SQEP Expectations: T73S06 Creep Rupture

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References to R5 are based on Issue 3 (June 2003)

These brief notes have now been augmented by the transcripts of Tutorial Sessions 23 to 29 which can be found on this site by following the "T73S06 Tutorial notes" link: http://rickbradford.co.uk/T73S06Tutorials.html

What Is Creep?

1.1 Explain what is meant by 'creep' and when it is significant

This was originally intended as a Heading, not a separate question. As a question it is subsumed by 1.2 to 1.6 below.

1.2 Describe the macroscopic symptoms of a creeping structure under primary loading

Mentees must know that the defining characteristic of creep is that the strain due to a constant load increases over time. They must also know that after a sufficiently long period this will result in failure of a structure (creep rupture). The macroscopic symptoms of creep strain will ultimately be distortion of the structure, e.g. bulging in the case of a pipe under internal pressure. However, this will be obvious to the eye only in the advanced stages of creep, when failure is not far off. An engineering precaution which may be used on plant is to mark the surface of a component with 'creep pips' to enable accurate measurements of their distance apart. This can indicate the build up of creep strains before it is obvious to the naked eye – but again only when creep is well advanced. More sensitive would be strain gauges, but the long term stability and robustness of strain gauges operating at high temperatures and exposed to the vicissitudes of plant life is questionable.

1.3 Describe the macroscopic symptoms of a creeping structure under secondary loading

The Mentee should be able to work this out. As creep strain accumulates, if the total strain is fixed (i.e. there is no elastic follow-up) then the elastic strain decreases by the same amount and therefore the load reduces. So the macroscopic symptom is relaxation of pre-load, or residual stress, or whatever the secondary load happens to be. It is important that Mentees understand that creep relaxation can be calculated from 'forward creep' (i.e. from the creep behaviour under primary loading).

A purely secondary load (with no elastic follow-up) is unlikely to result in creep rupture in a creep-ductile material. However, it may result in the initiation of a crack. Other mechanisms may then propagate the crack to failure. However, assessments of material with sufficiently poor creep ductility can suggest both crack initiation and propagation to failure under the action of a single, purely secondary, load. This would not normally be classed as creep rupture, though the end result is the same. Assessment of this mechanism would require both R5V2/3 (initiation) and R5V4/5/7 (crack growth), not merely the assessment of creep rupture.

1.4 Describe graphically the meaning of primary, secondary and tertiary creep

The Mentee must know these basic facts: Primary creep is the rapid strain rate period on first loading. The strain rates reduce quickly, tending towards a minimum strain rate which is the secondary creep phase. In classic cases this secondary creep persists for most of the life of the specimen or component. The tertiary creep phase is marked by rising strain rates, leading ultimately to failure.

One possible cause of tertiary creep is the build up of creep damage (cavitation) which reduces the net cross-sectional area available to carry the load. The true stress on the uncracked material therefore increases, leading to increasing strain rates, and a positive feedback which leads rapidly to failure. However this is not the only possible cause of tertiary creep. Sometimes material taken into tertiary creep actually has no significant creep cavitation upon metallurgical examination. So tertiary creep may simply be the matrix material becoming softer due to thermal ageing (or something else!).

The Mentee should be aware that the behaviour of real structures and materials does not always conform to this pattern. For example, the θ-fit to low alloy ferritic creep deformation behaviour does not exhibit any clear period of constant (secondary) strain rate. Another example is the low ductility failure of austenitic materials at temperatures of 500-550^{o}C or so. In the latter example, primary creep tends to last for the whole plant life (at sensible design stress levels) but this does not prevent failure – which will generally be preceded by a tertiary phase – so again there may be no secondary phase. Moreover, materials which display primary then secondary behaviour may exhibit a "second primary" phase of accelerated creep rates, before settling into longer lasting secondary creep, and ultimately tertiary creep. Virgin/annealed 316ss can be an example of the latter.

1.5 Describe creep rupture data and isochronous creep data

The key issue here is the distinction between deformation and rupture. The Mentee must appreciate all the following: Rupture data is simply the creep rupture time (hours) for a range of applied loads. Generally this will be obtained from a deadweight test, so 'constant load' is the correct description, not constant stress. The true stress will increase as the cross-section of the specimen decreases.

Isochronous creep curves are a particular way of expressing creep deformation behaviour. They consist of the applied stress plotted against total strain (comprising elastic, plastic and creep strains), all points on the curve applying for the same time. The data should relate to a test at constant stress, I believe, but how this is achieved is a question to address to the high temperature testing SQEPs. The zero-hour isochronous curve is, of course, just the monotonic stress-strain curve (i.e., elastic and plastic strains only). Hence, creep strains are obtained from the isochronous curves by subtraction of the zero-hour curve. The data is then in a suitable form for curve fitting, e.g., expressing the creep strain as a power law of stress and time.

1.6 State the R5 definition of insignificant creep and give examples of the insignificant creep temperature for common ferritic and austenitic steels

The first thing to appreciate is that, like many aspects of creep, both time and temperature are important to whether creep is significant. (This is often shortened to the phrase, "time-temperature"). Thus, a temperature at which creep is insignificant must be with reference to a specified time period. Generally this will be the plant design life (or extended life).

The R5 definition of insignificant creep is given in R5 V2/3 Appendix A1, Section A1.6, and is that,

- EITHER, relaxation from an initial stress of 1.35Sy, at constant total strain, produces less than 20% relaxation of stress;
- OR, the creep strain accumulated at a constant stress of 1.25Sy is less than 0.03%.

where Sy is the lower bound 0.2% proof stress.

Example results are shown in R5 V2/3 Figures 5.3(a,b). Thus, for 316ss creep is insignificant over 300,000 hours for temperatures below ~470^{o}C using the R5 definition, whereas for, say, 2.25Cr1Mo creep is insignificant over 300,000 hours only below a temperature of ~345^{o}C.

2. **Reference Stress and Rupture Reference Stress**

2.1 Define 'reference stress'

The intention here is to define the 'proper' reference stress, based on primary loads alone. (As opposed to the pseudo-reference stress which is employed in R5V4/5 and which also involves secondary loading). The definition is therefore identical to that of R6. It is $\sigma_{ref} = (P / P_L)\sigma_y$, where P represents the applied primary load and P_L is the value of the primary load at 'collapse', according to classical limit load analysis and based upon elastic perfect plastic behaviour with yield strength σ_y. If several primary loads are applied, then all loads should be scaled up in proportion (so that P_L / P is then the overload factor to apply to all loads to cause 'collapse').

2.2 Define 'rupture reference stress' and state the R5 definition / formula. Explain how the difference between creep brittle and creep ductile behaviour is incorporated in the procedure.

See R5 V2/3 Section 6.5 and R5 V7 Appendix A3, Section A3.5. The Mentee should appreciate why the distinction between rupture reference stress and reference stress is regarded as necessary. Why is this distinction not required in plasticity, e.g. for the reference stress employed in R6, for example?

Note that guidance on creep ductile and creep brittle materials is given in R5 V2/3 Appendix A1, Section A1.7. The Mentee/Mentor may like to discuss whether a material with a creep ductility of less than 1% should be regarded as creep ductile or not.

2.3 Describe qualitatively the formulae for the reference stress in a cylindrical butt weld under internal pressure loading, with and without system moments, and state where the detailed formulae would be found

Uncracked Cylinders: Under pressure load alone, the Mentee should be familiar with the log-solution for thick cylinders (i.e. $P_y = \sigma_y \log(R_0 / R_i)$. Under combined pressure, moment and additional end-load the best solution is that of Ainsworth, item (3i) on the recommended reading list in the Mentor Guide. A simpler derivation, based on a thin shell and for either end load and bending, or pressure and bending, can be found in the "Collapse Solutions" note on this web site. The Mentee should understand what is meant by "circular interaction" when two primary loads are applied. Note that circular interaction is valid for, (a)pressure and moment loading, and, (b)pressure and end load; but not for, (c)end load and moment loading, which is a cosine interaction.

The best single source of advice on reference stress solutions for use in CMV weldment rupture life assessments is the Informal Methodology Advice Note, IMAN#4: *Detailed Procedure for CMV Weldment Rupture Life Assessments*, by Julian Johns. Note, however, that it is not a verified report, nor is it maintained, and cannot be referenced as a source. Tutorial session 25, available on this site, also covers many of these solutions and discusses the issues surrounding their use.

A good exercise is to ask the Mentee to derive a collapse solution for an uncracked body using the lower bound theorem approach. The "Collapse Solutions" note on this web site gives some examples – but dream up a new one if you can.

Cracked Cylinders: Strictly this is beyond the scope of T73S06 which deals with creep rupture of uncracked items. However, see the recommended reading list in the Mentor Guide. Jones & Eshelby, Miller and the R6 Compendium are perhaps the most widely quoted. However, for semi-elliptic cracks and combined pressure, moment and axial load, the solution of Lei & Budden is definitive (this is not in the reading list).

2.4 Describe qualitatively the formulae for the reference stress in a pipe branch weld under internal pressure loading, with and without system moments, and state where the detailed formulae would be found

Again, consult the recommended reading list in the Mentor Guide. Of particular note is the report by Stuart Booth which describes how to use the so-called inverse code approach (S.J.Booth, *The Calculation of Operating Stresses At Branches and End Caps in Boiler Headers For Use In GOM101 Creep Life Assessment*, SWR/SSD/0447/N/84, April 1984). Inverse code approaches are the basis of the most commonly used reference stresses at pipe branches. See also R5 V7 Appendix A3, Section A3.4.3.

A good overall *aide memoir* is the Informal Methodology Advice Note, IMAN#4: *Detailed Procedure for CMV Weldment Rupture Life Assessments*, by Julian Johns. This may be useful generally to the Mentee for this sub-role, not just for branch reference stress solutions. Note, however, that it is not a verified report, nor is it maintained, and cannot be referenced as a source. Tutorial session 25, available on this site, also covers many of these solutions and discusses the issues surrounding their use.

The Mentee should appreciate the distinct stressing conditions of a pipe trunnion compared with a branch, and the corresponding distinct reference stress solutions (e.g. see R5V7 Section A3.4.4 and IMAN#4).

These branch/trunnion reference stress solutions can be used, in conjunction with R5 methodology and CMV Type IV rupture data, to provide lifetime or creep damage estimates for large scale tests. A comparison of such estimates with the results of full scale tests is given in E/EAN/STAN/0144/AGR/02 and its references.

2.5 State how the reference stress would be found for welds joining non-matching materials (e.g. CMV to 2.25Cr1Mo, but <u>not</u> ferritic/austenitic transition joints)

I guess what I had in mind was the stress redistribution factor (k) method, as described in R5 V7 Appendix A3, Section A3.6 (see also 4.4 below). This factors the homogeneous reference stress based on parent properties by a factor k which is determined by the relative creep deformation rates of the constituent materials. Advice on the value of k is given in R5 V7 Appendix A1, Section A1.3 and Table A1.1, as well as in rather more detail in IMAN#4 and the references therein.

There is another possible method (though I've just made this up, it's not in R5). R6 contains advice on limit loads for welds of mis-matched strength (in R6 Chapter IV, Part IV.2). These solutions could be used, but, for a creep rupture application, the ratio of strengths which is used in R6 Chapter IV, Part IV.2 would have to be replaced by some appropriate ratio of creep strengths. This is not an approved R5 method, though.

2.6 Identify appropriate sources of reference stress solutions.

See the recommended reading list in the Mentor Guide and the references mentioned above, especially IMAN#4 (or rather the references therein)

3. **Rupture Life Under Variable Operating Conditions**

3.1 Define the methods for evaluating the rupture life usage for variable operating conditions

This was originally intended as a Heading, not a separate question. As a question it is subsumed by 3.2 to 3.3 below.

3.2 State the procedure for applying Robinson's Rule to a plant item which experiences variable loading and variable operating temperature.

Sum the time fractions: the rupture time for each interval employing the loading and temperature relevant for that interval. See R5 V7 Appendix A4, Section A4.2.2, for example. Note that this is a time-fraction definition of creep damage, but the use of a time fraction method is only sanctioned in certain parts of R5 and not others. For example, in R5 V2/3 the creep damage is most often defined in terms of ductility exhaustion (i.e. strain fraction).

3.3 Define Mean Effective Creep Temperature (MECT) and describe how it is calculated

Suppose that a structure is subject to varying stresses and varying temperatures at different times. The mean effective creep temperature can be defined in two different ways:-

- The MECT is that temperature which, if constant over life, would produce the same creep strain as the actual load and temperature history; OR,
- The MECT is that temperature which, if constant over life, would produce the same time-fraction creep damage as the actual load and temperature history.

The difference is that the first definition is based on deformation whereas the second is based on creep rupture.

In most cases the MECT is estimated based upon some assumed constant stress, rather than taking the stress variation into account. Generally this is a good approximation. Occasionally the rupture based definition has been calculated by including stress variations. But modest stress variations would not be expected to make a significant difference to the MECT. Attempting to account for stress variations when using the deformation based MECT is problematical when in the primary creep regime. However, simple and accurate estimation formulae for the deformation based MECT can be devised if the constant-stress approximation is used. An example for 316ss is included on this web site.

Rupture based definitions have most often been employed in the past. However, the definition adopted should be the most appropriate for the likely failure mode. Commonly this will be rupture for ferritic materials but deformation for austenitics (but not invariably).

Question 3.4 in the first issue of Mentor Guide T73S06 was misplaced. It appears here as question 5.4, which is where it will be placed when the Mentor Guide is up-issued shortly.

4. The Metallurgical Zones Comprising a Ferritic Weldment and Their Import on Creep Rupture Lives

4.1 Define the five metallurgical zones in a typical ferritic weldment (e.g. CMV parent with 2.25Cr1Mo filler)

In order: weld metal; coarse grained heat affected zone (HAZ); refined HAZ; inter-critically transformed HAZ, commonly known as the Type IV zone; parent metal. See R5V7 Appendix A1.

4.2 Describe how the various metallurgical zones within a CMV/2.25Cr1Mo weldment differ as regards (a)creep strength; (b)creep deformation rates; (c)creep ductility.

The following statements are rather broad-brush. There may be exceptions for certain combinations of temperature and stress. Moreover, materials behaviour recommendations are subject to change. So always consult the latest reports and obtain expert advice for each application. That said…

- Refined HAZ creep properties are generally taken to be the same as those of parent material.
- 2.25Cr1Mo weld creeps faster than the other weldment zones or CMV parent ($k < 1$).
- Coarse HAZ creeps more slowly than weld or parent ($k > 1$).
- Type IV zone creeps faster than parent, but not as fast as weld material (k can be a little less than 1).
- 2.25Cr1Mo weld material has lower creep strength than parent material.
- Coarse HAZ has better rupture strength than parent. R66 advice at the time of writing is that the lower bound rupture strength of coarse HAZ equals the mean rupture strength of parent.
- The rupture strength of Type IV zone material is intermediate between that of weld and parent.

NB: Welds onto 2.25Cr1Mo parent will have different properties (see R66 and IMAN#4).

4.3 Explain what is meant by “mixed HAZ” and how the mixing parameter α can be found

A plane through HAZ necessarily cuts through the different HAZ zones, i.e. coarse and refined, because such zones form around successive weld beads (see Figure A1.1 in R5V7). Consequently, if the assessment relates to the average structural response, e.g. for rupture across such a plane or crack propagation along such a plane, then an average response of this mixture of HAZ types is required. The mixing parameter, α, is a measure of how much the different HAZ types contribute to the mixture. The value of α depends upon weld prep angle and welding process (see R5V7 Appendix A1).

The use of mixed (averaged) properties is being challenged by coarse grained HAZ cracking in the HRH drain pots at HYA/HRA and elsewhere.

4.4 Explain the physical relevance of the redistribution factors, k, within R5 Volume 7, and state their typical magnitudes in each of the weldment zones.

The physical relevance is that material zones which creep faster tend to shed stress onto neighbouring zones which creep more slowly – provided that this is possible whilst respecting equilibrium. In the case of a circumferential butt weld in a pressurised cylinder, such offloading is possible for the hoop stresses but not for the axial stresses. The k-factor is the fraction of the reference stress which remains acting on the material zone in question after redistribution has occurred. Thus, for fast creeping zones k < 1 (e.g. 0.7 for weld, and perhaps 0.9 for Type IV zone), whereas for slow creeping zones k > 1 (e.g. 1.4 for coarse HAZ, and perhaps ~1.2 for mixed HAZ, depending upon α). But these apply only for hoop dominated loading. All zones have k = 1 for axially dominated loading.

Note, from 4.2, the tendency for zones with higher creep strength to have slower creep strain rates and hence larger k-factors (though there's no guarantee that this will always be the case in other materials). Consequently there is a degree of auto-correction in that the zones which pick up additional stress due to redistribution also tend to have greater creep strength, and zones with lower strength tend to have reduced stresses.

Note that R5V7 does not require the use of the k-factors in calculating creep strain rates – see the notes in italics in Sections A4.3.2 and A6.1. However, the k-factors are included in the secondary stress contribution to rupture via ductility exhaustion (R5V7 Section A4.3) and in crack growth C* estimates (R5V7 Section A6.1), as well as in creep rupture.

Note that an axial seam weld would have non-unity k-factors for axial dominance, but k = 1 for hoop dominance. This is academic for BE plant since we have no axial seam welds in creeping pipes (I think – perhaps someone knows of some?). However, seam welded steam pipes are used abroad. (The Americans have lots, some of which are of P91 and cracking nicely).

4.5 Explain the terms "hoop dominance" and "axial dominance". Describe how hoop/axial dominance is decided for, (a)a butt weld, (b)a branch weld.

For a pipe butt weld hoop/axial dominance simply means that the hoop/axial stress is the larger. The ambiguity lies in exactly what is meant by 'stress'. A clear definition is made in IMAN#4 and usually followed by assessors. If the Tresca pressure-only reference stress is larger than the pressure-plus-moment Mises reference stress, then it is hoop dominated – otherwise axial dominated.

For pipe branches a simple definition based on stress magnitudes is not available due to the complex stressing at the branch junction (and the axial direction for the branch may be closer to hoop for the main). The definition in common usage is that hoop dominance is assumed for $\gamma > 0.9$, and axial dominance for $\gamma < 0.9$, where γ is the term in the inverse code expression for a branch reference stress which accounts for the contribution of system loading (see IMAN#4).

5. **The Influence of Secondary Stresses on Creep Rupture Life**

5.1 Describe the methods used to account for the influence of secondary stresses on rupture life.

This was originally intended as a Heading, not a separate question. As a question it is subsumed by 5.2 to 5.4 below.

5.2 Describe the provisions made within R5 Volume 7 to ensure that secondary stresses do not undermine the creep rupture assessment based on primary stresses alone (ferritic weldments)

The advice is given in R5 V7 Appendix A4, Section A4.3. The effects of secondary loading may be ignored if Equ.(A4.8) is obeyed. My interpretation of this equation is that the creep strain attributable to the secondary stresses should not exceed 10% of the creep ductility. Strictly, the RHS of Equ.(A4.8) is the elastic strain due to the combined primary and secondary stresses. However, this can be interpreted as a bound on the creep strain due to secondary stresses provided that the elastic follow-up (Z) is not too great.

[Incidentally, the elastic follow-up factor, Z, which plays a major role in the other volumes of R5, does not appear in Volume 7 at all. It may make an interesting discussion as to why this is].

Note that the combination $\frac{k\sigma_{ref}}{E}\left(\frac{K_{TOT}}{K_P}\right)^2$ occurs frequently in R5V7. It should be noted that this is an estimate of the total elastic reference strain, as stated explicitly by Equ.(A6.7). [Here $K_{TOT} = K_P + K_S$, the latter being the primary and secondary SIFs respectively]. Another interesting discussion is why the ratio of SIFs in this expression is ***squared***, rather than linear.

If Equ.(A4.8) is not obeyed, i.e. the elastic strain exceeds 10% of the ductility, then Section A4.3.2 simply requires that rupture be based on ductility exhaustion using reference strains (the sum of the creep reference strain and the elastic reference strain). Another interesting discussion point is just how consistent the stress-rupture and ductility exhaustion approaches might be expected to be. A case where the elastic strain increases from 9% to 11% of the creep ductility might involve a discontinuous change in the assessment of rupture.

NB: Note that this advice applies explicitly only to ferritic weldments – because the whole of R5V7 is specific to ferritic similar metal welds.

5.3 Describe the provisions made within R5 Volume 2/3 to enable secondary stresses to be incorporated within a creep rupture assessment.

Secondary stresses contribute in many places in an R5 V2/3 assessment. It is not the purpose of this question to examine them all, which would subsume the greater part of the R5 V2/3 sub-role area. Two relevant provisions within R5 V2/3 are "cyclically enhanced creep" and the monotonic relaxation of stresses unperturbed by cyclic loading.

Cyclically enhanced creep is addressed in R5 V2/3 Section 7.5. The initial assessment of creep rupture in R5 V2/3, addressed by Section 6.5, is based on the primary reference stress, together with an allowance for F-stresses via the χ-factor. However, this does not fully account for the potential effects of secondary stresses on the gross ligament. A particular concern is that the effects of secondary stresses might be enhanced by the cyclic loading (which is generally the principle subject of an R5 V2/3 assessment). Creep strains due to secondary stresses might accumulate on successive load cycles, due to the re-priming of stresses on each cycle. The guidance of R5 V2/3 Section 7.5 is designed to give reassurance against this threat.

The Mentee should be aware that the equations of Section 7.5.3 are based on the venerable Bree diagram. The Mentee might perhaps have some acquaintance with their derivation – see Appendix A9. A very detailed re-derivation of the Bree diagram has now been included on this site, http://rickbradford.co.uk/BreeDiagram.html. Similar equations appear in many design codes, e.g., ASME.

The second area where secondary stresses contribute relates to creep damage arising due to monotonic relaxation. In cases where service load cycles 'wash out' the initial stress distributions, this issue may relate only to the first creep dwell. In cases where creep is monotonic throughout life, being unperturbed by cyclic loading (e.g. as illustrated in R5 Figure A3.5) the secondary loadings have a sustained contribution to creep damage, until naturally limited by relaxation. In either case, the creep damage is evaluated via a ductility exhaustion approach, as defined in R4 V2/3 Appendix A4, Section A4.6.1.3 (noting that any secondary stresses may be substituted for the residual stresses considered). The key features of the ductility exhaustion approach are, (a)the strain rate dependence of the ductility, which therefore requires that the damage is calculated as an integral rather than a simple ratio of total creep strain to ductility; and, (b)the deleterious effect of multiaxial stressing on the creep ductility.

Strictly, this assessment of monotonic creep relaxation via the ductility exhaustion approach does not fit well into a question on creep rupture, since it concerns crack initiation due to peak stresses rather than gross ligament failure. However, it is important that the Mentee has some appreciation of what limitations poor creep ductility might impose on assessments based only on primary stresses.

5.4 Discuss whether the provisions of 5.3 are more likely to be significant for ferritic or austenitic weldments, and describe the implications of this methodology for reheat cracking

The assessment of monotonic creep relaxation via the ductility exhaustion approach described above ***is*** a reheat cracking assessment. Reheat cracking assessments within BE have become synonymous with austenitic steels in recent years. However, the Mentee should be aware that this is only because the design codes (still) permit thick section austenitic weldments to enter service un-stress-relieved. The very high welding residual stresses and their associated high levels of triaxiality are responsible for the subsequent formation of reheat cracks in service. In contrast, the design codes require that thick section ferritic weldments be adequately heat treated. Because of this, reheat cracking has not been a threat in ferritic components in BE for many years. But the Mentee should appreciate that it used to be, in the days before PWHT became *de rigueur* for ferritics. In the early 1970s, the CEGB (our glorious forebear) had quite a headache in this area (before even my time).

Aside: A great deal of grief is being caused to fossil fuel generating companies by the use of P91 and similar materials as replacements for main steam pipework/header components. These materials were sold to the utilities on the basis of good creep strength. However, there are now extensive creep cracks appearing (in the UK and the US, and almost everywhere). The problem is either poor creep ductility or poor rupture strength of critical weldment zones (especially the Type IV region). The former would have been identified via a ductility exhaustion approach. Unfortunately, the proving tests of the material focussed on creep rupture strength and not on strain at failure. The latter would have been identified by carrying out creep testing programmes on weldments, not just parent material.

5.5 State the criteria within R5 for determining whether cyclic effects, or creep-fatigue interactions, are significant

See R5 V2/3 Section 6.6.2.

6. **Creep and Fatigue Damage of Transition joints**

6.1 Define the terms contributing to the creep and fatigue damage of transition joints, and how they are calculated

This was originally intended as a Heading, not a separate question. As a question it is subsumed by 6.2 to 6.9 below

6.2 Define the R5 Volume 6 damage term ‘A’

‘A’ is the life-fraction creep rupture damage using Robinson’s rule and based on primary stresses only. System stresses are treated as primary.

6.3 Describe the reference stress to be used in calculating term ‘A’, and the origin of the required creep rupture data

The “reference” stress must be that defined in Appendix A2 of R5 V6, and referred to as the “representative rupture stress”. It differs from the reference stress or limit load based approaches used elsewhere in R5.

The rupture life must be based on cross-weld data for the transition joint type in question.

6.4 Define the R5 Volume 6 damage term ‘B’

‘B’ is the fatigue damage fraction defined via Miner’s law in the usual way. It includes the effects of strain cycles due to all major plant load cycles, including the effects of the associated temperature cycles, e.g. as regards the α-mismatch effects (see below). It also includes any other secondary stress cycles.

6.5 Define the procedure for finding the strain range which contributes to term ‘B’

The procedure is specified in R5 V6 Appendix A3. As written this would be the most involved part of applying R5 V6 because it appears to require the total elastic-plastic strain range to be evaluated using the same hysteresis cycle construction methodology as defined in R5 V2/3 Appendix A7 for homogeneous structures. However, actually this is a glitch in the procedure because R5V6 applies only to elastic cycling. So there is no need to employ R5 V2/3 Appendix A7.

This is fortunate because otherwise Mentees seeking accreditation in T73S06 would have found that they needed to understand the hysteresis lop construction in R5 V2/3 Appendix A7, thus taking on board the greater part of T73S04. But actually this is not required.

The unique feature of R5 V6 for transition joints is that in addition to the elastic strain range, evaluation of term B for fatigue must include a contribution to the strain range from the α-mismatch. This is $\Delta\bar{\varepsilon}_t = 1.5\Delta\alpha\Delta T$. I believe that the factor of 1.5 relates specifically to fatigue issues (at least, I conclude this from the absence of this factor in term ‘C’, see below). Note that the ΔT used for the α-mismatch in term ‘B’ is the temperature range associated with the major operating cycles, e.g. from perhaps 20^{o}C to operating temperature.

The Mentee should be aware that a plane junction between two materials with different coefficients of thermal expansion, α, will produce shear strains at the ends of the interface which are divergent (when calculated elastically). The recommended formula, $\Delta\bar{\varepsilon}_t = 1.5\Delta\alpha\Delta T$, is therefore pragmatically based. (Historically it was derived from FEA).

An interesting discussion point is whether a similar $\Delta\bar{\varepsilon}_t = 1.5\Delta\alpha\Delta T$ term should really be included in the fatigue assessment of a nominally similar metal weld. The point is that the coefficient of thermal expansion has a significant degree of anisotropy when grains have a preferred orientation – as they do in the weld material near the fusion boundary. Consequently, I suspect there could be a significant $\Delta\alpha$ even for nominally similar metal welds.

6.6 State the source of the fatigue endurance data used in calculating term 'B'. In the absence of such data, state the fall-back position.
Evaluation of 'B' ideally requires cross-weld fatigue endurance data for the transition joint type in question. If not available, use of the lower of the fatigue endurances for the two parent materials may be a reasonable assumption, provided that a suitable fatigue strength reduction factor (FSRF) is also incorporated.

6.7 State the Fatigue Strength Reduction Factor (FSRF) to be used in evaluating term 'B'

Provided that lower bound cross-weld endurance data is used in the assessment, and provided that the α-mismatch strain is included in the assessment, as it should be, then no FSRF is required since this should be implicit within the data. However, if parent endurance data is being used as a surrogate for cross-weld endurance, then a FSRF of 2 must be used together with the lower bound parent endurance line (see R5 V6 Appendix A3, Section A3.2).

6.8 Define the R5 Volume 6 damage term 'C'

Term 'C' is the creep damage due to the secondary (thermal) stressing which arises due to successive dwells being at different temperatures. If all dwells are at exactly the same temperature then C = 0. Otherwise C is defined via a sum over the creep strain/ductility fractions for each dwell. The creep strain is identified with the elastic strain due to the α-mismatch between successive dwells, $\varepsilon = \Delta\alpha\Delta T_k$, noting that this assumes that relaxation is complete. The temperature range, ΔT_k, is the difference between each successive pair of dwell temperatures.

Note that the temperature ranges used in term C are not the same as those used in term B. The former will generally be far smaller than the latter.

The creep ductility used in defining 'C' should, in principle, account for strain rate and stress triaxiality effects. In recognition that it may be problematical to obtain such data, R5 V6 Appendix A4 sanctions the use of uniaxial parent ductility, provided this relates to the lower shelf. Rather helpfully it sanctions the use of 5% as the lower bound ductility for ferritic parent.

6.9 Explain what is meant by the "mismatch stress" and what is its magnitude for (a)term 'B', and, (b)term 'C'. Define, and contrast, the value of ΔT for each term.

This is covered in 6.5 and 6.8.

7. **Inspection Requirements Which Follow From Creep Rupture Life Assessments**

7.1 Describe the rules relating to inspection requirements which follow from creep rupture life usage.

This was originally intended as a Heading, not a separate question. As a question it is subsumed by 7.2 to 7.7 below.

7.2 Describe the process used to determine if a ferritic weldment should be inspected at a forthcoming statutory outage on the basis of creep life usage (based on TGN043, and assuming an "infrequent" tolerability of failure weld)

The Mentee should have read TGN043. The following brief words are no substitute for reading the guidance note. Broadly, there are three reasons why a weld might be scheduled for a so-called ISI (in-service inspection): (a)Because the feature is in a category which has some known degradation mechanism, e.g. small bore branches on steam pipework are potentially subject to reflux induced thermal fatigue cracking; (b)Because inspection is motivated by an adverse structural assessment result; or, (c)Because the TGNs require a small speculative sample of weld inspections (i.e. chosen at random).

Here we are concerned with category (b). Very roughly & incompletely, the rule here is to inspect all welds for which 80% of the lower bound rupture life is less than the operating hours to the subsequent statutory outage, i.e. to the statutory outage following the forthcoming outage (at which the inspections must take place).

Note, however, that there may be other reasons to inspect stemming from adverse structural analysis. For example, there may be a perceived threat from thermal transient induced bore cracking (TTIBC) identified by assessment (albeit, this is likely to be a crack initiation assessment). It is not possible to list all such potential instances.

Another reason for inspection may be that physical work is being carried out on, or adjacent to, the weld in question. The inspection may be required under the associated Cat 2 or 3 modification. This is normally termed “non-ISI”, which is a misnomer, but which distinguishes it from the TGN requirements.

7.3 Describe the process used to determine if an austenitic weldment should be inspected at a forthcoming statutory outage on the basis of creep life usage (based on TGN044, and assuming an “infrequent” tolerability of failure weld)

The Mentee should have read TGN044. As for CMV welds (TGN043), there is a requirement to inspect austenitic welds if 80% of the lower bound rupture life is less than the operating time at the next-but-one statutory outage. However, it is unlikely that this rupture requirement will result in inspections for austenitic welds.

TGN044 includes discussion of several specific cracking and degradation mechanisms, and some have associated assessment activities which might impact on inspection requirements. Consult the TGN. It’s too complex to summarise briefly. Various types of low creep ductility cracking mechanisms are relevant, as are environmentally related cracking issues (e.g. inter-granular attack). Thermal fatigue mechanisms are also important due to the high temperatures usually associated with austenitic materials together with their lower thermal conductivity and high coefficient of thermal expansion.

7.4 Describe the process used to determine if a ferritic/austenitic transition joint should be inspected at a forthcoming statutory outage on the basis of creep life usage (based on TGN046, and assuming an “infrequent” tolerability of failure weld)

The Mentee should have read TGN046. It applies to transition joints external to the reactors, and hence does not cover UTJs and LTJs within the boilers. These TJs are likely to be in the “frequent” failure tolerability category in any case. I cannot do justice to the full scope of the TGN briefly. But there is a requirement for R5 V6 assessments, and a requirement to inspect if 80% of the lower bound life does not extend to the end of the next operating period following the outage in question, i.e., broadly similar to the requirements for similar metal weldments in TGN043 and TGN044.

In addition, at the outage before the outage in which the life usage first exceeds 50%, a speculative sample of 5% of an “infrequent” population shall be inspected, or 2% of a “frequent” population. I presume this is an extra safeguard against the specific threat of the TJ cracking mechanism being active. The rules for graded joints are slightly different.

7.5 State why the rules in 7.2, 7.3, 7.4 are not sufficient in the case of higher nuclear safety duty items (i.e. HI/IoGF/IoF).

NB: IoF = Incrediblity of Failure; HI = High Integrity; IoGF = Incredibility of Guillotine Failure.

The simplest approach to this is to recommend that the Mentee look briefly at the guidance on producing structural integrity dominated safety cases, BEG/SPEC/DAO/011 , which discusses, amongst other things, the requirement for a “forewarning of failure” leg in these safety cases. Note that forewarning of failure is the more general requirement. If inspection is the chosen means of satisfying the forewarning of failure requirement (but it may not be) then Table 3 gives guidance for these highest safety duty categories. Subject to ALARP considerations, the recommended inspection levels may be 25%, 50% or 100% of the population, depending upon the active degradation mechanisms.

These higher safety duty categories will generally require a demonstration of defect tolerance, even when inspections reveal no defects. These are beyond the scope of this sub-role (falling within R6 and R5V4/5/7). However, note that the resulting 'safe lives', calculated assuming the presence of defects, will be required to provide a justification for the next operating period.

7.6 State how the rules in 7.2, 7.3, 7.4 differ in the case of "frequent" tolerability of failure items

For austenitic welds and transition joints, TGN044 and TGN046 include advice specific to welds in the "frequent" tolerability of failure category. For CMV welds, there is specific advice which augments that of TGN043 in report E/REP/STAN/0041/AGR/01 Rev.001. As regards assessments, the chief change is that, providing the weld has already been inspected in-service once, the requirement to demonstrate a rupture life extending beyond the next-but-one outage may be based on best estimate creep rupture data for the weldment zones (excepting parent material for which lower bound data is retained). There are also relaxations of other requirements for welds with large calculated creep damage, e.g. the need for replication and the need for an assessment of the growth of postulated cracks (see 7.6). The report should be consulted for details.

7.7 Describe the process used to underwrite continued operation in the case of CMV/2.25Cr1Mo weldments whose lower-bound creep rupture life has expired, or will expire in the next operating period (assuming "infrequent" or "frequent" tolerability of failure)

As far as I can recall there is no formalised procedure to deploy when lower bound rupture lives expire within the next operating period. However, the main point is that exceedance of the lower bound rupture life is not automatically unacceptable. There is a *de facto* procedure which is summarised in E/REP/STAN/0041/AGR/01 Rev.001, Section 4.2. This is,

[1] Use replication to quantify the creep damage (cavity density) in the Type IV region;

[2] Estimate the (upper bound) life usage from the measured cavity density;

[3] Check that the use of mean rupture data results in a calculated, expired life fraction exceeding that estimated on the basis of the cavity density;

[4] If so, adopt mean rupture data as the basis for the projected life, and hence as the basis of the safety case for continued operation / return to service;

[5] A further 'leg' to the safety case would usually be provided by postulating the presence of a crack at the NDT detection limit, calculating its growth in service, and demonstrating that the defect remained stable over the required operating period.

For "frequent" tolerability of failure items, [1], [2], [3] and [5] might be omitted, relying only on [4] (see 7.5).