# Mentor Expectation Guide: T73S01 - Perform Structural Assessments using Pressure Vessel or Pipework Design Codes

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*These Mentor Expectation Guides are a personal opinion regarding the minimum knowledge and understanding commensurate with professional expertise in the area. They are not definitive and are not endorsed by any organisations.*

## 1.1 Explain the scope of pressure vessel and pipework design codes, their major elements and the responsibilities implied.

It is particularly problematical to define expectations for Mentor Guide T73S01 due to the huge scope of the relevant design codes. Whilst the R5 and R6 documents are large, they do fit into a single physical file – making the corresponding Expectations reasonably tractable. Many design codes are of similar bulk, but there are a great many of them. Moreover, the ASME BPV code alone fills an entire cabinet. Also, whereas R5 and R6 are concerned exclusively with structural assessment, the design codes cover both this area and all aspects of design, construction, inspection and testing. Hence many different professional disciplines would be involved in a complete understanding of all aspects of design codes. However, the purpose of T73S01 is to ensure competence in respect of the structural assessment issues of pressure vessel and piping codes. The important distinction here is between how structural analysts use design codes (i.e., as a structural assessment methodology) and the overall purpose and scope of design codes. Nevertheless it is important, even for a structural analyst, to have some appreciation for the other aspects of the codes. This is required under T73S01.

Design codes are intended to define the whole design process from the point at which a requirement for a pressure vessel/pipework (PV/P) is identified to the hand over of the completed PV/P to the purchaser. Compliance with **all** of these requirements provides a high level of confidence in the structural integrity of the vessel/pipework against the design conditions and can be a legal requirement to operate such plant, though not always (see 1.3 below).

The major elements of any PV/P design code are:

- Scope of work (including Function) and Responsibilities
- Materials
- Design
- Manufacture/Installation
- Inspection
- Testing

The responsibilities are defined in each code, but typically distinguish between the purchaser, the manufacturer and an inspection and/or regulating authority. As an example, BS-EN13480 says,

- The **manufacturer** is the person or organization that takes full responsibility for the design and manufacture of the piping system and its conformity to EN 13480[*].

- The manufacturer is responsible for carrying out all relevant production processes and testing as specified in the applicable standards.
- If a manufacturer employs subcontractors or fabricators/installers for certain items he is responsible for their work.
- In the EC Member States a manufacturer or his representative is responsible for the conformance of a piping system he puts on the market, with the essential safety requirements of the PED (see 1.3 below).
- The manufacturer shall be responsible for the identification of the piping class of the piping system. (Note the contrast with the USA/ASME, where, "*it is the responsibility of the owner to satisfy the regulatory requirements*", from which the Class is derived[1]).
- The **piping fabricator and/or installer** is the individual or organization that takes responsibility for the fabrication and/or installation of industrial piping. This is just a tautology, but the point is that this body may be different from the manufacturer.
- *Confusingly it also says that the **designer** is the individual or organization that takes responsibility for the design of industrial piping complying with the requirements of EN 13480.

However, responsibilities may differ in other codes, particularly in ASME, in which US state legislature plays a significant role.

The **purchaser/operator** is notably absent from the above bullet list of responsibilities. Quite how the above list would be interpreted in the case of *modifications* to our existing plant (with which we are currently most concerned in Nuclear Generation) would make an interesting discussion point.

However, irrespective of what the design codes may say, in the nuclear context a UK Licensee has an overriding responsibility via the Nuclear Installations Act, the Ionising Radiation Regulations and other Acts of Parliament. The continued maintenance of a nuclear site licence requires processes of assessment and review to be in place which subsume and considerably enhance the minimum requirements for non-nuclear pressurised systems. In particular, nuclear plant is subject to formal safety case submissions to the Office of Nuclear Regulation (formerly the Nuclear Installations Inspectorate) and this forms part of the licensing procedure.

A key message is that design codes should ideally be adopted *in their entirety*. Using one design code for one aspect of design, but another code for another aspect, is referred to as "cherry picking" and is discouraged in principle. The reason is that the codes give assurance of the integrity of the assembly in a holistic manner. For example, a more lenient thickness requirement in a code may be compensated by more onerous requirements elsewhere, such as in flexibility requirements or as regards inspection or testing. Adopting the most lenient requirements from a selection of different codes is not acceptable.

There are occasions, however, when the use of multiple codes or other methodologies is unavoidable – and may actually be desirable to enhance integrity. This may arise if the principle design code contains no guidance on certain issue, e.g., seismic design,

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[1] See §8.1 of the "*Companion Guide to the ASME Boiler and Pressure Vessel, Volume 1*", edited by K.R.Rao.

and additional restrictions must be imported from another code. Another example is if knowledge of specific degradation mechanisms has advanced, but not yet been accommodated within the design code. For example, a competent practitioner would be aware of the potential threat of reheat cracking in thick section austenitic weldments intended for operation in the creep regime and might stipulate post-weld heat treatment even though the chosen code may not require it.

A structural analyst may wish to use design codes to demonstrate that the condition of installed and in-service plant complies with (some portion of) the design aspects of a code in a *post hoc* manner. In other words, in the context of operating plant, the analyst may use a design code as a “fitness-for-purpose” (FfP) methodology. Further discussion of FfP methodologies is beyond the scope of this Mentor Guide. In brief, however, the onus is upon the competent practitioner to ensure that the methodology deployed is technically capable of assessing the threats which purport to be addressed. Structural parts of design codes may well be useful in this context, although undesirable cherry-picking should be avoided. This is part of the responsibility of the assessor.

Is compliance with a design code necessary? Is it sufficient? The answers will vary according to the duty of the component. For components of little or no nuclear safety significance, satisfaction of design code criteria may be sufficient. However, for components of nuclear safety significance, satisfaction of design code criteria alone is often not sufficient – see BEG/SPEC/DAO/011 *Guidance on AGR Structural Integrity Related Safety Cases* for more guidance. Furthermore, for existing plant, safety cases may not regard design code compliance as necessary. Instead the structural integrity may be assured using other methodologies, such as R5 or R6 or purpose written procedures for specific plant areas – see for example E/REP/BDGBB/0100/AGR/06 *Methodology for Calculating Minimum Acceptable Thicknesses for AGR Outage Referrals and Databases.*

### 1.2 Define the major component parts of a typical design code.

The major elements of any PV/P design code have already been listed above, i.e.,

- Scope (including Function) and Responsibilities
- Materials
- Design
- Manufacture/Installation
- Inspection
- Testing

However, interpreting the “major component parts” as actual physical components then the following typically are considered:-

- Vessel nominal shell / plain pipe
- Vessel ends / domes
- Nozzles or branches: large / medium / small bore
- Tubeplates

- Elbows, bends (including mitres) and reducers
- Supports, including their attachments to the vessel/pipe
- Connections (e.g. bolted flanges)
- And, of course, the weldments that occur on all the above

### 1.3 Describe the role of the Pressure Equipment Directive, the Pressure Equipment Regulations and the Pressure Systems Safety Regulations.

Pressure Equipment Directive / Pressure Equipment Regulations

The Pressure Equipment Directive 97/23/EC (PED) of the European Parliament, 29 May 1997, came into force in the UK via the Pressure Equipment Regulations 1999 (29 November 1999). The main aim of this legislation is to remove technical barriers to free trade in respect of the design, manufacturing and supply of pressurised equipment. As such, the PED does not address issues of use, servicing, repair or minor modifications to existing equipment. Completely new pressurised equipment, or equipment being subject to significant modification, would potentially be subject to the requirements of the PED. However, the scope of the PED (Article 1, paragraph 3.8) excludes "*items specifically designed for nuclear use, failure of which may cause an emission of radioactivity*."

This same "nuclear exclusion clause" occurs verbatim within the Euro-codes such as BS-EN13480 and BS-EN13445 (about which more is said in 1.4 below).

The adoption of the harmonised European codes, such as BS-EN13480 and BS-EN13445 will ensure compliance with the PED. Older BS codes may provide a mapping between the PED requirements and those of the code, e.g., Annex Z of PD5500. This facilitates demonstration that code compliance implies compliance with the PED.

The Pressure Systems Safety Regulations 2000 (PSSR)

The PSSR came into force by act of parliament on 21 February 2000, replacing the earlier Pressure Systems Regulations. They are specific to Great Britain. In contrast to the European PED, the PSSR primarily concerns the ***safety*** of pressurised systems in use. Hence, the PSSR are complementary to the PED. Consistent with the main thrust of the PSSR being safe usage, the main component of the regulations concerns the drawing up of, and adherence to, Written Schemes of Examination. However, the PSSR is not prescriptive as regards the required design code. In respect of design, the PSSR requires only that, "*the pressure system or article, as the case may be, shall be properly designed and properly constructed from suitable material, so as to prevent danger*".

Hence, the PED/PER are most relevant to new plant, whereas the PSSR is most relevant to existing plant. In practice it is the PSSR which has the most significant impact upon Nuclear Generation (whereas, I suppose, the PED/PER will have most impact upon New Build).

Some more thoughts on the PSSR:-

- Limits on pressure/volume product (250 bar.litres)

- Implications of relevant fluid (e.g. steam is special)
- Not applicable to transportable gas cylinders, but is applicable to pipework which can be pressurised by a non-permanent source
- Difference between pipework and pipelines

### 1.4 Explain which specific design codes are most relevant to nuclear power plant pipework and pressure vessels (excluding PCPVs)

The most relevant design codes are:

- ASME BPV – more specifically,
  - Section III *Rules for Construction of Nuclear Facility Components*, especially,
    - ➢ Subsection NB (Class 1 components);
    - ➢ Subsection NC (Class 2 components);
    - ➢ Subsection ND (Class 3 components);
    - ➢ Subsections NB,NC,ND-3600 (nuclear piping – formerly B31.7)
    - ➢ Subsection NF (supports)
    - ➢ Subsection NH (components at high temperatures);
    - ➢ Division 3 subsection WC (spent nuclear fuel storage containment)
  - Section I (boilers);
  - Section II (materials);
  - Section VIII (pressure vessels) ;
  - Section XI (inspection);
  - ASME B31.1 (power piping – not nuclear specific)
- PD5500:2009: This superseded BS5500 and its predecessors (BS1500, BS1515). It was downgraded to a Published Document (PD) as a result of national design codes having to be withdrawn following the publication of the Euro Norm code BS-EN13445. So it is not now a British Standard. Quite where this half-dead status leaves us I'm not sure.
- BS806:1993. This code was withdrawn by British Standards in July 2002. Unfortunately this left the UK with no piping code applicable to nuclear significant pipework (due to the "no-nuclear" exclusion clause in the Euro code replacement, BS-EN13480). This is discussed in detail below.
- BS1113:1999 (water-tube boilers): This is specific to boilers and hence is not often used these days for modification purposes in Nuclear Generation (since mods are almost invariably external to the PCPV). However, the ubiquitous "inverse code" reference stress solution for pipework branches is based on the design curves in this code.
- BS EN 13445 (pressure vessels) – "new" euro norm code, but specifically excludes application to components *specifically designed for nuclear use, failure*

*of which may cause an emission of radioactivity*." Unlike pipework, for which this "no nuclear" clause has caused considerable difficulty, in the case of pressure vessels the older PD5500 is still available (albeit downgraded in status).

- BS EN 13480 (piping) – "new" euro norm code, specifically excludes application to components *specifically designed for nuclear use, failure of which may cause an emission of radioactivity*." This is discussed in detail below.
- RCC-M: The French nuclear code, which started off essentially as a copy of ASME but which may have diverged by now. This code will be of increasing importance due to its use in EPR new build.
- RCC-MR: The fast reactor version of RCC-M.
- Others potentially relevant codes include,
  - BS3351 (petrochemical plant)
  - BS3274 (heat exchangers)
  - For more relevant design codes see the reviews conducted for station-specific PSR Discipline Based Reviews (DR2), e.g. E/REP/BDGBC/0068/AGR/05.

Also deserving of an honorary mention, though not relevant to this Mentor Guide, are,

- BS 7910 – fracture mechanics methodologies (essentially a cut-down version of parts of R5 and R6)
- API-579-1 – fitness for purpose assessment methodology, which majors on corrosion issues.

Specific observations on some of these codes are as follows,

- Users of ASME are strongly recommended to read the relevant parts of the "*Companion Guide to the ASME Boiler and Pressure Vessel, Volume 1*", edited by K.R.Rao. This provides a readable account of the thinking behind the design rules in ASME, which is often hard to unravel from the code itself.
- The 1967 version of BS806 1967 was used for the design of much of the pipework in the older AGRs. Unfortunately the pipe branch reinforcement rules in the 1967 version were insufficiently restrictive, a fact that was realised in later issues of BS806, and in other more recent piping codes. This has led to widespread under-design of pipework branches in the older AGRs compared to modern design standards. This has been recognised for a long time and has been addressed by appropriate fitness-for-purpose assessments.
- On the issue of which design code to employ, it is the engineer's responsibility to use their professional judgement as to the most appropriate code, taking account of the scope of each code. The following observations are relevant,
- In the "*Companion Guide to the ASME Boiler and Pressure Vessel Code*" it is noted that "*the selection of the appropriate Code Section or Division is a decision to be made by a responsible, knowledgeable engineer. Selection of the appropriate Code should be based on Code content and the user's needs, not on the title of the Code book.*"
- In ASME B31.1 (power piping) it is stated that *" It is the owner's responsibility to select the Code Section which most nearly applies to a proposed piping*

*installation. Factors to be considered by the owner include: limitations of the Code Section; jurisdictional requirements; and the applicability of other codes and standards".*

- For advice on the code to employ following the withdrawal of BS806 see E/EAN/BDGBB/0122/AGR/06 *Advice on Pipework Design Codes Applicable to AGRs Following the Withdrawal of BS806*.

This last point is amplified in detail below.

<u>Piping Design Codes for use in Existing UK Nuclear Plant</u>

The withdrawal of BS806 in 2002 together with the "no nuclear" clause in its intended Euro-code replacement, BS-EN13480, left the UK with no piping code applicable to nuclear significant pipework. As a result, for many years after 2002, BS806 continued to be used in British Energy (now EdF Energy Nuclear Generation) for modifications to existing nuclear power plant. The issue of which piping code to use for modifications to existing nuclear plant in the UK was addressed in 2006 by Bradford in E/EAN/BDGBB/0122/AGR/06 *Advice on Pipework Design Codes Applicable to AGRs Following the Withdrawal of BS806*. This advised that,

- For piping systems in the "frequent" tolerability of failure category, or of no nuclear safety significance, the Eurocode BS-EN13480 is recommended.
- For piping systems in the "infrequent" nuclear safety category operating below the creep temperature regime, the ASME Boiler & Pressure Vessel Code, Section III, Subsection NC is recommended as regards the mechanical design.
- For piping components in the higher nuclear safety categories (IoGF, HI, IoF), or for "infrequent" category creeping systems, the ASME Boiler & Pressure Vessel Code, Section III, Subsections NB and NH are recommended as regards the mechanical design.

In particular the continued use of the withdrawn BS806 was not recommended. Formal instruction to cease use of BS806 in favour of BS-EN13480 for plant in the "frequent" category has been issued by the Chief Mechanical Engineer via Learning Briefs and AR 589208, 7th June 2010 and 4th March 2011, "*It is no longer acceptable to utilise BS 806 for any work undertaken at station, even direct replacement of components within existing pipework systems qualified to BS 806 must adopt the requirements of BS EN 13480 for this work*" (OPEX Event Brief EB-11-108). In addition issues relating to inspection and acceptance criteria are addressed in Event Brief EB-11-109. In particular, "*the default NDT acceptance criteria shall always be BS EN ISO 5817:2007 Quality Category B*". Further detailed guidance on welding, inspection, testing and acceptance criteria in relation to the adoption of BS-EN13480 is being devised by a Working Group at the time of writing and will be the subject of staff training in due course.

Note that the guidance in E/EAN/BDGBB/0122/AGR/06 regarding the appropriate code versus the nuclear safety duty was based upon the assumption that the following approximate correspondence with ASME Class was sound,

"Frequent" = ASME Class 3 = ASME III ND or EN13480

"Infrequent" = ASME Class 2 = ASME III NC

"IOGF/HI/IOF" = ASME Class 1 = ASME III NB / NH

(Note that the ASME Class bears no relation to the Class used by the Eurocodes).

It is worth noting that EdF New Build in the UK (and in France) intends to apply BS-EN13480 to EPR components which would otherwise be ASME/RCC-M Class 3. The justification of this for UK New Build is presented in EdF report ENRE110035, "*Comparison of the Requirements of RCC-M Class 3 and EN Standards plus Supplementary EDF Specification Requirements*", by Y.Yuan and C.Faidy. However, the UK regulator has not yet accepted this. Moreover the ONR response to date makes clear that any attempt to be more bullish and apply BS-EN13480 to "infrequent" plant would be roundly rejected. This is because it would be seen as failing to meet the requirements of the SAPs Paragraphs 158 to 160. Consequently the position adopted in E/EAN/BDGBB/0122/AGR/06 appears to be in line with the probable outcome for EPR new build.

For the record, three formal questions were raised in regard to the "no nuclear" clause with CEN (the European standards body responsible for the Euro-codes) with responses as given below,

(1) "*In respect of the exclusion of items specifically designed for nuclear use, is this exclusion: (a)intended to apply only to primary circuits of nuclear plant, or, (b)to any item at a nuclear site whose failure may lead indirectly to a radioactive release through some subsequent sequence of events?*"

The response of the appropriate maintenance group of the CEN was that, "this includes the primary circuits, together with the associated safety circuits". In E/EAN/BDGBB/0122/AGR/06 this was interpreted to mean (b), above, i.e., that the exclusion applies to any pipework of sufficient nuclear safety significance - taken to mean "infrequent" and above.

(2) "*What BS/Eurocode, or other standard, should be used for the design of new piping systems specifically for nuclear use?*"

The response was that, "the appropriate code for nuclear safety significant applications is a matter for national legislature".

(3) "*Is there any **technical** reason which would preclude the application of EN 13480 to **modifications** of pipework of nuclear safety significance in existing nuclear plant in the UK (gas cooled reactors)?"*

The response was: "Industrial pipes specifically designed for nuclear use are excluded from EN 13480-1:2002, because they are excluded from the Pressure Equipment Directive (97/23/EC). Pressure equipments for nuclear use have to comply with national legislations. Only the national legislative authorities are competent to answer this question."

The responses to (2) and (3) are less than helpful, though the agreement of the "legislative authority" (ONR) to the advice given above is likely to be forthcoming shortly in the context of new build.

### 1.5 Describe the potential structural failure mechanisms covered by the design codes and the broad approach taken to ensuring good design against these threats.

This is considered to be a catch-all heading for points 1.6 and 1.7, which are discussed below.

### 1.6 Identify the potential failure mechanisms.

The principal failure mechanisms are,

[1] Plastic collapse

[2] Incremental plastic collapse (ratcheting)

[3] Creep rupture

[4] Fatigue

[5] Fast fracture

[6] Buckling

[7] Creep-fatigue interaction

[8] Initiation of crack-like defects (by many different mechanisms)

[9] Growth of pre-existing, or service initiated, defects

Contributory mechanisms to structural failure include,

[10] Oxidation / metal loss

[11] Corrosion of many types (metal loss and/or defect formation)

[12] Irradiation (embrittlement)

[13] Thermal ageing (many different effects on material properties)

### 1.7 State in broad terms the stipulations guarding against each potential failure mechanism within each of the design codes, or the absence thereof

Once we start to discuss specific criteria it is only possible to give an indication of what assessment methods or limits the codes typically use. Some codes may differ. It is not practicable to represent all codes in these brief notes.

#### [1] Plastic Collapse

Plastic collapse is most commonly addressed in design codes via limits imposed on the linearised elastic stresses. For this purpose the linearised elastic stresses are categorised into various types, including primary versus secondary and membrane stress versus bending stress. The limits are expressed in terms of a design stress allowable times a factor which varies according to stress category. Plastic collapse imposes limits on the primary stresses only. Typical limits are given in 1.12, 1.13 below. The reasoning is that these limits will prevent plastic straining other than that due to peak stresses (i.e., stresses in excess of the linearised stresses). In the basic procedures of codes the User is not required to carry out limit load analysis. The elastic stress limits are employed as a simpler surrogate for limit analysis. However, limit analysis may also be sanctioned at the user’s discretion in some codes.

#### [2] Incremental Plastic Collapse (Ratcheting)

Codes generally impose a limit on the range of the primary plus secondary linearised elastic stresses, $\Delta(P+Q)$. This limit is typically $\Delta(P+Q) \leq 3S_m$ where $S_m$ is the design stress which may typically be $S_m = 2\sigma_y / 3$, at least below the creep regime.

Consequently this criterion limits the linearised elastic stress range to twice yield. In

ASME the purpose of this limit is, "*to prevent excessive deformation leading to incremental collapse, and to validate the application of elastic analysis when performing the fatigue evaluation*" ("Companion Guide to ASME…", K.R.Rao, 6.5.1). This suggests that the criterion ensures the avoidance of ratcheting.

To be more precise (in my opinion) it actually ensures that, if ratcheting does not occur, then the cycling is elastic. Unfortunately the widespread belief that $\Delta(P+Q) \leq 2\sigma_y$ is sufficient to avoid ratcheting is not strictly justified. It is probably OK in practice so long as both the primary and the secondary loads cycle, especially if the material actual has a significant capacity to work harden. This is justified by the rarity of ratcheting failures in plant which is code compliant. However, the classic Bree analysis illustrated that if the primary stress is large and unvarying, it requires only a small cyclic secondary stress to create ratcheting in a perfectly plastic material. However this observation is beyond the code requirements.

Note that in the creep regime, codes will generally replace the $2\sigma_y$ ratcheting limit with a limit dependent upon creep rupture strength ($\sigma_{rup}$), for example $\Delta(P+Q) \leq (\sigma_y + \sigma_{rup})$. Some codes may also introduce a factor such as $\Delta(P+Q) \leq H(\sigma_y + \sigma_{rup})$ analogous to the shakedown factor Ks used in R5.

### [3] Creep Rupture

Codes most commonly deal with potential creep rupture in the same manner as plastic collapse. In fact the stress criteria are often identical with only the allowable being changed to reflect the creep mechanism. This is generally accommodated by defining the design stress as the lower of a yield-based definition or a rupture stress based definition. Both are appropriately factored. For example, the time independent design stress is typically $\sigma_y / 1.5$, where $\sigma_y$ is the lower bound of some appropriate proof stress, whereas the time dependent design stress may be $\sigma_{rup} / 1.3$, where $\sigma_{rup}$ is the mean rupture stress for the design temperature and design life. (BS-EN13480 uses $\sigma_{rup} / 1.25$ for lives of 200,000 hours or more). By using the smaller of these two definitions both plastic collapse and creep rupture are addressed through a single set of primary stress limits.

Note that most codes contain no explicit restriction arising from the creep effects due to secondary loads.

### [4] Fatigue

In some piping codes, such as BS806, there are no explicit requirements for fatigue. Instead these codes rely upon stipulated flexibility requirements to restrict the system stresses. For example, meeting the flexibility requirements in BS806 is stated as guaranteeing a tolerance of 10,000 full operating/shutdown cycles.

Similarly the boiler code BS1113 states that, "*The cyclic loadings to which boilers are normally subject are such that fatigue analysis of pressure parts made from materials listed in table 2.1.2 is unnecessary*". However if there is anything unusual it refers out to PD5500 for fatigue assessment.

The Euro piping code BS-EN13480 permits a full fatigue analysis to be omitted if certain conditions are met, such as being exposed to less than 1000 equivalent full load cycles. Otherwise a full fatigue assessment is required, including consideration of thermal stresses.

All codes include stress range criteria, as discussed under "Incremental Plastic Collapse". In the case of piping code ASME B31.1 there is a stress range limit which is dependent upon number of cycles, thus providing fatigue protection explicitly. This code (perhaps others also) warns about the effects of a corrosive environment in markedly reducing fatigue life.

In contrast to the piping codes where fatigue assessments may not be required, or are done in a highly simplified manner, the pressure vessel codes such as PD5500 or ASME BPVC require explicit fatigue assessments including SCF effects. Most codes which require fatigue assessment have explicit guidance on fatigue assessment for weldments, usually as some form of FSRF (though that term may not be used), e.g., BS-EN13480, PD5500, ASME BPVC.

### [5] Fast Fracture

Some might argue that code compliance offers implicit protection against fast fracture, even if there is no explicit fracture mechanics requirement (and generally there is not). Stresses are limited by other design code requirements, crack sizes by fabrication/inspection requirements and minimum toughness by materials specification/certification. HOWEVER, care needs to be taken for low temperature (< 20°C) assessments where lower shelf toughness may be prevail. Use of a suitable code, e.g. B31.5 *Refrigeration Piping and Heat Transfer Components*, may be appropriate, or you could do an explicit fracture assessment, e.g., using BS 7910 (in which case you might as well use R6).

Codes will often have specific requirements for low temperature operation, e.g. Annex D in PD5500 for vessels below $0^oC$. The requirement for impact testing (Charpy energy) is usually part of this, though this is standard in some codes anyway (e.g., the 'new' Euro codes). Other codes might just exclude low temperature plant – and you may have to look hard to find where this exclusion resides.

### [6] Buckling

There are substantial sections on buckling in ASME BPVC III, PD5500, BS EN 13480, etc. Sometimes there are simple rules for modest external pressures, low temperatures and standard steels (see, for example, BS EN 13480 Section 9). The codes typically address buckling of large shell/pipe sections under external pressure, but there is also some consideration of buckling of bends/elbows under global bending. Some detailed features (e.g., nozzles) may be much less susceptible to buckling under external pressure due to their geometry. However, buckling may not be addressed explicitly in some codes (e.g., BS806).

Buckling in general is a tricky subject, being intrinsically non-linear. External pressure or compressive loading are not the only instances where buckling can be the failure mode. The classic example is a torispherical head on a cylindrical vessel. The typical failure mode under ***internal*** pressure is circumferential buckling of the toroidal region, not something which is intuitively obvious.

### [7] Creep-fatigue interaction

Creep-fatigue is explicitly addressed in ASME III NH, and I presume also in RCC-MR (though I'm not familiar with it). I am not aware of other codes which do so. The only alternative is R5. This is a major shortcoming of the majority of design codes since creep-fatigue is an onerous (and realistic) mechanism.

### [8] Initiation of crack-like defects / Growth of defects

I am not aware of any ***design*** codes which address this (though BS 7910 does). Codes implicitly assume that inspection ensures that significant defects do not enter service and that satisfaction of the design criteria will prevent cracks initiating in service. Unfortunately this is not always true.

### [9] Oxidation / Corrosion / Metal Loss

This tends to be addressed in codes simply by requiring the User to add a suitable corrosion allowance onto the calculated required thickness. Some guidance on this allowance might be given, but in reality it is highly application/environment specific.

### [10] Irradiation (embrittlement)

Nuclear specific codes like ASME and RCC-M will specify the need to include the effects of irradiation embrittlement of materials subject to neutron irradiation (and presumably gamma too, though it is normally expressed as neutron irradiation). However I do not know how explicit they are regarding methodology. In practice we (EdF Energy) have our own dose-damage relations derived largely from our own surveillance schemes. Such surveillance schemes are required by the codes.

### [11] Thermal ageing (many different effects on material properties)

Thermal ageing is not generally addressed by codes, though this is probably a significant shortfall since the effects of 30+ years exposure to power plant temperatures can be very substantial. Tensile and cyclic strength properties can be affected (in either direction), as can fatigue endurance, fracture toughness, creep strain rate, ductility – everything really. This is an area where far too little is known.

## 1.8 Explain the use of component Class and loading Service Level within the ASME codes.

Curiously the Classes are not defined within ASME itself. This is left to the purchaser, i.e., to request the Class required. ASME III Div.1 NB, NC and ND align with Classes 1, 2 and 3 respectively. So it is clear that Class 1 is the top quality standard, and Class 3 the lowest.

See ASME BPVC Section III Article NCA-2000 and also K.R. Rao, “Companion Guide to the ASME BPVC”, p.158

> “*NCA-2100 General Requirements*
>
> *Section III provides for several Classes of construction, as can be seen in the following paragraphs. However, Section III does not provide guidance for selecting specific classifications to fit a component in a given system. This guidance is derived from system-safety criteria for specific types of nuclear power systems, such as Pressurized Water Reactors (PWRs) or Boiling Water Reactors (BWRs). The system safety criteria may be found in engineering standards such as those published by the American Nuclear Society or in NRC Regulatory Guides and “NUREGS.”*
>
> *The Owner is responsible for applying the appropriate system safety criteria for the Class of equipment in the nuclear power plant in accordance with the requirements of Section III. The appropriate*

> *classifications are required to be identified in the Design Specification for the equipment*."

In the context of PWR plant, there is broad consistency internationally which major parts align with the three Classes (see §1.9 below).

The Euro piping code BS-EN13480 employs a "piping class", defined by the pressure, the size of pipe, and the fluid group of its contents Hence this class relates to the potential hazard. It is a completely different classification from that of ASME.

### 1.9 Interpret 'Component Class' in the context of British Energy plant.

For Sizewell an interpretation was formally produced (SXB-IP-772001 Chapter 3 Section 2, p.3). Very roughly this makes the primary pressure boundary and the no-break zone within the containment Class 1, whereas outside the containment the secondary circuit is mostly Class 2, but specific systems may be Class 3 depending upon duty, failure consequences and isolation capability. In the USA the classification conforms to American National Standards Institute (ANSI), "Safety and Pressure Integrity Classification Criteria for Light Water Reactors", ANS 58.14.

For AGRs no formal interpretation exists but I would consider the following to be reasonable and to be broadly consistent with the Sizewell interpretation:-

| | |
|---|---|
| Class 1 | No full line of protection (i.e., IoF, IoGF, HI) |
| Class 2 | One line of protection (i.e., "infrequent") |
| Class 3 | At least two lines of protection (i.e., "frequent")) |

This is consistent with E/EAN/BDGBB/0122/AGR/06 and the way EPR new build is going. See also §1.4 above.

### 1.10 Define ASME Service Levels A, B, C, D and interpret them by approximate alignment with British Energy fault frequencies.

The starting point is ASME BPVC Section III Article NCA-2000, but see also K.R.Rao, "*Companion Guide to the ASME BPVC*", p. 159. Some salient points are,

- Design Loading – this is differs from Service Loading.
- Service Loading is only required for Class 1 components – they are assumed to be bounded by design loadings.

The design specification should specify service loadings:-

- **Level A** Service Limits – "NORMAL": Design and normal service loadings.
- **Level B** Service Limits – "UPSET": Those loadings exceeding design or normal service, but which would not require repair.
- **Level C** Service Limits – "EMERGENCY": Loadings which may produce large deformations; Areas of structural discontinuity may require repair. However, subsequent normal operation is expected to be justifiable after such loading, i.e., the anticipated damage is tolerable.
- **Level D** Service Limits – "FAULTED": Loads which would result in gross general deformation; Damage is expected to require repair prior to RTS, and it

cannot be presumed that the plant will necessarily be economically operable thereafter.

Of course, one could design a component such that all loading conditions met the most onerous service limits, rather than addressing each set of service limits individually. This would be very costly, however.

There is no exact or ubiquitous translation of the ASME Service Levels into fault frequencies. However, guidance is given in BEG/SPEC/DAO/011 (*Guidance on AGR Structural Integrity Related Safety Cases*). A rough guide is,

Level A: The normal operating condition

Level B: Frequent Events, i.e., $>10^{-3}$ pry, except that…

Level C: Frequent Events, between $10^{-3}$ pry and $10^{-2}$ pry, for plant in the “frequent” or “infrequent” tolerability of failure categories if no defects are expected

Level C: Infrequent Events, between $10^{-4}$ pry and $10^{-3}$ pry, for IOF/IOGF/HI plant items, except that…

Level D: Seismic events $\leq 10^{-3}$ pry, all plant

Level D: Infrequent Events, $\leq 10^{-3}$ pry, for “frequent” and “infrequent” plant

Level D: Very infrequent Events, $\leq 10^{-4}$ pry, all plant

[BEG/SPEC/DAO/011 also calls for fracture mechanics in some cases, and various other safety cases requirements, which are not pertinent here].

### 1.11 Describe the stress categories used by the design codes and the definitions of the corresponding allowable stress limits for each category.

This is a header for the following questions.

### 1.12 Specify the stress categories used by each design code.

### 1.13 Specify the stress limits for each relevant stress category and for ASME Service Levels A and B, or the equivalent

Design codes tend to put the emphasis on “design by rule”. This is a methodology which typically tells you what thickness is needed, and is most useful to design engineers. The alternative is “design by analysis”. This methodology requires the engineer to calculate stresses (usually elastic stresses) and then to compare these with certain allowable limits. This is the most appropriate type of requirement for *post-hoc* assessments. The stress limits vary according to the stress category. There is a broad similarity in the general stress limits imposed by the various codes. In outline these are, for Service Levels A and B,

- Primary membrane stress to be less than the design stress ($f$ or $S_m$);
- Primary membrane plus primary bending stress to be less than 1.5 times the design stress ($1.5f$ or $1.5S_m$, which, for temperatures below the creep regime will generally equal the lower bound proof strength);

- Primary membrane plus primary bending stress plus the linearised secondary stress to be less than 3 times the design stress ($3f$ or $3S_m$, which, for temperatures below the creep regime will generally equal twice the lower bound proof strength).
- Peak stress (or F-stress) is defined as the local maximum stress minus the linearised stress at that point. The structural limit on the peak stress, if any, is usually via a fatigue assessment (see, for example, AMSE III NB §3222.4).

By "stress" is generally meant an equivalent stress (confusingly called "stress intensity" in many codes). Many codes adopt the Tresca stress (which contrasts with the use of Mises stress in R5 and R6).

For more detail see PD5500 Annex A, Figure A.1 and Table A.1. The latter includes examples of stress categories for various geometries. The equivalent in ASME III Div.1 Subsection NB are Figures NB3221-1 and 3222-1 and Table NB3217-1 (see also §3212 to §3222). The latter are for design conditions or Level A or B service levels. The ASME and PD5500 stress categories and limits are very similar (identical?). Very similar stress categories and limits occur in R5V2/3 §6.3.

It is not always straightforward how to categorise a particular stress. For example, the wall bending stress at the junction between a cylindrical shell and a flat end cap or tubesheet due to internal pressure. The codes classify this as secondary despite being due to pressure. However other cases of wall bending due to pressure are often classed as primary bending. Global bending load gives rise to primary *membrane* stress.

Mentees should be able to rationalise the factor of 1.5 used in the primary membrane plus bending limit. One rationalisation is that this avoids yielding due to the linearised primary stresses. In addition, if the membrane loading is small, a bending stress restricted to $1.5f$ maintains the same reserve factor as a membrane stress restricted to $f$, due to the nature of the plastic limit load under bending.

Mentees should also be able to rationalise the factor of 3 in the primary plus secondary stress limit, $3f$. Because this equates to twice yield (at least below the creep regime) this suggests that the bulk of the section will cycle elastically. The primary plus secondary stress limit is therefore related to shakedown.

Thus the design philosophy can be summarised as requiring predominantly elastic behaviour, possibly after some initial shakedown and ignoring localised effects due to peak stresses. Given the broad brush approach that design codes are obliged to adopt, this is a sound basis for good design.

Piping codes may use different terminology and possibly employ slightly different limits. One reason for this is the prevalence of cold pull, which is unique to pipework. Another reason is the importance of flexibility to pipework systems to avoid excessive stresses due to thermal expansions. Consequently piping codes are more explicit about hot-condition stress limits and flexibility requirements. Like the pressure vessel codes there is recognition of the difference between primary stresses (e.g., deadweight) and secondary stresses, of which thermal expansion is the most important. Consequently there are specific and separate limits for (say) "sustained stress", which is a primary stress category, and "hot stress", which includes the thermal expansion stress. This is BS806 terminology but the distinctions exist in other piping codes, e.g., BS-EN13480 under different names. However the acceptable limits may differ. For example, the total hot stress is limited to the average rupture stress in BS806, whereas BS-EN13480 permits you to include only one-third of the thermal expansion stress in the hot stress but limits the total to the design stress, defined as the average rupture stress divided by 1.25 (assuming operation for 200,000 hours or more).

### 1.14 Specify the stress limits for each relevant stress category and for ASME Service Levels C and D, or the equivalent.

**Service Level C**: In recognition of the infrequent nature of such loadings, the limits in ASME III NB are relaxed – see §NB-3224 and Table NB-3224.1. The most important distinction from Service Levels A and B is that there is no requirement to assess peak loads or secondary loads. Moreover the primary stress limits are more lenient. For time independent (below creep regime) design stresses the primary stress limits are typically relaxed by a factor of 1.5 since the design stress is effectively replaced by the lower bound yield strength. For time dependent (creep regime) design stresses the primary stress limits are typically relaxed by a factor of ~1.2 although the situation here is rather more complicated because of the relevance of the duration of the fault condition. See ASME §NB-3224 and Table NB-3224.1 for details, or, for a succinct summary try E/REP/BDGBB/0024/AGR/03, §3.2.

It is possible that, in the event of Service Level C loadings occurring, some local repairs may be required. However, satisfaction of Service Level C criteria is expected to ensure that the plant remains viable, possibly after some minor repairs.

The absence of limits on the secondary and peak stresses may be rationalised as follows. Recall that the secondary stress limit for Service Levels A and B is related to shakedown to elastic cycling. This is not an essential limit for loading conditions which are sufficiently infrequent or not expected at all. Similarly, the Service Level A and B limits on the peak stresses, being related to fatigue considerations, are not relevant to Service Level C loads.

**Service Level D**: The faulted conditions assessed under Service Level D are not expected to occur. Secondary or peak stresses are not assessed. Level D requires only the primary stresses to be limited, as for Level C, but the limits are more generous still. For time independent (below creep regime) design stresses the primary stress limits for Service Level D are typically double those for Service Level C. However, for time dependent (creep regime) design stresses the primary stress limits may be little different between Levels C and D. Very short duration faults will mean that the time independent (strength-based) limits apply, so that Level D will often be far more lenient that Level C.

This is in recognition of the fact that, by definition of Service Level D, the plant in question cannot be presumed to be in a fit state to be re-usable merely because it meets Level D criteria. These criteria are intended only to ensure safe shutdown in such an event, albeit the plant may be damaged. A Level D event may be an economic write-off.

The Level D primary limits are defined in ASME III NB Appendix F. For a succinct summary try E/REP/BDGBB/0024/AGR/03, §3.2.

### 1.15 Explain the rationale behind the different stress categories and limits, and why the latter vary with Level of Service loading.

This is covered in the 1.13 and 1.14.

### 1.16 Summarise the key features of the defect acceptance limits and manufacturing tolerances (‘workmanship standards’) specified in the design codes.

### 1.17 Identify which codes contain explicit defect acceptance limits.

All codes specify standards of workmanship, i.e., in regard to acceptable dimensional tolerances, out-of-roundness, etc. All include requirements for NDT. Most also include explicit defect acceptance limits, though some prefer to refer out to other standards for the acceptance limits. A brief (and incomplete) summary of a few of the major codes is…

**PD5500**: Acceptance limits are discussed in §5.7 and made explicit in Tables 5.7-1, 5.7-2 and 5.7-3 for radiography, ultrasonic inspection and surface techniques respectively.

**BS-EN13445-5**: Table 6.6.3-1 gives acceptance limits for radiography

**BS-EN13480-5**: Table 8.4-1 refers out to other standards for acceptance limits, but nevertheless explicit advice is also given in Table 8.4-2 for surface defects and Table 8.4-3 for radiography. It is important that the piping class is defined for any work undertaken to BS EN 13480 as this, along with the material, determines the extent of testing and the associated acceptance criteria.

**ASME III NB**: Explicit defect acceptance limits are given for a wide range of inspection techniques in §5300.

**BS806:** This code (now withdrawn) referred out to other British Standards for its defect acceptance limits, e.g., BS2633, BS2971 and BS4677.

**BS1113:** This refers out to BS6208 and ASME VIII-1 for some limits, but also contains explicit guidance in Tables 5.9.2 and 5.9.4.

In the context of pipework, the current intention within EDF Energy Nuclear Generation is to produce a Company Technical Standard specifying welding defect acceptance standards. The interim guidance is that the default NDT acceptance criteria shall always be BS EN ISO 5817:2007 Quality Category B.

### 1.18 Illustrate by examples acceptable and unacceptable defects according to the design codes.

There are examples a-plenty in the Tables referenced in the answer to 1.16, 1.17 above.

### 1.19 Describe typical Concession Routes in operation within BE and its suppliers, and the advantages and disadvantages of accepting defects which are outwith the design code workmanship standards.

A “concession” is an agreement between the supplier and the customer that a deviation from the code workmanship or defect acceptance standards can be accepted. Ideally there should be no concessions.

In principle the concession route should be,

- Routine practices identify a shortfall from the code;
- The supplier, if he considers the shortfall to be minor, writes down the reason why the shortfall might be considered acceptable and presents this to the customer ("concession application");
- The customer decides if this argument is convincing, and if so the concession is agreed and formally recorded (otherwise some other course of action must be agreed, e.g., repair).

In practice, however, it may be the customer who provides the detailed assessment which justifies the concession. This may be due to the technical limitations of the supplier, e.g., in performing fracture mechanics assessment.

It is undesirable for the customer to accept concessions too readily or too often. The main reasons are that,

- Concessions represent an increase in risk which may accumulate if too many are permitted;
- A culture of accepting concessions readily may lead to diminishing workmanship standards.

On the other hand, if the customer were to take too hard a line on accepting concessions this might also be to his disadvantage. The reasons are,

- The defect in question may genuinely be completely innocuous;
- Repairs (e.g., repair welding) can *increase* the risk of subsequent failure compared to leaving a trivial defect;
- Expediency – adding several days to an outage in order to fix a defect which would have had no adverse consequences is not a good decision. This is where professional judgment is paramount. Sometimes weeks have been added to an outage duration in order to carry out a repair properly (e.g., with proper pipework restraints and PWHT) – and quite right too!

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