014, Annex B, [9] contains design rules for low temperature duties. Similar rules can be found in the previous British Standard, now a Published Document, PD 5500: 2018, Annex D [10]. These rules take into account good engineering practices to ensure that materials and design details are adequate to resist brittle fracture under specified design conditions, although it is worth noting that with some materials, particularly lower-strength steels in the post-weld heat treated condition, BS EN 13445-2:2014 has reduced toughness requirements, which in turn could lead to a less defect tolerant vessel. Both design codes were derived from research work carried out in the early 1960s into the mechanism of crack initiation. This work was first incorporated into a 1972 revision of BS 1515, Appendix C, entitled *Tentative recommended practice for vessels required to operate at low temperature*. Earlier editions of BS 1515 and BS 1500 contained different recommendations on this subject.

9 There are many pressure vessels in use and operating at low temperatures which were designed to these earlier standards. Some of these vessels may not have been evaluated for low temperature conditions or may have been assessed to alternative rules. This may create difficulties for competent persons if the vessels have to be reassessed in the light of changes to required low temperature operating conditions. It is important that a valid assessment method, to confirm safe operating limits, is possible for all vessels. In this respect, it should not be assumed that vessels that fully comply with the original design standard, but do not comply with the later standards, are unfit for their intended purpose. Further analysis may however be required to make a suitable demonstration of fitness for service. The Published Document PD 5500 Annex U and American Petroleum Institute/American Society of Mechanical Engineers document API 579/AMSE FFS-1

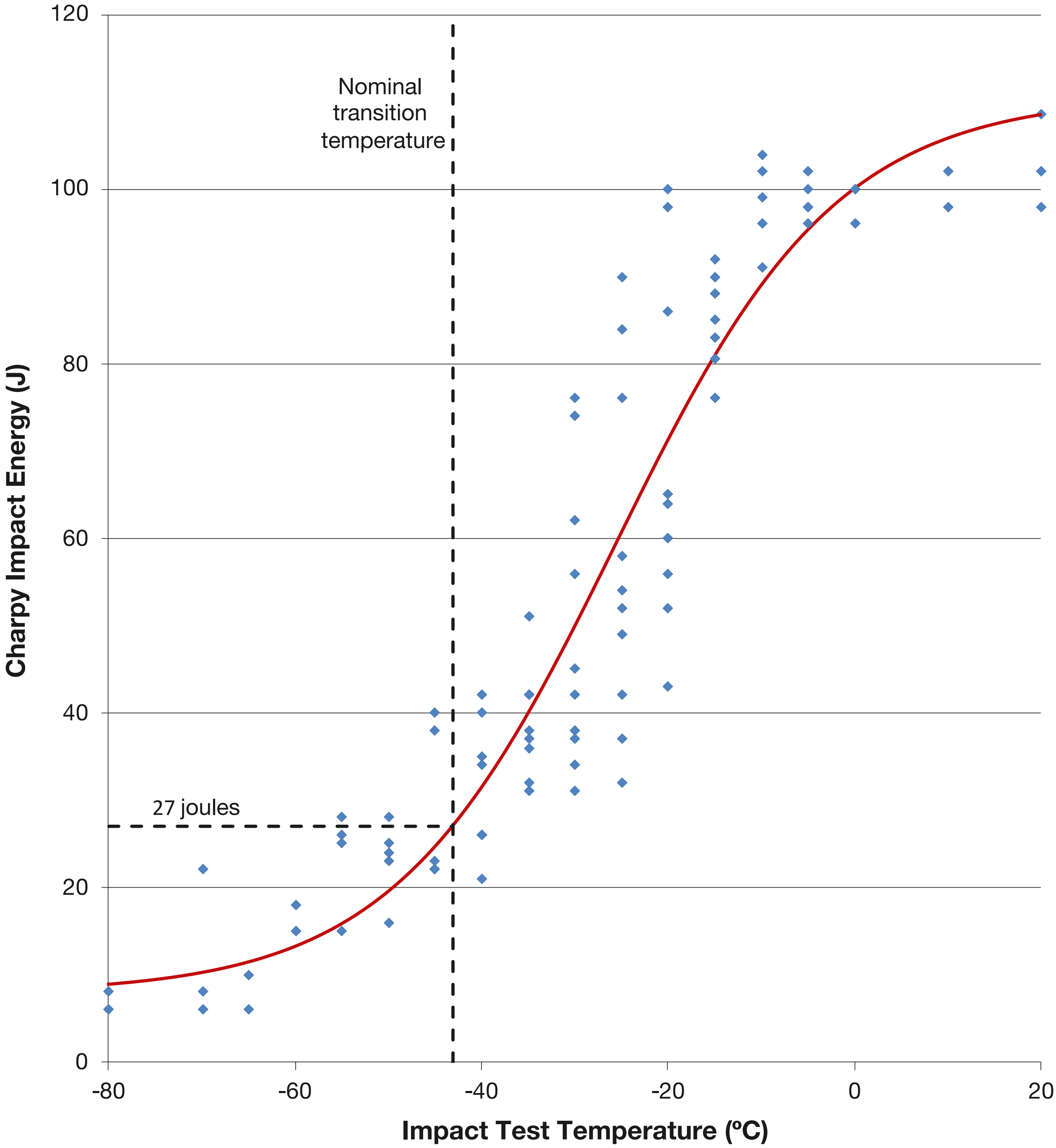


Figure 1 Typical Charpy-V test results for BS 1501 – 213 equivalent steel

Part 3 level 3 and Part 9 [11] provide guidance on additional levels of assessment that may be required if initial screening level assessments fail to demonstrate suitability for the required low temperature operating conditions. These approaches are described in more detail in later sections of this guidance.

10 The basic principle of the approaches is that a material used for a vessel should have acceptable toughness (e.g. $C_v > 27$ J) at the lowest temperature that the material would be exposed to. Allowances are made for conditions where brittle fracture would be less likely to occur, such as where the material is thin, or the stresses are low.

11 The likelihood of a pressure vessel failure due to brittle fracture depends on the combination of a number of adverse factors. The three main factors are:

a. fracture toughness;
b. the existence of crack-like flaws; and
c. stress at the crack tip.

12 Vessels that operate at temperatures in the lower bounds of the ductile-to-brittle transition range are at risk. This risk is only likely to be realised if the vessel contains significant crack-like defects and if operational procedures result in high loadings occurring while the vessel walls are at low temperature. Proper operating procedures, particularly during filling, and regular thorough examinations are among the measures necessary to minimise this risk. The assessment methods included in this guidance should be used to determine equipment safe operating limits upon which the operating procedures are based. Periodic inspection methods should be implemented to detect the presence of any crack-like flaws, particularly if it is considered credible that cracks will grow in service.

13 The acceptability or significance of a flaw in a vessel or section of pipework is normally determined using a fracture mechanics based fitness for service assessment. Done using either BS 7910:2015 or API 579/ASME FFS-1 Section 9, both standards contain a methodology for determining the significance of a defect and use a Failure Assessment Diagram (FAD) approach to determine when a defect becomes unacceptable. An understanding of the size, orientation and potential growth rate of a defect, and at what point it becomes intolerable, is fundamental to any assessment of brittle fracture potential where crack-like flaws are found during inspections or where screening assessments fail to demonstrate suitability for specified process conditions.

14 It should be noted that standards permit the use of construction materials that may be at the lower end of the ductile-to-brittle transition curve. BS 1500, BS 1515 and the earlier editions of BS 5500 were written with the intention of using standard BS 1501 steels which were not impact tested. Experience with vessels designed to these standards has shown that this is acceptable so long as adverse operational factors are not present, but if such factors are there, the probability of brittle fracture of the vessel will increase. This potential problem is reduced when materials with higher notch toughness are used and the problem is eliminated with materials that retain full notch ductility at the minimum operating temperature.

15 It is important that pressure vessels and pipework systems should be properly assessed as fit to operate at the required low temperature. If, for whatever reason, it is not possible to carry out a satisfactory assessment of the vessel to demonstrate this, then operational measures of sufficient integrity should be implemented to avoid the unsafe operating conditions that have been identified. The vessel should then be rerated and re-certified for the revised safe operating limits and the changes should be recorded and authorised through management of change procedures.

Table 1 Summary of assumptions for assessment routes

Route 1	Route 2	Route 3
Screening methods		Fracture mechanics based Engineering critical assessment
• Vessel is already designed to a code for low temperature • Required process conditions found to potentially fall outside design parameters • Material property data are available (e.g. Charpy) • No significant defects present	• Vessel is designed to a code, but not assessed for low temperature use • Required process conditions found to potentially fall outside design parameters • Material property data not initially known (e.g. Charpy) • No significant defects present	• Vessel is designed to a relevant code and EITHER • Route 1 or 2 did not provide acceptable assessment OR • The vessel contains, or is assumed to contain, significant defects

Alternatively, the vessel should be replaced by one which is suitable for its intended purpose. The recommended assessment procedures for carrying out this work are illustrated in the algorithms in Figures 2, 3 and 4. These are summarised in an overview table (see Table 1 below). The routes are not prescriptive, and some variation may be appropriate but they demonstrate three ways in which vessel design codes and fitness for service/engineering critical assessment methods can be applied to demonstrate fitness for service at rerated design conditions. Typical examples of how the procedures may be applied are provided in the Appendices. Appendices 1-4 are based on vessels designed to UK codes. Appendix 5 provides an assessment based on API 579-1/ASME FFS-1 2007. Similar example calculations based on ASME FFS-1/API 579-1 2007 [11] Fitness for Service Code are available in ASME FFS-2 [12].

ASSESSMENT PROCEDURES

16 In order to fully demonstrate fitness for service of existing equipment at a new or revised set of low temperature conditions, it is necessary to establish the required operational details in order to determine whether the safe operating limits of the vessel are suitable for the required low temperature duty. This information should cover the full range of conditions including, where appropriate, transient conditions, which may determine the limiting design criteria. In addition, the pressure vessel or piping system will at some stage need to be subject to a thorough examination to confirm the absence of significant defects that could act as the initiator for brittle fracture. The extent of this examination and the selection of visual and non-destructive inspection techniques should be consistent with the need to detect significant defects. Critical areas at main seam welds, welded attachments, nozzles, reinforcing plates and supports should be identified within the scheme of examination.

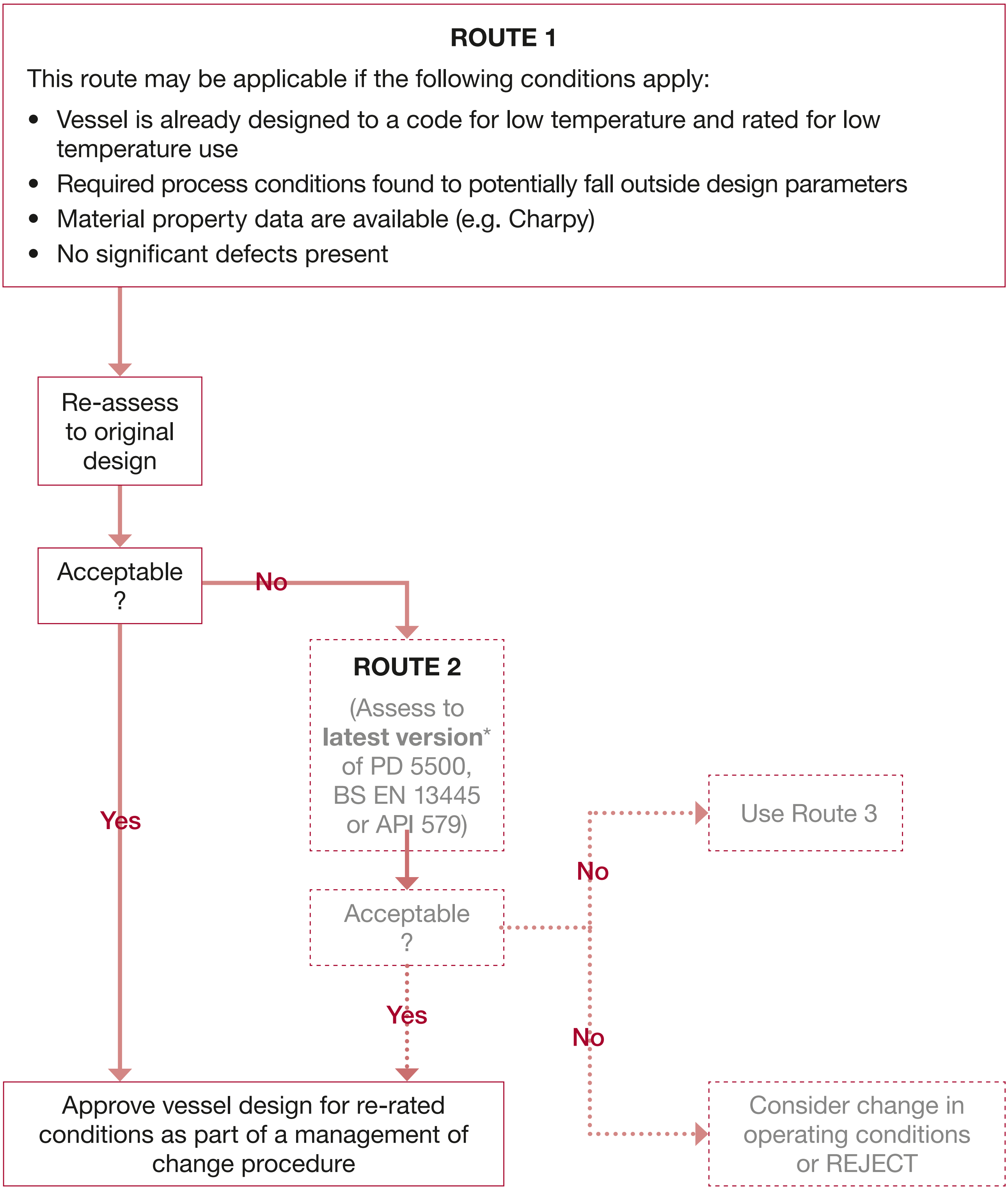
Vessel designed for low temperature (see Figure 2)

17 If the vessel has been designed and constructed to a recognised code for the defined low temperature duty and the vessel is satisfactory following examination, and if the safe operating limits can be established, then no further action is required. Where the vessel has been designed to a recognised code and the required low temperature operating conditions have changed, the vessel should be reassessed by an appropriate procedure. It is recommended that this procedure will be in accordance with the original design code or with the latest issue of a recognised national standard (e.g. BS EN 13445-2:2014, Annex B or PD 5500 Annex D). If this procedure fails to confirm the revised safe operating limits meet the required low temperature operating conditions, then an appropriate fracture mechanics based fitness for service assessment route should be considered. By these means, it should be possible to confirm the required safe operating limits or to decide on necessary changes to operating methods and controls that satisfy the assessment procedures. Alternatively, if necessary, reject the vessel on the basis that it cannot be assessed as fit for its intended purpose.

18 Where the code used to evaluate revised design conditions differs from the original design and construction code, it is particularly important to ensure that an engineer, competent in pressure vessel design, approves the final calculations. Guidance in API 579-1/ASME FFS-1 2007 Parts 1 and 2 provides advice on appropriate levels of competence. The use of Hazard and Operability (HAZOP) and Process Hazard Analysis (PHA) methodologies utilising a multi discipline approach is recommended to assess whether revised safe operating limits of vessels fully satisfy the required range of operating conditions, including foreseeable process deviations. The conduct of such HAZOP/PHA studies is outside of the scope of HSG 93 but appropriate guidance can be found in BS EN 61882:2016 'Hazard and Operability studies (HAZOP studies). Application Guide' [13].

Vessel not designed for low temperature (see Figure 3)

19 If a pressure vessel has been designed to a recognised code but not for low temperature limits, it may be necessary to carry out an assessment by Route 2. If the vessel examination confirms the absence of significant defects in respect of its original design code and the toughness properties of the material (including welds and heat affected zones) can be established, then it is sufficient to



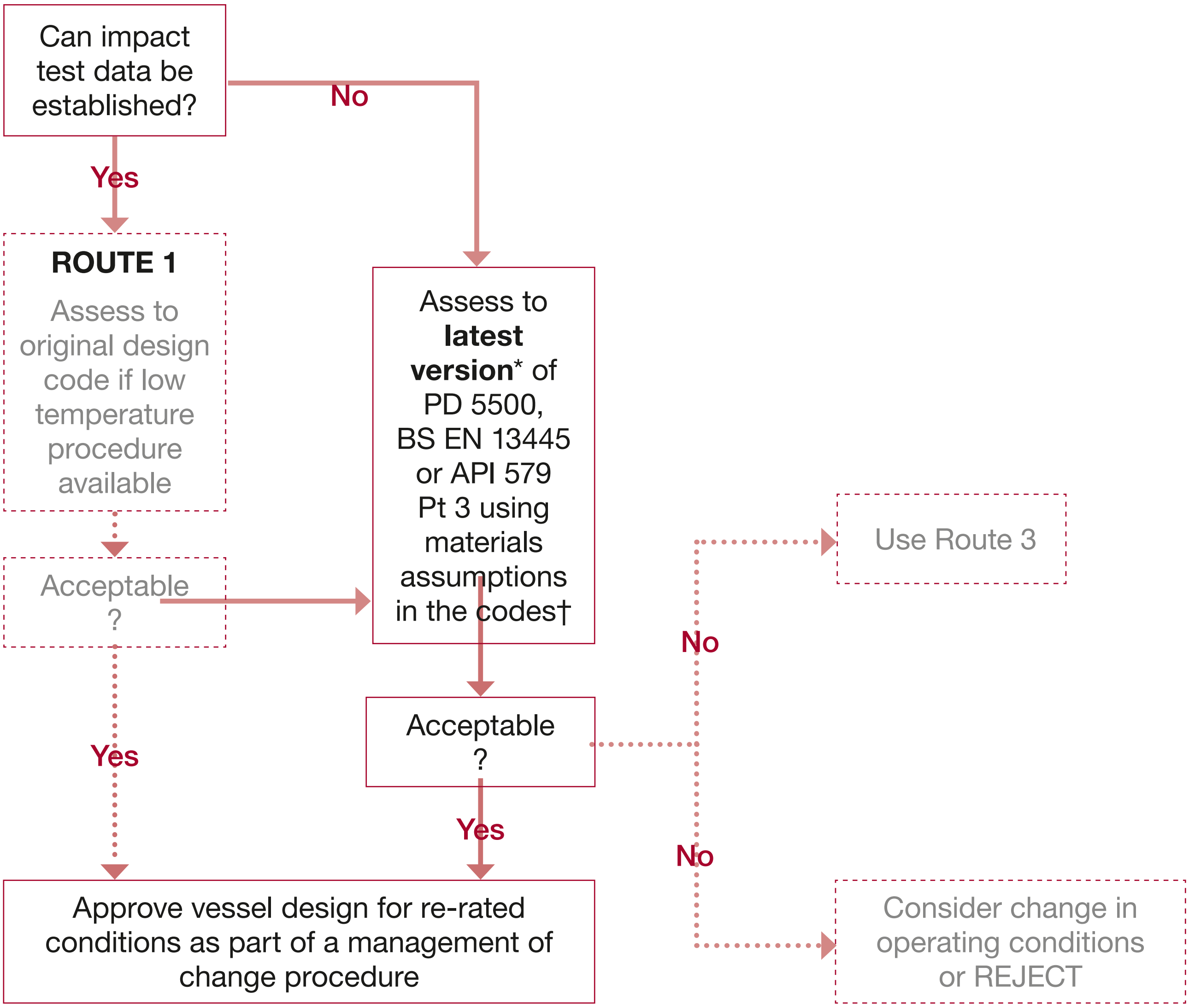
*It is recommended that assessments be performed to the **latest version** of the Standard/Published Document. This recommendation is based on the assumption that later Standards are based on the fullest information, sometimes correcting errors in earlier versions.

Figure 2 Low temperature assessment (route 1)

ROUTE 2

This route may be applicable if the following conditions apply:

- Vessel is designed to a code, but not assessed for low temperature use
- Required process conditions found to potentially fall outside design parameters
- Material property data not initially known (e.g. Charpy)
- No significant defects present



† See Paragraphs 21 and 22 for details on materials assumptions

*It is recommended that assessments be performed to the **latest version** of the Standard/Published Document. This recommendation is based on the assumption that later Standards are based on the fullest information, sometimes correcting errors in earlier versions. The exception is that steel quality has improved over time, hence the recommendation to assume properties appropriate for the date of manufacture.

Figure 3 Low temperature assessment (route 2) assess the vessel against its original design code. If the design code is other than BS/PD 5500 or BS EN 13445, e.g. BS 1500 or BS 1515, and it is not possible to establish the required safe operating limits, then it is sufficient to assess the vessel against the latest edition of PD 5500 or BS EN 13445. If this cannot be done, then, in the absence of a satisfactory fitness for service assessment, the vessel should be rejected, or additional control measures implemented and approved through management of change procedures.

20 A brief illustration of the assessment method that may be used in respect of PD 5500 is given in Appendix 1. The use of BS 1500 and BS 1515 for the same purpose is given in Appendix 2. A numerical example of the PD 5500 procedures in Appendix 3 provides further illustration, while Appendix 4 illustrates the use of BS EN 13445 for the same vessel. These Appendices should not be regarded as alternatives to use of the codes but are provided as additional guidance and examples of how the codes can be used.

21 There may be circumstances in which the materials of construction have no specified impact properties. It is not generally practicable to carry out impact tests on such vessels if they are in service as part of a fitness for service assessment and tests would be required on both plate and weld. A number of procedures are available that enable an assumption to be made for the temperature at which satisfactory impact values could be achieved:

a. If the material is made to a modern European standard, BS EN 13445-2: 2014, Annex B can be used to establish a minimum design reference temperature based on the material grade, thickness and weld condition. For example, grade P355N (to EN 10216-3:2013) would be assumed to be acceptable down to a design reference temperature of -20 °C provided the thickness was no more than 35 mm if in the as-welded condition, or 70 mm if post-weld heat treated. For some materials, the temperature obtained using this route in BS EN 13445-2 may be less conservative than using PD 5500.
b. An assumption that most pressure vessel steels would attain a satisfactory impact value at +20 °C can be made when using PD 5500, Annex D. There are some exceptions, such as rimming steels, where this assumption cannot be made, as detailed in PD 5500, Appendix K.
c. For versions of BS 5500 predating the 1988 edition, assumptions on minimum impact temperatures are based on material strength and thickness.

22 If there is any significant doubt about the impact properties of a vessel steel, then a fracture mechanics based fitness for service assessment route should be considered using appropriately conservative values of fracture toughness before the vessel can be validated for use at the required low temperature conditions.

Fracture mechanics based assessment (see Figure 4)

23 It may not be possible to follow either of the two previous assessment routes. For example, the notch toughness or notch ductility of the parent material or welds may be in doubt, or significant defects may have been detected during the examination. In either case, the fracture mechanics based fitness for service assessment route may be necessary to establish the safe operating limits of the vessel (see paragraph 21 above). This will generally involve accurate assessment of stresses and derivation of fracture toughness properties of parent metal, weld and heat affected zones. A fracture mechanics assessment to British Standard document BS 7910 [14] or API 579-1/ASME FFS-1 [11] can then be carried out and known defects evaluated or tolerable defect sizes assessed.

24 Care should be taken to ensure that all sections of the vessel are considered during an assessment. Material properties may vary across the vessel, or even through thickness. For example, there have been cases where hot-formed dished ends exhibit a coarser microstructure, and therefore lower toughness, than the cylindrical shell section, or where the microstructure of the surface varies to that of the remainder of the plate.

ROUTE 3

Assumptions:

- Vessel is designed to a relevant code

AND EITHER

- Route 1 or 2 did not provide acceptable assessment

OR

- The vessel contains, or is assumed to contain, significant defects

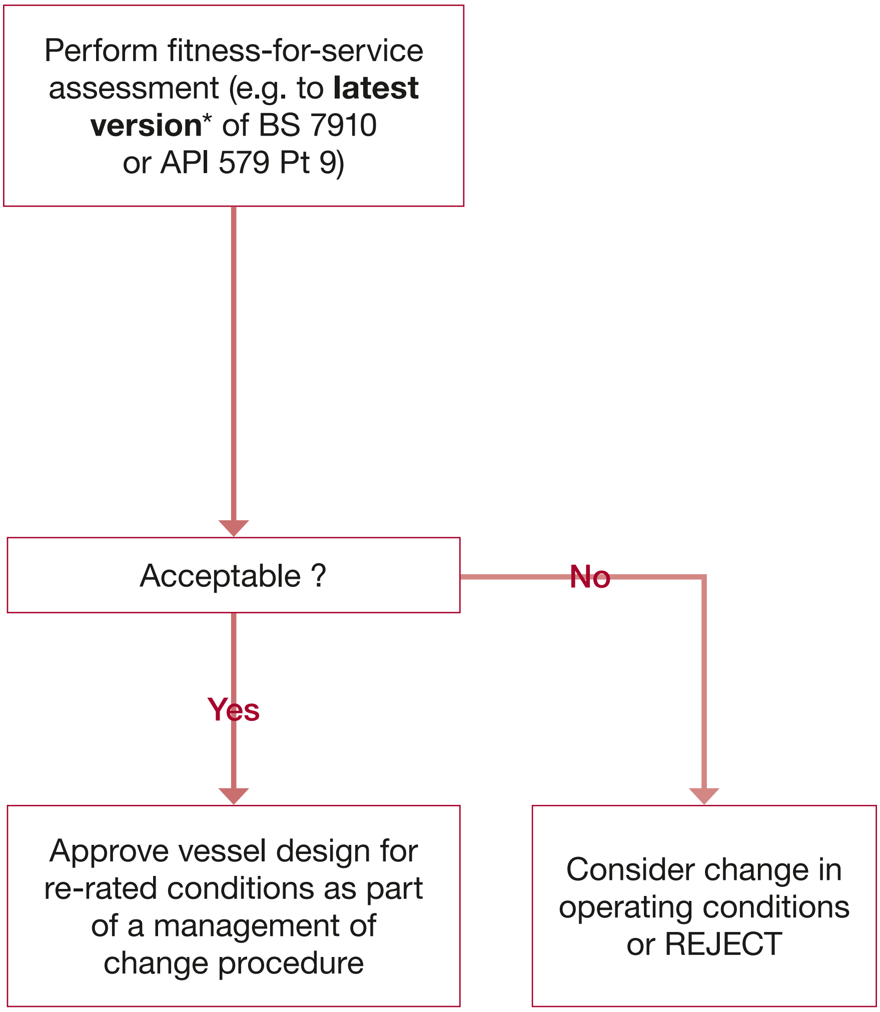


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Figure 4 Low temperature assessment (route 3)

25 Appendix U of PD 5500: 2018 and BS EN 13445-2: 2014, Annex B make recommendations on the use of fracture mechanics analyses. These recommendations apply only to a limited range of steels, and the combined requirements for limiting stresses and weld defects with certain notch ductilities may be unduly conservative in some circumstances. Subject to the availability of properly validated test data, fracture mechanics as specified in BS 7910 can be used to carry out fitness for purpose assessments beyond the limitations of PD 5500, Appendix U. BS 7910 may be used to establish the level of visual or non-destructive examination appropriate to the calculated significant defect size and location. It may also be used to give some assurance that the failure will result in crack arrest rather than rupture.

26 It is the responsibility of a competent person with expertise in fracture mechanics and stress analysis to provide the assurance of fitness for purpose.

APPROACHES BASED ON ASME/ API CODES

27 The American Standards, ASME VIII [15] and API 579-1/ASME FFS-1 [11] use a different approach to the assessment of vessels for low temperature use. These approaches are based on a *Minimum Allowable Temperature*, *MAT* (as a safe operating limit). As with BS EN 13445, there are three levels of assessment, with Level 1 being a basic screening level, Level 2 being similar to the procedure in PD 5500, and Level 3 being a full fitness-for-service assessment. Within Level 2 there are three different methods, *A*, *B* and *C*. An example of an assessment using method *B* is included in Appendix 5.

API 579 Level 2 Method A – Stress Ratio method (Calculation of safe envelope of operation in terms of allowable actual stress)

28 **STEP 1 – Determine starting MAT**
This can be based on actual impact test results or inferred from a chart relating *MAT* to plate thickness for different classes of material (exemption curves taken from ASME Code Section VIII, Division 1); thicker material (governing thickness) leads to higher minimum allowable temperature.

Note:

- These exemption curves are limited to components designed to the ASME Code, Section VIII, Division 1 or 2, and other recognized pressure vessel codes provided the design allowable stress is less than or equal to 172.5 MPa (25 ksi).
- Piping systems should meet the toughness requirements contained in ASME B31.3 at the time the piping system was constructed (or an equivalent piping code if that code contains material toughness requirements).

29 **STEP 2 – Calculate/evaluate *LOSS, FCA, E, E** and t_{min}**
The metal loss occurred to date, future corrosion allowance, weld joint efficiencies and required thickness for the vessel are calculated.

30 **STEP 3 – Determine stress ratio, R_{ts}**
The stress ratio can be calculated in terms of thickness, applied and allowable stresses, or applied and permissible pressures.

31 **STEP 4 – Determine the reduction in *MAT* based on the R_{ts} ratio**
The minimum allowable temperature can be reduced according to the value of R_{ts}. For low stress ratios, e.g. less than or equal to 0.4 for low strength materials, a reduction of up to 104 °C can be applied.

32 **STEP 5 – Further reduction in *MAT* of 17 °C if all the following criteria are met:**

a. Starting *MAT* inferred from material class and thickness
b. Component fabricated from ASME P1 Group 1 or Group 2 materials

c. Component wall thickness less than or equal to 38 mm

d. Component subject to PWHT

33 **STEP 6 – Repeat previous steps for all components**

API 579 Level 2 Method B – Hydrotest Method (Determination of MAT based on the original hydrotest temperature)

34 The starting point for the hydrotest method is the temperature at which a successful hydrotest has been performed on the vessel being assessed. A chart is provided showing the relationship between the allowable temperature reduction below hydrotest pressure, T_{RH} and ratio of expected operating pressure to hydrotest pressure, H_R. A T_{RH} value of 110 °C is applicable for pressure ratios of 0.25 and lower, to a minimum *MAT* of -104 °C. If the vessel is subjected to multiple operating conditions, a *MAT* curve can be established by plotting the temperature versus the permissible temperature.

Note: This method is largely impractical for the majority of applications.

API 579 Level 2 Method C – Approval based on past operation (grandfathering approach based on previous history)

35 This method is based on the assumption that past operation without problems shows that further use would not result in failure. This requires that no future foreseeable conditions exceed conditions experienced in the past. A detailed history of operating conditions, inspection and any repairs is required. This method cannot be used where cyclic service is a design requirement, or where the equipment is subjected to environmental cracking.

API 579 Level 3

36 A Level 3 assessment should be considered when:

- The original design did not consider susceptibility to brittle fracture
- There has been a change in operating conditions, which increases the risk of low temperatures occurring
- A PHA or HAZOP identifies process temperatures lower than the original design temperature (blowdown, auto-refrigeration, etc)
- Lower design margins are required

In some cases, it should be noted that a Level 2 assessment may provide non-conservative estimates of the MAT; in these cases, where brittle fracture is a legitimate concern or where crack-like flaws are known to exist, a Level 3 assessment will be required.

37 For Level 3 assessments, the API 579-1/ASME FFS-1 standard provides some overall guidelines, but the details of the assessment are left to the user. The fact that there is little in the way of guidance provided for a Level 3 assessment is by design. There is no practical way to codify step-by-step procedures for advanced engineering analyses because every situation is different, and there are a wide range of approaches that may be suitable for a given situation.

38 That said, a minimum number of key inputs will be required for a Level 3 assessment - in terms of: component geometry; global and local stress levels; inspection data – including for example defect size/orientation & joint efficiency; and material properties – including for example strength, ductility and toughness.

39 If the potential exists for the vessel metal temperature to drop below the MAT during service, there are a number of options available:

- Procedures may be introduced to limit the operating pressure until the vessel has warmed to the MAT.
- Re-hydrotest of the vessel at a lower temperature or higher pressure. API 579-1/ASME FFS-1 allows for a reduction in the MAT based on hydrostatic proof testing.
- In order to reduce the levels of weld residual stress in the vessel, a post weld heat treatment (PWHT) could be carried out – which could lower the MAT by 30F for some materials (provided the material thickness < 1.5").
- If the vessel material limits/sets the MAT, it may be possible to upgrade the material, i.e. a different exemption curve may be utilised. Thinner materials will have a higher toughness and hence a lower MAT.
- API 579-1/ASME FFS-1 provides a curve for determining the reduction in MAT, where vessels have excess wall thickness (based on design pressure and temperature).

CONCLUDING REMARKS

40 This guidance shows that there are three assessment routes that can be used to establish low temperature safe operating limits of a pressure vessel. Users of pressure vessels or their competent persons should have some assurance that in following an appropriate assessment route, they can demonstrate compliance with the relevant parts of current legislation.

41 The pressure vessel assessment routes for low temperature duties should be based upon the original design standard such as BS 5500 or earlier issues of BS 1500 or BS 1515. If this is not possible or the results are unacceptable then an appropriate fitness for purpose method should be used to verify that the vessel is fit for low temperature duty. The procedures in BS 1500, BS 1515, BS 5500 and BS EN 13445 are theoretical appraisals based upon known design conditions and material specifications. The fitness for purpose methods are more practical in nature and require specific data about the quality of the material and its resistance to brittle fracture. The algorithms in Figure 2, Figure 3 and Figure 4 illustrate the various assessment options. These procedures may be interpreted to apply to other recognised design standards or, in light of subsequent changes, to future standards.

42 The following general points should be noted:

- Vessels which require low temperature assessment should be subject to a thorough examination using appropriate non-destructive testing (NDT) methods for crack detection at critical locations.
- The latest issue of PD 5500, Annex D, or BS EN 13445, Annex B should be used only for the assessment of the impact property of the steel for low temperature duties. It should not be used to evaluate the design of the vessel without a thorough design review including all sources of loading, such as nozzle/piping loads.
- The use of fracture mechanics depends upon accurate metallurgical data for the grade of steel or quality of weld in question. Careful research may be needed to establish these data and the level of residual stress in or adjacent to welds.

43 Failure of a pressure vessel as a result of brittle fracture is a comparatively rare occurrence, but failures have occurred generally when a number of adverse factors have combined. The design codes do permit vessels to operate at low temperature with the material properties at or near the lower bounds of the ductile-to-brittle transition region. Experience with the use of these codes has been satisfactory when the codes are properly applied.

44 If the assessment methods used to establish the safe operating limits of low temperature are unable to achieve this objective, then the operating limits should be changed so that the vessel may be revalidated, or the vessel should be rejected and replaced by one that can be certified as fit for service.

45 In assessing any vessel, it is important to consider all the parts of the vessel. For example, it is possible that the increased reference thickness at nozzles may lead to a lower material impact test temperature being required for a given design reference temperature. Similarly, the assessment methodology should also take in to account other features, such as reinforcing pads and shell attachments, etc.

46 Self-weight, product weight, nozzle loadings, etc should also be considered. The latter will have a bearing on the stress calculation; with the worst-case scenario being the relief case (local to the nozzle). Modifications to the original design of older vessels are common, and in many cases, no PWHT would have been applied to the area of the modification. Any assessment should therefore ensure that PWHT vessels, which have been modified, are not at risk from brittle fracture.

47 It is important to record full details of the assessment. The record should include physical details of the vessel, the expected duty, material properties and the basis of any assumptions made during the assessment.

48 Consideration should be given to the inspection regime, especially if the duty of the vessel has changed in which case management of change procedures must be followed. The new regime should be recorded, together with the justifications on which it is based.

APPENDIX 1

Assessment method using PD 5500: 2018

1 PD 5500: 2018 requires that the minimum design temperature, which is used to determine the suitability of a steel to resist brittle fracture, should be the lowest metal temperature expected in service. In cases where the calculated membrane stress can vary with the minimum design temperature, for example auto refrigeration during de-pressurisation, the various combinations of stress and temperature should be evaluated to determine the combination that is most onerous for the purposes of selection of the material. A procedure for carrying out this evaluation for vessels that have a minimum design temperature of less than 0 °C is contained in Annex D of PD 5500. This procedure was derived from earlier recommended practices contained in BS 1515.

2 Annex D of PD 5500 also states that where it is difficult to meet the requirements of the standard using the specified criteria, alternative methods such as fracture mechanics, in accordance with PD 5500: 2018, Appendix U, are permitted by agreement between the purchaser, the manufacturer and the inspection authority. This flexibility in approach should be kept in mind when applying this method to existing pressure vessels built to earlier standards.

3 PD 5500 recognises that resistance to brittle fracture is related to the proper selection of materials and consideration of the following factors:

- stress level
- notch ductility of the steel
- plate thickness
- post-weld heat treatment
- extent of crack-like defects present in the vessel

4 The procedures to be used in PD 5500 are based upon determination of three parameters relevant to the material and its use:

- reference thickness of the material
- design reference temperature
- material impact test temperature

5 These parameters are determined in accordance with the rules in Annex D to cover three ranges of membrane stress in order to determine the necessary impact properties. Figure 5 and Figure 6, which are reproduced from Figures D1 and D2 of PD 5500, Annex D, are used to determine the suitability of these steels for low temperature duties. Figure 5 [D1] is for ‘as-welded’ components and Figure 6 [D2] is for ‘post-weld heat treated’ components. These figures may be used in one of three ways when this method of assessment is adopted.

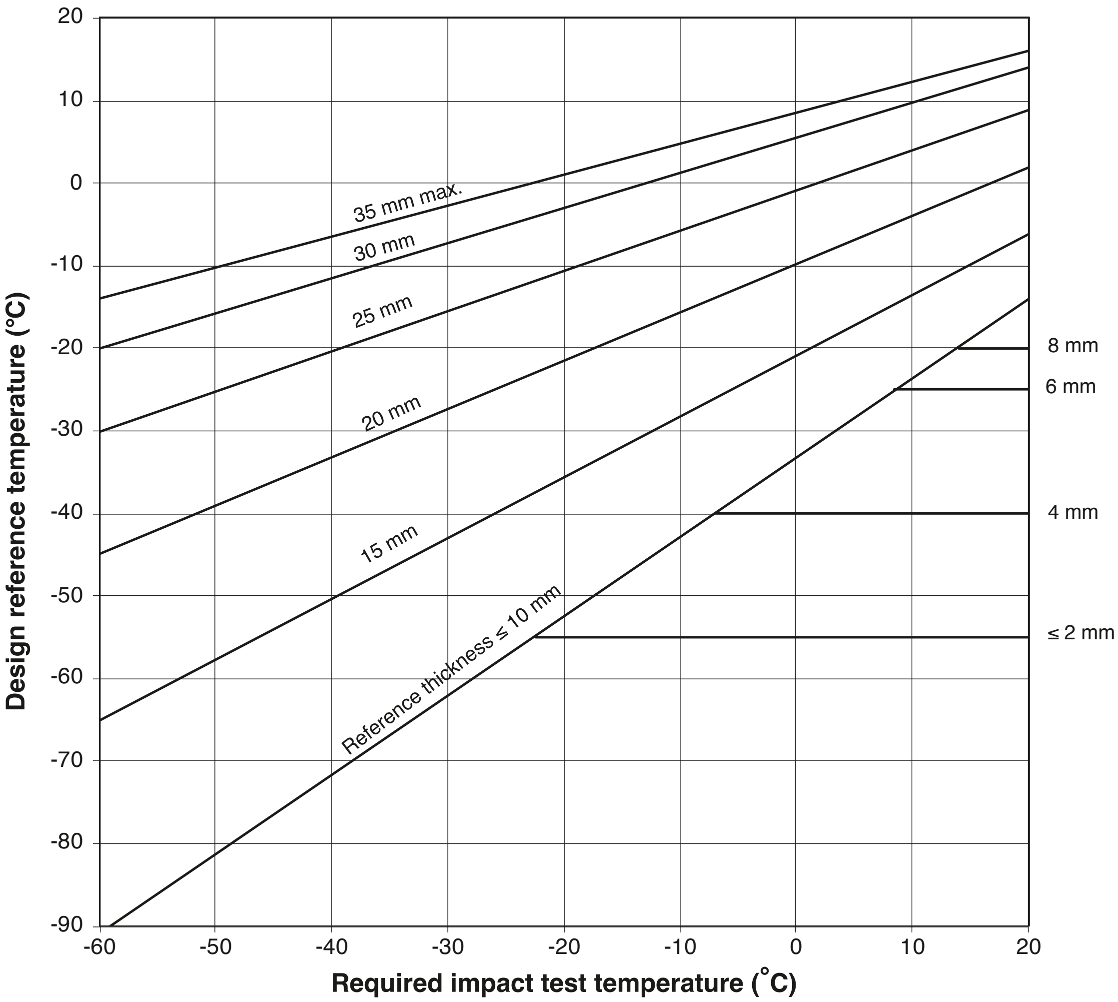

Figure 5 Relationship between design reference temperature and impact test for the as-welded condition (reproduction of Figure D.1 of PD 5500: 2018 with permission of BSI)

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6 The choice of how to use the charts is dictated by what information is readily available. For example:

i. If the material impact properties are known and the reference thickness has been established, the design reference temperatures can be found. This may be the best approach if multiple process conditions need to be assessed, as a safe operation limit envelope can be constructed.

ii. If there is initial uncertainty about the material properties, then the required material impact temperature can be found from the design reference temperature and the reference thickness. If this required temperature was obviously higher than the likely material impact temperature, then a detailed assessment of the material properties may not be necessary.

iii. If the design reference temperature is established and the material impact temperature for the steel is known, then it may be convenient to calculate the maximum allowable reference thickness. This may avoid detailed assessment of all the thicknesses of welds and connections on the vessel, if the allowable reference thickness was clearly larger than likely thicknesses.

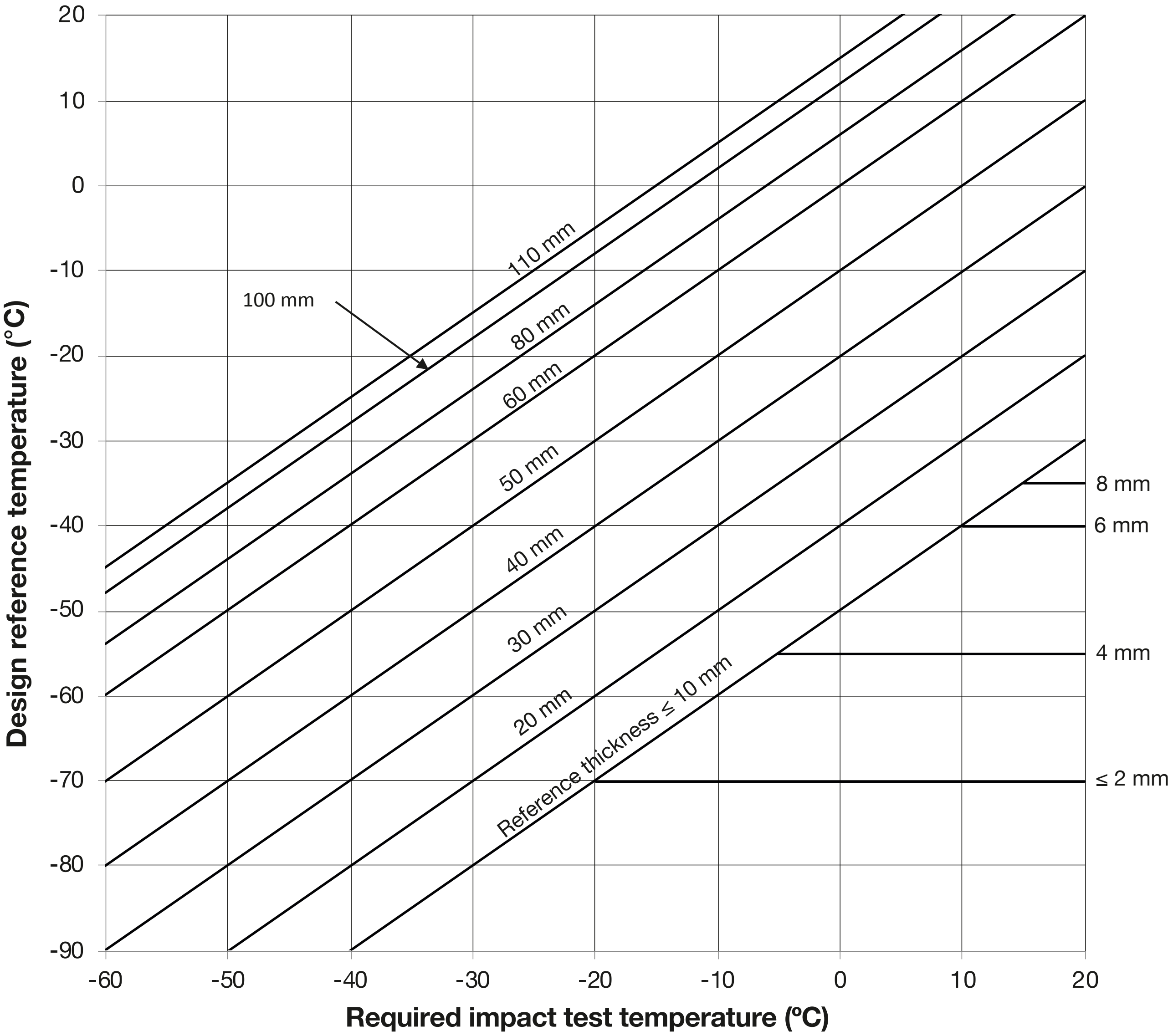

Figure 6 Relationship between design reference temperature and impact test for the non-welded or post-weld heat treated (PWHT) condition (reproduction of Figure D.2 of PD 5500: 2018 with permission of BSI)

(a) Material impact property known

If the material impact property is known (i.e. the average Charpy impact value and its test temperature), then Figure 5 and Figure 6 can be entered from the horizontal axis to cross the appropriate reference thickness to determine the design reference temperature. To satisfy PD 5500 the Charpy value may be adjusted in accordance with the rules of the standard to determine the appropriate value of 27 Joules or 40 Joules depending on the tensile strength of the steel. Where the standard permits the use of steels which are not impact tested then it is permissible to assume that the required impact properties are satisfied at 20 °C. It should be noted however that the standard specifically excludes some steels from this concession because of limitations in earlier steel specifications, as indicated in Clause 17. Figure 5 or Figure 6 can be entered at this point. If there is any doubt about the quality of a steel, then an impact value should not be assumed without further investigation.

(b) Design reference temperature known

The design reference temperature that is used for assessment purposes should be not higher than the minimum design temperature adjusted as appropriate according to the membrane stress. If the adjusted design reference temperature is known, then Figure 5 and Figure 6 can be entered on the vertical axis to cross the appropriate reference thickness to determine the required material impact test temperature. The material must achieve 27 J or 40 J at this temperature, depending on the tensile strength of the steel. The design reference temperature is calculated from the rules of the standard.

(c) Reference thickness unknown

When both the design reference temperature and the impact test temperature are known then the maximum reference thickness of the vessel can be determined. This may be a useful approach where there are significant thickness transitions, such as welded flanges or tubeplates. Annex D of PD 5500 contains rules for converting these changes in thickness to a maximum reference thickness. Calculating the maximum reference thickness may avoid the need to calculate the actual reference thicknesses in a number of areas if the maximum value is obviously greater.

7 For most cases in the assessment of operational vessels, the minimum design temperature is generally known, therefore the design reference temperature can be calculated, and (b) above should be used to determine the suitability of the steel for its low temperature duty. Where appropriate, and in addition to the minimum design temperature, the intermediate design temperatures that coincide with membrane stresses at 50 N/mm^2, ⅔*f* and *f* should be calculated and may be used as assessment check points.

8 PD 5500 also requires that other intermediate design temperatures should be evaluated at other intermediate values of membrane stress, where allowance has to be made for possible re-pressurisation while the vessel is still cold. The condition that results in the lowest value of design reference temperature should be used for the purpose of material selection. The lowest value is used to enter Figure 5 or Figure 6 at the appropriate reference thickness in order to determine the required impact test temperature at which the Charpy value specified in the standard is to be achieved. The method to be used is contained in Annex D of PD 5500 and is illustrated in Appendix 3 of this guidance.

9 It is an important part of this and other assessment methods to ensure that the vessel is subject to a thorough examination to determine the presence of any significant defects that might act as an initiator of a brittle fracture. Even if the properties do not meet the requirements of PD 5500 it is possible for a further assessment to declare the vessel fit for purpose, providing the vessel is free from significant defects. Special attention should be given to the examination of all weld seams.

APPENDIX 2

Assessment method using BS 1500/BS 1515

1 Many pressure vessels that are currently in service were designed in accordance with the superseded pressure vessel standards, BS 1500 and BS 1515. BS 5500 replaced both standards in 1976. Prior to 1972, BS 1500 and BS 1515 contained similar recommended practices for vessels required to operate at temperatures below 0 °C. In 1972, amendment number 5 to BS 1515 introduced new tentative recommended practices in Appendix C of the standard. This amendment was subsequently incorporated into the first edition of BS 5500, and was subject to revisions in later editions of BS 5500 and PD 5500.

2 The earlier versions of BS 1500 and BS 1515, prior to amendment, contained recommendations based upon the understanding at that time of the potential problem of brittle fracture of pressure vessels. These recommendations, or those of the BS 1515: 1972, Appendix C revision, may be incorporated into the assessment methods for vessels that were designed to these standards and currently remain in service. The Charpy impact test was recognised at that time and remains as the most convenient means of correlating the notch ductility of steels with service experience. It was considered then that carbon and low-alloy steels showing a Charpy-V notch impact strength of 15 ft lbs at the service temperature would have adequate notch ductility for use in fusion welded pressure vessels, with due consideration of material, thickness and operating requirements.

3 On the basis of service experience and experimental work carried out at that time it was concluded that brittle fractures were unlikely to occur except when two conditions occurred simultaneously:

a. The material exhibits low notch ductility at the service temperature; and
b. A tensile force, which may be produced by applied loads or residual stresses, of a magnitude sufficient to cause plastic deformation, is present at an existing crack or other severe notch.

4 It was considered that (a) would be eliminated if the relevant impact tested material was used and (b) would not occur in vessels designed and constructed in accordance with the standard, except possibly adjacent to welded seams in vessels not stress relieved, or at other high stress areas. The beneficial effect of the initial hydraulic test was recognised by the standards, on the assumption that the vessel would receive a controlled overstress at a temperature where the material is more ductile.

5 The recommended practices contained in BS 1500 and BS 1515 recognised two conditions that are relevant to vessels operating at low temperature.

a. That in which the pressure at the sub-zero design temperature is not less than that which would be permitted for the vessel at 0 °C by the standards;
b. That in which the pressure at low temperature will be considerably below the pressure permitted at 0 °C (e.g. in refrigerating equipment).

6 In 5(a), the relevant editions of BS 1500 and BS 1515 contain tables which set out the limits of operating temperature for vessels designed in accordance with the permitted stress levels. These limits are dependent on the grade of steel, the thickness of steel, whether it is welded and whether the vessel is stress-relieved.

7 In 5(b), consideration is given to equipment that will normally operate at low coincident temperature and pressure, and which must also be designed to withstand stresses arising during shut-down periods or during filling, when the material may remain cold as the vapour pressure of the contents rises. This equipment should be assessed in accordance with the standard using design stresses permitted for the higher pressure that may occur. It should then be verified that the nominal stresses calculated at low temperatures do not exceed the appropriate values given in the tables in the relevant edition of BS 1500 or BS 1515, for all combinations of pressure and temperature that may occur. If it is found that the stress level at some lower temperature is higher than that permitted, the design is unsuitable for these conditions.

8 The changes to BS 1515, Appendix C, in 1972 were based upon the results of a number of notched and welded Wells Wide Plate tests (WWP tests). This appendix was subsequently incorporated into the first edition of BS 5500 as recommended practice and has now become a mandatory requirement since the 1988 revision. It may be sufficient to assess vessels designed and constructed to the 1972 revision of BS 1515 in accordance with the current requirements of PD 5500. If there is any doubt, then the original design standard should be used. A similar consideration may be necessary for vessels designed to the earlier editions of BS 5500.

APPENDIX 3

Procedure for assessing potential for brittle fracture arising from primary pressure stresses using PD 5500: 2018, Annex D

1 This Appendix is for illustrative purposes only as an aid to understanding the assessment procedures. The appropriate edition of the design standard should be used for actual assessment purposes.

2 The latest issue of PD 5500: 2018, Annex D, notes that the calculated stress can vary with the minimum design temperature. The co-incident values of θ_D and θ_S, should be evaluated, allowing where appropriate for the possibility of re-pressurisation while still cold. The condition that results in the lowest value of θ_R should be used for the purposes of selection of material.

3 The design reference temperature θ_R is the temperature to be used in Figures 5 and 6 for determining the notch ductility requirements and hence the suitability of materials for resisting brittle fracture. In cases where the calculated membrane stress may vary with the minimum design temperature, it is permissible to adjust the design reference temperature to compensate for the lower stress levels, as follows:

$$\theta_R \leq \theta_D + \theta_S + \theta_C + \theta_H \qquad \textit{Equation 1}$$

where

θ_D is the minimum design temperature

θ_S is an adjustment depending on the calculated membrane stress, as follows:

> θ_S is 0 °C when the calculated membrane stress is equal to or exceeds ⅔*f*
>
> θ_S is +10 °C when the calculated membrane stress is equal to or exceeds 50 N/mm2 but does not exceed ⅔*f*
>
> θ_S is +50 °C when the calculated membrane stress does not exceed 50 N/mm^2. In this case the membrane stress should take account of internal and external pressure, static head and self-weight.

θ_C is an adjustment depending upon the construction category:

> θ_C is 0 °C for category 1 vessels
>
> θ_C is -10 °C for category 2 vessels.
>
> Note: Unlike earlier versions of BS 5500, the latest version does not allow category 3 vessels to be used for low temperature use unless high alloy (Group 8) materials are used.

θ_H is an adjustment in applications where all plates incorporating sub-assemblies are post-weld heat treated before they are butt-welded together, but the main seams are not subsequently post-weld heat treated. In these applications θ_H is +15 °C.

4 Calculating the condition that results in the lowest value of θ_R should be used for the purpose of verifying the selection of material with the necessary impact test properties as required by PD 5500. This is found by entering Figure 5 or 6 at the calculated value of θ_R and appropriate reference thickness to determine the impact test temperature. PD 5500, Annex D, should be consulted on methods for calculating the reference thickness.

Example of the use of PD 5500: 2018, Annex D

5 Consider a propane storage vessel built to BS 1515, Class 2. Assess the suitability of the vessel to operate at a minimum design temperature of -40 °C, given that the plate material is BS 1501-151-28A with acceptable impact test properties at +20 °C. The following design details are known and are used to construct Figure 7:

Shell thickness	14 mm
Shell diameter	2286 mm
Design pressure	14.5 barg
Max design temperature	+38 °C
Hydraulic test pressure	18.8 barg
Stress relief	None
Corrosion allowance	None
Vapour pressure at ⅔*f*	13.45 barg
Vapour pressure at 50 N/mm^2	6.14 barg

6 Figure 7 shows the operational duty envelope for the vessel, which in this example follows the vapour pressure/temperature curve between -40 °C and +38 °C. The minimum design temperature θ_D appropriate to the membrane stress levels of 50 N/mm^2 and ⅔*f* N/mm^2 are obtained from the curve.

Method A: Find minimum impact test temperature knowing appropriate values of θ_D.

7 The significant design temperatures are assessed; these correspond to the lowest temperature, and the temperatures at which pressures corresponding to membrane stresses of 50 N/mm^2 and ⅔*f* occur, as shown in Figure 7. At these temperatures, the membrane stress adjustments, θ_S, reduce.

8 The design reference temperatures, θ_R, are obtained for each of design temperatures, θ_D, identified using equation 1:

At θ_{D1} = -40 °C,

f < 50 N/mm^2, so θ_S = +500 °C

$\theta_{R1} = \theta_D + \theta_S + \theta_C + \theta_H$

$\theta_{R1} = -40 + 50 - 10 + 0$

θ_{R1} = 0 °C

At θ_{D2} = +11 °C,

$f \geq 50$ N/mm^2, so θ_S = +10 °C

$\theta_{R2} = +11 + 10 - 10 + 0$

θ_{R2} = +11 °C

At θ_{D3} = +36 °C,

$f \geq ⅔f$, so θ_S = 0 °C

$\theta_{R3} = +36 + 0 - 10 + 0$

θ_{R3} = +26 °C

Therefore, lowest design reference temperature (θ_{R1} = 0 °C) occurs at θ_{D1}, the minimum operation temperature. It is only the lowest value of design reference temperature that needs to be assessed in the next stage.

9 With reference to Figure 8 using the lowest design reference temperature of 0 °C, it can be concluded that a maximum reference thickness of 18 mm would be acceptable at +20 °C. This vessel, with a shell thickness of 14 mm, is therefore satisfactory for its intended duty under normal operating conditions, i.e. following that vapour pressure curve.

10 The upset condition also needs to be assessed. This corresponds to a condition where the vessel material is at a lower temperature (-18 °C) while it is pressurised to 8 bar. This pressure would correspond to a membrane stress in the region of between 50 N/mm^2 and *⅔f.*

$f > 50$ N/mm^2, so θ_S = +10 °C

$\theta_{RU} = \theta_D + \theta_S + \theta_C + \theta_H$

$\theta_{RU} = -18 + 10 - 10 + 0$

θ_{RU} = -18 °C

11 With reference to Figure 8, given a reference thickness of 14 mm, the vessel would not be acceptable under the upset condition. There are a number of options available:

- Obtain more accurate material data. The original assessment may have been based on minimum standards for a generic pressure vessel steel. Obtaining more data, for example, the specific grade of steel used, or actually testing samples at the required impact temperature, may enable the acceptability of the vessel to be established. In this case, if it could be demonstrated that acceptable impact values could be obtained at a temperature of +7 °C, the vessel would be suitable for use under the upset conditions.
- Reassess to a different code. It is possible that reassessing to a different code, such as BS EN 13445, API 579/ASME FFS-1 or a fracture mechanics approach, would provide a successful assessment. See Appendix 4 for an assessment of the same vessel to BS EN 13445.
- Take measures to ensure that the upset condition cannot happen. The vessel is suitable for normal operating conditions, so preventing the upset condition occurring would enable continue use of the vessel.
- Withdraw the vessel.

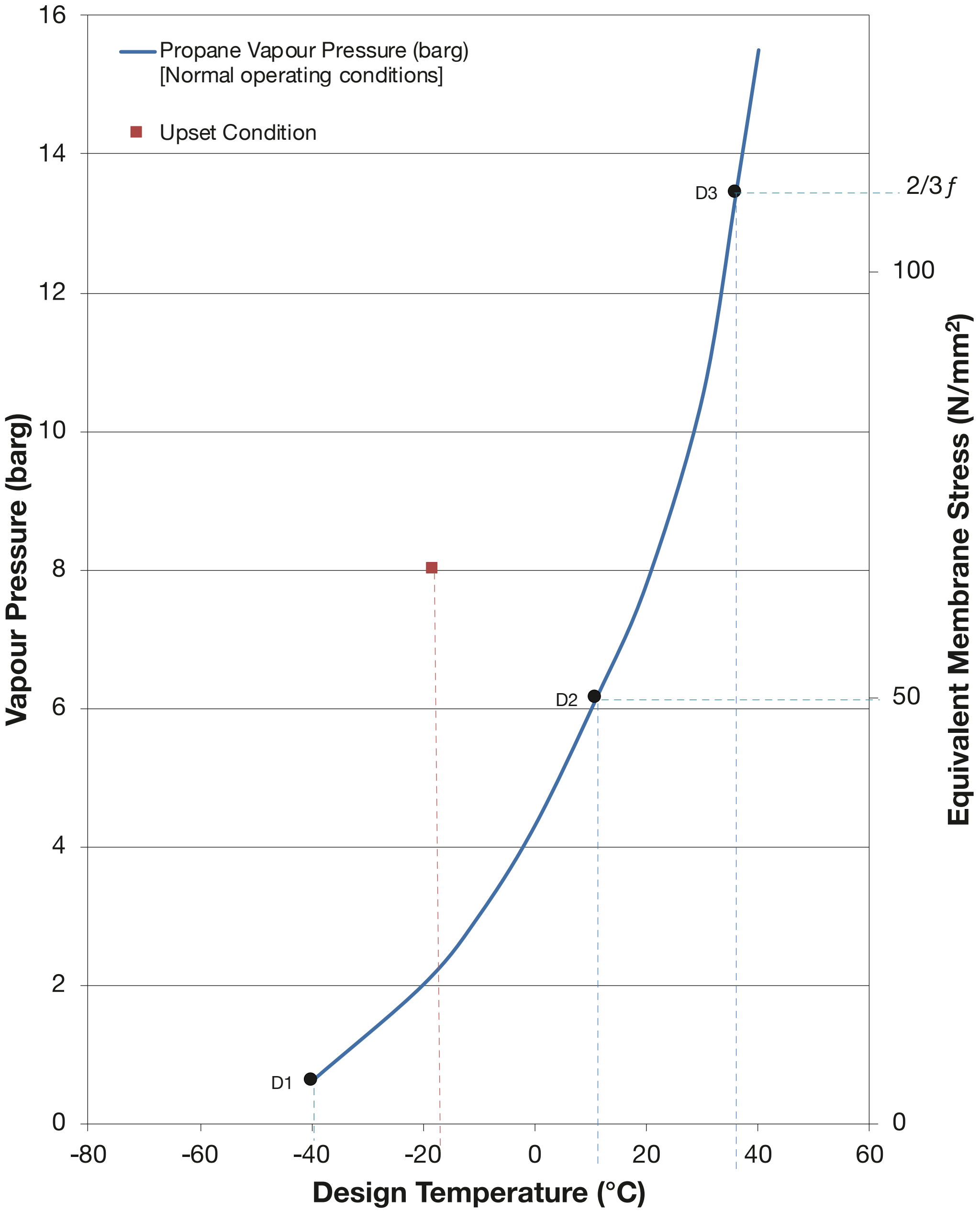

Figure 7 Obtaining the design temperatures to be assessed from the operating conditions

Method B: Find minimum design temperature θ_D, with known impact test properties at +20 °C.

12 With reference to Figure 8, at a test temperature of +20 °C for 14 mm plate, the design reference temperature has a value of θ_R = -8 °C. Substitute this in equation (1) (see paragraph 3) to obtain a design duty envelope (see Figure 9).

At f ≥ ⅔*f*

$$\theta_{D3} = \theta_R - \theta_S - \theta_C$$

$$\theta_{D3} = -8 - 0 + 10$$

$$\theta_{D3} = +2\ °C$$

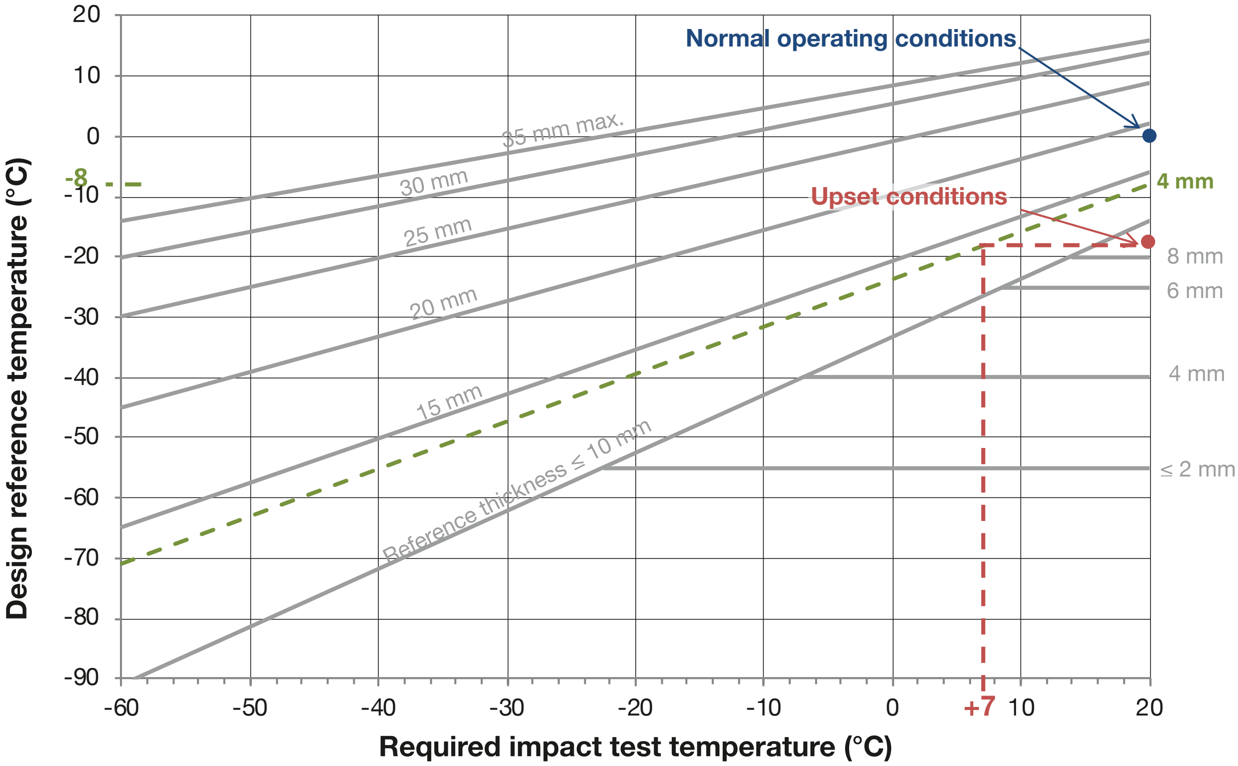

Figure 8 Normal operating conditions acceptable as allow thicknesses in excess of the vessel reference thickness. Upset conditions would require a lower impact test temperature.

At f ≥ 50 N/mm²

$\theta_{D2} = -8 - 10 + 10$

$\theta_{D2} = -8$ °C

At f < 50 N/mm²

$\theta_{D1} = -8 - 50 + 10$

$\theta_{D1} = -48$ °C

13 The modified safe operating envelope in Figure 9 shows that the impact test properties are satisfactory for all normal operating conditions (along the vapour pressure curve).

14 The upset condition, however, lies on the unacceptable side of the safe operating limits envelope. As for method A, a number of options are available when this is the case (see paragraph 11).

Note 1: Other parts of the vessel, for example the hemispherical heads, which have different reference thickness and different membrane stresses should be assessed accordingly.

Note 2: Where changes in thickness occur at transitions or reinforcements then the equivalent reference thickness should be calculated in accordance with PD 5500.

Note 3: The membrane stress in this example is based on the coincident vapour pressure of propane. If the vessel can be subject to other sources of stress, for example thermal stresses or pipework loading these should be taken into account. Guidance on the analysis of nozzle loads

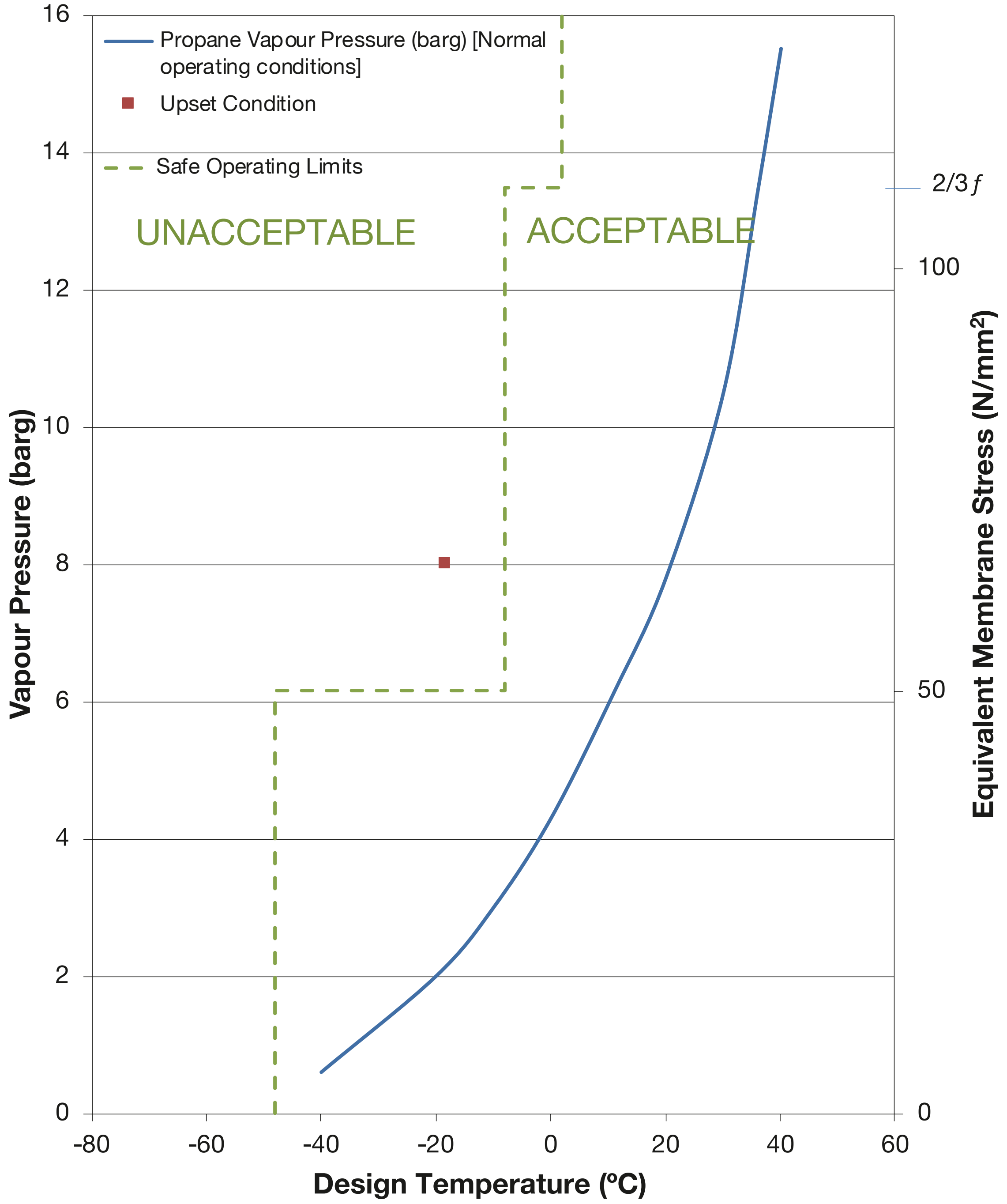

Figure 9 Operational Duty Envelope

should be carried out in accordance with the vessel design code. The methods for analysis and determination of piping loads and stresses can be found in ASME B 31.3 Process Piping, PIP PNC00004 Piping Stress Analysis Criteria for ASME B31.3 Metallic Piping and BS EN 13480 Metallic industrial piping. Consideration of the suitability of piping for low temperatures should also be determined by reference to these codes or API 579 -1/ASME FFS-1.

Note 4: Caution should be taken when applying Annex D to vessels not constructed to BS/PD 5500. A Level 3 fitness-for-service specialist should be consulted in this situation.

APPENDIX 4

Example of the use of BS EN 13445-2:2014, Annex B

1 The vessel assessed to PD 5500: 2018 in Appendix 3 was found to not conform to the requirements for the upset condition. BS EN 13445-2: 2014 contains a more detailed analysis, providing different relationships for different strengths of material, which can lead to a reduction in conservatism compared to PD5500, especially for materials of a low strength. Therefore, the vessel will be re-assessed using BS EN 13445-2: 2014.

2 The vessel details are the same as those listed in Appendix 3 (page 28).

3 The plate material (BS 1501-151-28A) has a specified minimum yield strength of below 265 MPa and the vessel was in the as-welded condition. Therefore, Figure B.22 of BS EN 13445-2:2014 should be used to assess the design reference temperature (T_R).

4 It is known that acceptable impact test properties (>27 J for this material) were obtained at a test temperature of +20 °C, and that the material thickness is 14 mm. For this example, this will be assumed to be the reference thickness; Table B.4-1 should be checked to determine if a different value for the reference thickness should be used to accommodate different construction details such as nozzles or flanges. Given this information, a design reference temperature can be obtained, as shown in Figure 10.

5 A temperature adjustment can be made, which has the effect of increasing the design reference temperature when stresses in the vessel are low. Table B.2-12 gives the values for the temperature adjustment, T_S. For the as-welded condition, the value of T_S when membrane stress is ≤50 MPa is +40 °C. Unlike PD5500, no other adjustments can be made.

6 The relationship between the design temperature, T_D and the design reference temperature T_R, is:

$$T_R = T_D + T_S$$

As the design reference temperature has been found to be -35 °C, the minimum design temperature is therefore -35 °C when the membrane stress is higher than 50 MPa, and 75 °C where the membrane stress does not exceed 50 MPa. The duty envelope can then be plotted onto the vapour pressure chart for propane, as shown in Figure 11. For this vessel, a vapour pressure of 6.1 barg corresponds to a membrane stress of 50 MPa. All combinations of temperature and pressure on the vapour pressure chart lie above the minimum design temperatures, so the vessel is safe under the normal operating conditions.

7 An upset condition, where the vessel could be charged with propane at 8 barg while the bulk temperature of the vessel is at -18 °C, is plotted on the chart. In contrast to the assessment to PD5500, this condition is acceptable to BS EN 13445.

Table 1 Temperature adjustment, T_s[a] (reproduction of Table B.2-12 of BS EN 13445-2:2014 with permission of BSI)

	Ratio of pressure induced general membrane stress f and maximum allowable design stress f_d			Membrane stress[b]
Condition	$f/f_d > 0.75$	$0.75 \geq f/f_d > 0.25$	$f/f_d \leq 0.25$	≤ 50 MPa
Non-welded or post-weld heat treated	0 °C	$T_s = 70 - 80 \times f/f_d$ [°C]	+50 °C	+50 °C
As-welded	0 °C	0 °C	0 °C	+40 °C

a Except for material group 9.1, 9.2 and 9.3, T_R shall not be lower than -110 °C for ferritic and austenitic-ferritic steels.

b The membrane stress shall take account of internal and external pressure and dead weight. For walls and pipes of heat exchangers the restraint of free end displacement of the heat exchanger pipes should also be taken into account.

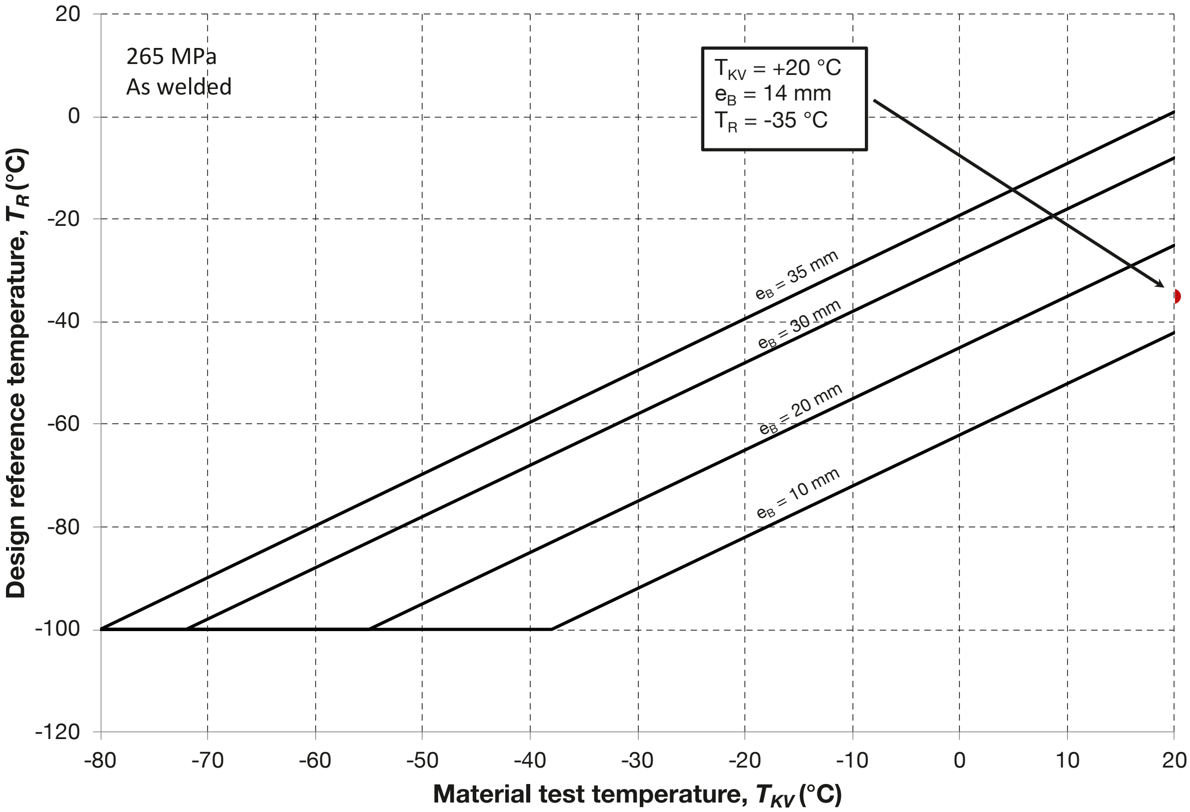

Figure 10 Determination of design reference temperature, T_R, from thickness and test temperature data using Figure B.2-2 of BS EN 13445-2:2014 with permission of BSI

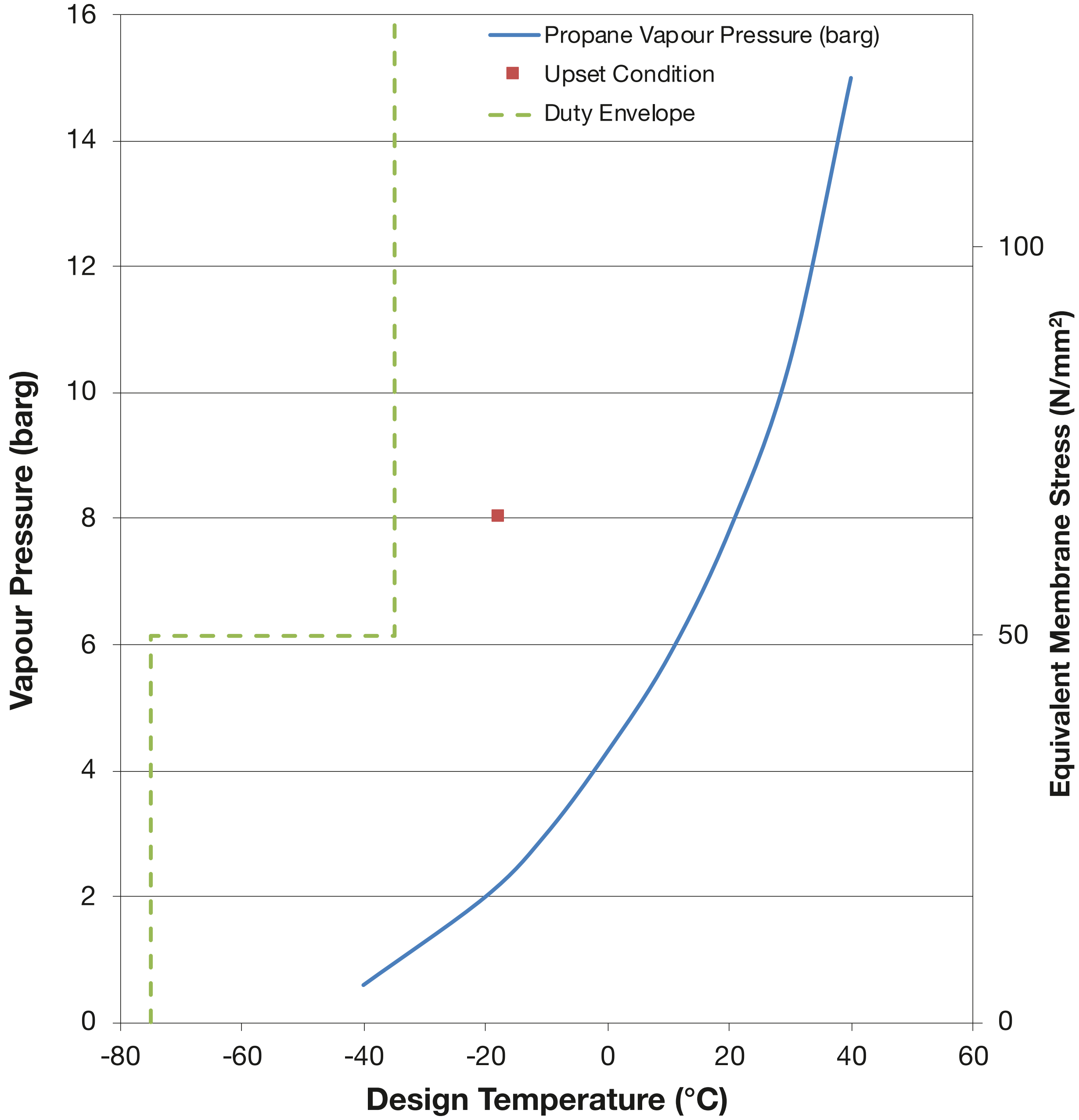

Figure 11 Vapour pressure diagram from propane showing duty envelope

APPENDIX 5

Assessment of chloromethane storage tank

Shell thickness	30 mm
Head thickness	43 mm
Shell diameter	2430 mm
Design pressure	8.6 barg
Max design temperature	+88 °C
Hydrotest pressure	12.9 barg
Hydrotest temperature	+20 °C
Stress relief	None
Corrosion allowance	None
Design strength	100 MPa
Lowest operating temperature	-24.2 °C

1 The thickness of the head of the vessel is 43 mm. As it is assumed that the vessel is in the as-welded condition, the thickness exceeds the maximum thickness of 35 mm according to PD 5500: 2018 and BS EN 13445: 2014.

2 As the thick head section is welded to a thinner shell section, it is possible that the maximum reference thickness of the joining weld is within the 35 mm limit. In this case, the full 43 mm thickness of the head would apply only to the non-welded head section. However, without detailed geometry data, this assumption should not be made.

3 The vessel was successfully hydrotested to a pressure of 12.9 barg (150 % of the design pressure) at a temperature of 20 °C. Therefore, the approach contained in Section 3 of API 579-1/ASME FFS-1 for the evaluation of vessels based on hydrotest can be used.

4 The design operating pressure of 8.6 bar would result in an H_R ratio (maximum expected operating pressures/hydrotest pressure) of 0.67.

5 Using the equation given in API 579/ASME FFS-1 for calculating the temperature reduction below hydrotest temperature, T_{RH}, a new minimum allowable temperature, *MAT*, can be obtained:

$$T_{RH}\,(^{\circ}\mathrm{F}) = 52.1971 - 53.3079H_R - 15.7024H_R^2 + \frac{16.7548}{H_R}$$

Equation 2

For the design pressure, T_{RH} would be 19 °C, which would give a minimum allowable temperature at the design pressure of +1 °C.

6 The vessel would not be safe to operate at the design pressure at temperatures below +1 °C under this assessment. However, at low temperatures the pressure would be much lower. The maximum operating pressure for various temperatures can be assessed to generate an operating

envelope (Figure 12). For example, the lowest operating temperature of -24.2 °C equates to a T_{RH} value of 44.2 °C, which in turn equates to an H_R value of 0.35 (4.5 barg).

7 The vessel would therefore be acceptable for use under normal conditions where the internal pressure is directly related to the temperature. Careful consideration must be given to the possibility of start-up, shutdown or upset conditions, to ensure that any foreseeable temperature/pressure combinations that may arise do not lead to pressures above the maximum operating pressure curve.

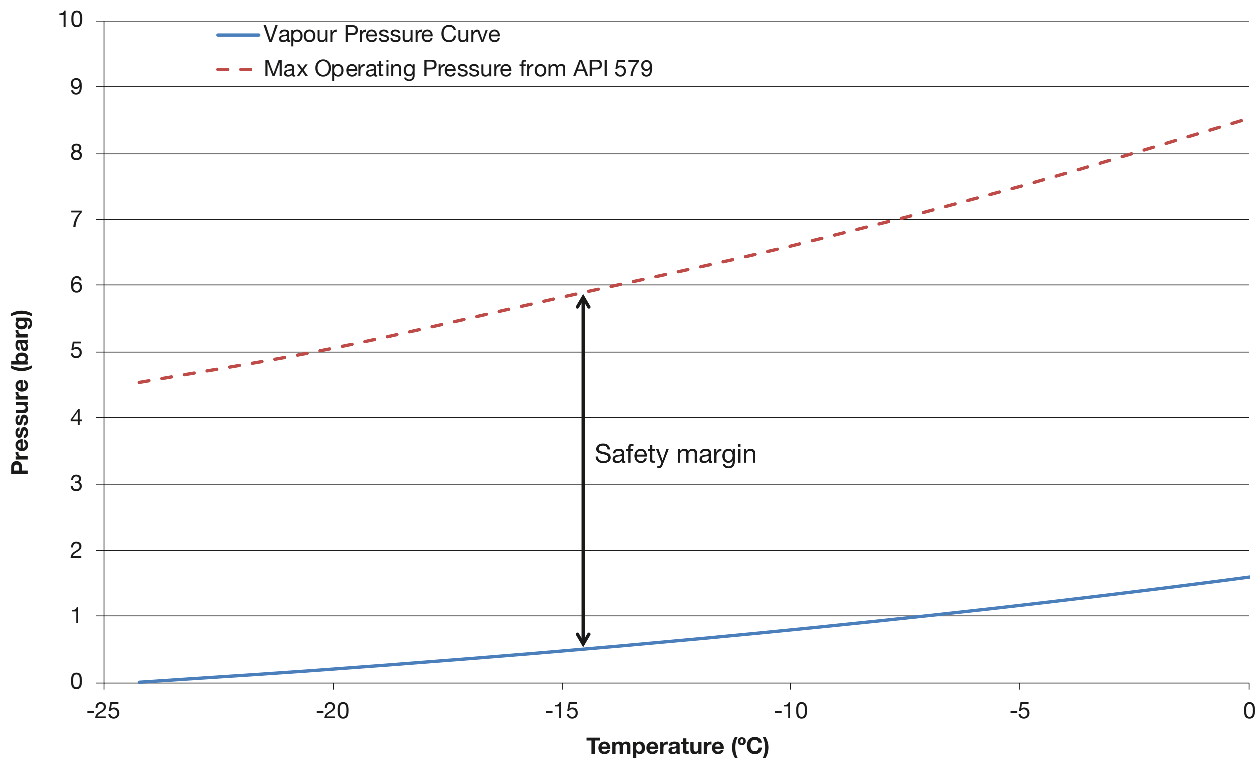

Figure 12 Pressure v temperature for a chloromethane storage tank

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