# SQEP Expectations Guide

## T73S04: Perform Creep-Fatigue Initiation Assessments Using R5 Volume 2/3

Last Update: 29/12/12

*These Expectations Guides are a personal opinion. They are not necessarily a definitive statement of the 'right' answer (Rick Bradford)*

All references to R5 relate to Issue 3 (June 2003). However the guidance on Weldments is based on the draft replacement for R5V2/3 Appendix A4. Additions at 2013 may anticipate other Revisions expected in 2013, but without guarantee. This update has changed the numbering of the question in line with that current at December 2012. Let's hope it doesn't change again.

### 1. **Define the objectives and materials data requirements of an R5 initiation assessment**

#### 1.1 State the failure modes addressed by an R5 Volume 2/3 assessment. State the assumed initial condition of the structure.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

The main objective is to assess whether a small crack will initiate due to the combined effects of creep and fatigue, including the effects of cyclic creep. To be pedantic, the main business of R5 V2/3 is therefore not about failure but only about crack initiation. However, candidates should appreciate that the size of the crack at initiation is not necessarily 'small'. Small initiation sizes are characteristic of classic creep-fatigue. But in reheat cracking, or in the creep-fatigue assessment of creep brittle materials, the crack may appear suddenly at a large size (due to widespread creep damage accumulation).

Notwithstanding the above observations, an initiation assessment to R5 V2/3 is only valid if the structure is first shown to be satisfactory as regards the following potential failure modes:-

- Plastic collapse (overload);
- Creep rupture;
- Ratchetting;
- Cyclically enhanced creep deformation.

These mechanisms are the subject of more detailed questions below.

The initial condition of the structure must be uncracked.

#### 1.2 State the materials data required to carry out an initiation assessment to R5 Volume 2/3 in the most general case.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes31.pdf.

These are listed in R5V2/3 Section 5 with further details in Appendix A1. In summary they are,

[1] E, $\nu$, $\alpha$.
[2] Monotonic tensile data <u>and</u> the cyclic stress-strain curve.
[3] S-N curve (continuous cycling).
[4] Insignificant creep curve OR a deformation equation which extends to sufficiently low temperature, sufficiently long times and sufficiently high stress, to determine the insignificant creep condition.
[5] Creep rupture.
[6] Creep deformation (e.g. isochronous stress-strain).
[7] Stress relaxation fit (optional, and now generally not used).
[8] Creep ductility, including its dependence on strain rate and stress triaxiality, and possibly dwell stress.
[9] Shakedown parameter, Ks – This is sometimes thought of as being an 'assessment parameter', but it is actually materials data, derived from materials tests.
[10] The creep deformation exponent, n.

Item [4] is not required if creep is assumed significant.

Item [7] is not essential since relaxation can be obtained by integration of [6].
Item [10] is listed explicitly because it is required at several places in the R5 procedure, but it will generally be obtained as part of Item [6].

## 1.3 State the Ramberg-Osgood equation for monotonic and cyclic stress-strain behaviour, and the variants used in R5.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes31.pdf.

As well as being able to write down the equation, candidates should be aware that;

(a)the parameters are different for cyclic and monotonic behaviour;

(b)the usual (e.g. R66) cyclic equation describes the locus of the hysteresis loop tips – not the shape of the loops themselves;

(c)the shape of a half-loop, e.g. Fig.A1.2(b) O'C, is described by the modified Equ.(A1.3), using a zero stress datum, not the stress range.

## 1.4 Discuss creep ductility and the factors upon which it depends

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes31.pdf.

and http://rickbradford.co.uk/T73S04TutorialNotes36.pdf.

Candidates should be aware of the effect of both strain rate and stress state on the creep ductility, and also its temperature dependence. They should be aware of the importance of these factors in explaining reheat cracking. They should be able to sketch creep ductility against strain rate for austenitic steels (i.e., demonstrating some familiarity with the data from R66 Section 7).

Candidates should also be aware of the formulations for biaxial and triaxial ductility in Appendix A1, Equs.(A1.5,6a,6b), colloquially known as the Spindler fraction. Candidates should appreciate that these dependencies can be sensitive, e.g., that highly triaxial stress fields can reduce creep ductility by a factor of ten or more in some cases. An example of the temperature dependence of creep ductility (for 316ss) is provided by Hales, E/REP/BDBB/0008/AGR/03 (Required Reading Item #5).

Candidates should be aware that the ductility can vary significantly between weld metal, HAZ and parent, and that this has a direct bearing on the vulnerability of these zones to cracking. They should be able to cite examples (e.g., 316H smallest ductility is often in the HAZ).

Candidates should be aware of the important distinction between creep strain at failure and total strain at failure, and which of the two is used as the definition of creep ductility. Relevant sources are, for example, Required Reading Items #6, #7, #8, #9. The Mentor Guide has omitted the reference for #9. It is E/REP/BDBB/0032/AGR/03.

Advice on creep ductility is changing all the time and the only safe advice is to consult the experts for each application. More advanced issues relating to creep ductility are addressed in Section 8 of this Guide.

## 1.5 Discuss the effects of prolonged service exposure to high temperatures on the material properties relevant to an R5 crack initiation assessment

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes31.pdf.

The tensile strength, the cyclic stress-strain curve and the fatigue endurance are potentially all adversely affected by thermal ageing (as is the toughness – see the Expectations Guide for T73S02 [R6]).

Note that A1.5.3.1 suggests that an FSRF of ~1.5 would account for thermal ageing in 2.25Cr1Mo after very modest amounts of ageing. I'd not spotted this before. Does anyone use it? Certainly the fatigue endurance of ferritic steels is far more affected by thermal ageing than for austenitic steels. The mechanism for the former may be thermal softening, leading to higher cyclic strains for a given cyclic load. A certain amount of advice on thermal ageing exists within R66, but this is another area in which new advice arises frequently and the experts should be consulted for each application.

### 1.6 Define the primary stress categories and state their maximum allowable values. State what these limits protect against.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

These are defined in R5V2/3 Section 3.6 and Equs.(6.1), (6.2).

They provide protection against plastic collapse (failure by overload).

Margins against plastic collapse may be demonstrated by other means in the event of failing these criteria (i.e., by limit load analysis).

### 1.7 Define the Equivalent Secondary Stress, Q, and the associated 'linear equivalent stress range'. State the maximum allowable value of the latter and what this protects against.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

These are defined in R5V2/3 Section 3.6 and Equs.(6.3) or (6.4).

They provide protection against failure by excessive plastic deformation.

The distinction between these criteria and the shakedown criteria, which also protect against excessive plastic deformation, is discussed in Tutorial Session 30.

### 1.8 State how the significance of creep can be determined, and how the creep rupture endurance is assessed

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

The necessary pre-requisite of being accredited in T73S06 (Creep Rupture) should make any further 'proof' in this area unnecessary. See the T73S06 Mentor Expectation Guide for details of expectations. See also R5 V2/3 Section 6.4.

### 1.9 State the requirements for cyclic loading to be insignificant and the features to which it applies

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

This is covered in R5V2/3 Section 6.6.2. In brief there are three requirements,

- Strict shakedown
- Total fatigue damage < 5%
- Creep behaviour is not perturbed by cycling.

The latter is demonstrated by Equ.(6.17) and also Figures A3.5 and A3.6.

If cyclic loading is insignificant, then the R5V2/3 assessment is a "null return".

However, no procedure is available in R5 for assessing the significance of cyclic loading for *weldments* – so the full R5V2/3 procedure must be used for weldments.

### 1.10 Define what is meant by "strict shakedown". Describe how the shakedown behaviour of a structure may be investigated in practice.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

Strict shakedown: In physical terms it can be defined as, "following the development of a residual stress field over a small number of load cycles, the structure thereafter behaves purely elastically."

In more mathematical terms this definition can be written as $\bar{\sigma}_s \le \mathrm{KsSy}$, and this must be obeyed at all times during the cyclic loading. Here $\bar{\sigma}_s$ is the Mises stress formed from the total stress components, including the shakedown residual stress field. This residual stress field must respect equilibrium. The shakedown factor, Ks, is a modification to the lower bound 0.2% proof stress, Sy, obtained empirically. It will be greater or less than unity depending upon whether the material cyclically hardens or softens.

The trouble with shakedown analyses is finding the residual stress field. Shakedown can be demonstrated rigorously with a sub-optimal residual stress field.

However, a rigorous demonstration that the structure does not shakedown requires a guarantee that the optimal residual stress field has been identified. This is most often not possible by hand.

FEA with a suitable elastic-plastic constitutive law can be used, in principle, to investigate whether shakedown occurs. There are, however, difficulties with the technology in the general case. Chief of these is that the constitutive models are not clever enough to get ratcheting right. They can produce apparent but spurious ratchet strains between successive cycles. However, if the structure does attain ***strict*** shakedown then this would usually be demonstrated convincingly by sound FE codes.

There used to be a program called ADAPT (I think) which was specific for investigating shakedown but it appears to be defunct. R5V2/3 Appendix A6 discusses shakedown generally.

Having made these general points, in practice the simple criterion of R5V2/3 Equ.(6.14) is usually used as the basis for deciding if the structure can be claimed to be within strict shakedown or not. This requires $\Delta\bar{\sigma}_{el,\max} < (K_S S_y)_{top} + (K_S S_y)_{bottom}$.

## 1.11 Describe the R5 concept of 'Global Shakedown' and how it is assessed.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

Basically, the answer is "the 20% rule". This is defined more precisely in R5V2/3 Section 7.1.4. It weakens the strict shakedown requirement to a more lenient requirement that $\bar{\sigma}_s \le \mathrm{KsSy}$ be respected over at least 80% of the thickness of every section of the structure, noting that the same 80% of the section must obey this inequality at all times during all loading cycles. R5V2/3 Appendix A6 discusses shakedown further, as do the status notes (Section 11.7).

The Mentee should appreciate that the restriction of the region outside of strict shakedown to 20% of the section implicitly appeals to the likelihood of any accumulation of strains being suppressed by the surrounding elastic material. I am unaware of a direct, quantitative, justification of this.

The Mentee should realise that the distinction between strict and global shakedown is crucial to the logic of the R5 initiation procedure. Structures which are outside strict shakedown will be subject to hysteresis cycles and hence the creep-fatigue mechanism which R5V2/3 assesses. The cases of greatest interest will therefore often be outside strict shakedown. However the procedure imposes the global shakedown limit as a precaution against ratcheting. Just how sacrosanct the 20% rule of global shakedown may be is unclear. In truth, much larger regions could probably be assessed successfully by the initiation procedure, but the threat of ratcheting becomes ever greater.

Warning: In R5 Issue 3 the appeal to global shakedown is intended to apply only to those cases where $\bar{\sigma}_s > KsSy$ is due to peak F-stresses. Both in §6.6.1 and §7.1.4 there are requirements that the *linearised* stresses be within the $KsSy$ limit everywhere. However I have User Query challenging this requirement on the grounds that it conflicts with the Bree analysis.

## 1.12 Define "shakedown reference stress" ( $\sigma^s_{ref}$ )

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

The shakedown reference stress, $\sigma^s_{ref}$ , is defined in R5 V2/3 Section 7.2.1. For a structure at uniform temperature during the creep dwell, it is the greatest value of $\bar{\sigma}_s$ at any point at the start of the dwell. This assumes that the shakedown residual stress field has been reasonably well optimised so as to minimise the value of $\bar{\sigma}_s$ (subject to the shakedown limits being respected). For a structure with a temperature gradient during the creep dwell, the most onerous point must be identified, such that the combination of temperature and $\bar{\sigma}_s$ at the point minimises the time to rupture. In general this definition includes all stresses; in particular the peak stresses (F-stresses).

However, in the assessment of cyclically enhanced creep, Section 7.2.1 sanctions the use of two alternative definitions of $\sigma^s_{ref}$ . The first uses only the linearised stresses to find $\sigma^s_{ref}$ , but is otherwise identical to the usual definition. Alternatively, Section 7.2.1 permits a definition based on the 'core' region, which is that region which is within strict shakedown (and hence ≥80% of the section, if global shakedown prevails). The shakedown reference stress is then the largest equivalent stress within the core region *in the steady state*. Defined in either of these ways, the shakedown reference stress cannot be used to approximate the dwell stress – only in the assessment of cyclically enhance creep.

## 1.13 Explain what is meant by "cyclically enhanced creep" and how it is assessed within R5 Volume 2/3.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

In my words: cyclically enhanced creep refers to the threat of gross section creep failure due to the accumulation of creep strains arising from the cyclic (partly secondary) stresses – in addition to the strains due to the primary, steady stresses. Roughly speaking a cyclically enhanced creep failure would be to creep what ratcheting is to plasticity.

R5 V2/3 Section 7.5 assesses cyclically enhanced creep using a time-to-rupture approach based on the shakedown reference stress or one of the alternative "core stress" definitions of the shakedown reference stress (see 2.7 above). Alternatively, a specially defined 'core stress' from Equs.(7.19a,b) can be used. The latter is based on the venerable Bree analysis of thin cylinders, as discussed in Appendix A.9. The assessment of cyclically enhanced creep results in a damage time-fraction, W.

[Equs.(7.19a,b) reduce to the thermal ratchetting equations of ASME III NB-3222.5 for a linear temperature distribution in the case "core stress = Sy", i.e. for a plastic ratchet limit rather than the creep limit being addressed by R5].

I am not aware of any requirement to consider an interaction between this 'gross section' assessment, and the main initiation assessment (is anyone else?). Thus, W ~ 0.99 does not require any acceleration of the crack initiation rate, as far as I know.

## 1.14 Define "signed equivalent stress" and explain why it is important in an R5 Volume 2/3 initiation assessment

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes32.pdf.

See R5 V2/3 Appendix A2, Section A2.3.3. The signed equivalent stress is the Mises stress given the sign of the principal stress with the largest *magnitude*. The signed equivalent stress is important because it is the stress measure that is used to define the stress-strain hysteresis cycles, upon which the initiation assessment is based. There are difficulties with it in practice, though, as discussed in the tutorial notes. But these difficulties do not detract from the R5V2/3 assessment.

## 1.15 Define the equivalent stress range and equivalent strain range used by R5 Volume 2/3

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes32.pdf.

The point here is that the *equivalent range* is evaluated by putting the *component ranges* into the Mises formula (as opposed from taking the difference of two signed equivalents) – see for example Appendix A2, Equs.(A2.7) and (A2.9).

The candidate should also be aware that the equivalent strain formula is essentially a *convention*. It is actually correct only for the plastic strain, since it assumes $\nu = 0.5$, i.e., incompressibility. The use of (A2.9) for elastic strains is strictly wrong. However it is effectively corrected elsewhere by the use of the modified elastic modulus, $\overline{E} = \frac{3E}{2(1+\nu)}$, and the inclusion of the "volumetric strain" in the procedure.

## 1.16 Describe qualitatively the elastic stresses arising due to a sequence of thermal transient conditions

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes32.pdf.

The intention here is to suggest to the candidate a sequence of loadings on a given structure. For example, a thick section with some notch or weld feature which is subject to a fluid with a rapidly changing temperature. There may be primary loadings also, but the secondary loadings are the key issue to start with. The candidate should be able to work out whether the 'weak' (stress concentration) feature is under tension or compression at key times, and hence to draw a qualitative graph of *elastic* stress against time. The main point is that, for purely thermal stressing, the *elastic* stress builds to a maximum and then reduces back to zero as steady conditions are regained. Superposition of a primary stress will produce an appropriate offset.

The homework to tutorial session 32 is an example of this type of qualitative exercise.

## 1.17 Describe qualitatively the stress-strain hysteresis cycles corresponding to the loading sequence in 1.16

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes32.pdf.

This is perhaps the most important question of all. Starting from the elastic stress v time graph from 3.3, the candidate should be able to translate it into an elastic-plastic-creep stress-strain hysteresis loop (qualitatively). The Mentor will need to define the magnitudes of the stresses in 3.3 wrt $S_y$. Assuming these are sufficiently large, the main points are that: (a)times of zero (or primary-only) stress in 3.3 have non-zero stress (or differ from primary-only) because of the residual stresses; (b)consequently the dwell stress, and the cyclic creep strain, depend upon constructing the whole cycle; (c)the strain range is far greater than the elastic strain range.

If the stress range is within $K_sS_y + K_sS_y$ then the candidate should have some appreciation for the types of behaviour that may result, as illustrated in Appendix A3, Figures A3.5, A3.6.

## 1.18 Describe the effect of small cycles superimposed on large cycles

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes32.pdf.

and http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

This is illustrated in Appendix A3, Figure A3.4. Typically the small cycles, if small enough to be elastic, will contribute very little damage.

The interaction of cycle types when both are large enough to cause yielding is more challenging. Because it takes a few cycles for a structure to achieve a steady cyclic state, if the load cycle changes frequently enough then no steady cycling will ever be achieved. There's a leap of faith involved in the pragmatic assumption that two different major cycle types can be assessed as if they both achieved the steady cyclic state (an impossible situation if the load types alternate). However, this simple approximation may not be too far out in practice.

To estimate the effects of cycle interaction the guidance of R5 V2/3 Appendix A7 Section A7.6.2 can be used. This effectively shifts a cycle along the stress axis according to the forward stress datum defined by the previous cycle. Hence, the dwell stresses are modified but not the strain ranges. Thus the creep damage is altered but not the fatigue damage. The session 33 tutorial notes expand upon the advice in R5. Note in particular that the result of cycle interaction depends upon the time in the cycle that one cycle type gives way to the other.

## 1.19 State the crudest method in R5 for assigning a value to the dwell stress, $\sigma_0$ , without constructing the hysteresis cycle.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes32.pdf.

This refers to R5 V2/3 Section 7.2.2. There are essentially three simple approximations for the dwell stress which do not depend upon hysteresis cycle construction.

The first is to set the dwell stress equal to the shakedown reference stress (as defined in 2.7). This is only valid if the full definition of $\sigma_{ref}^{s}$ has been used, including the peak F-stresses and the whole of the section.

The second approximation for the dwell stress is $\Delta\overline{\sigma}_{\text{el,max}} - \text{KsSy}$ . This method is pretty useless, in my view, since this dwell stress estimate will generally be excessively large except when the structure is within strict shakedown (when it is probably OK).

The third approximation is to set the dwell stress to KsSy, but with Sy defined by the best estimate data rather than the lower bound. However, this is only valid if the result exceeds the dwell stress obtained from hysteresis cycle construction. Since the hysteresis cycle must therefore be constructed anyway, there is therefore no saving of labour.

My advice is to just construct the hysteresis cycle (covered below) and do not bother with these 'simplified' techniques.

## 1.20 State how a cyclic stress-range/strain-range curve is derived for use in constructing a hysteresis cycle according to R5V2/3

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

There is some relevant advice in §A7.2.1. Note, however, that §A7.2.2 is not likely to be relevant if you are constructing the hysteresis cycle with the intention of using it to define the creep dwell stress. In that case the title of §A7.2.1 and §A7.2.2 are misleading and you should use §A7.2.1 even though there is creep in the cycle.

The more practical point, though, is that the two half-cycles comprising the whole hysteresis loop (one with creep and the other without creep) employ different stress(range)/strain(range) formulations. This is not what §A7.2.1/§A7.2.2 are referring to. Rather this is dealt with in §A7.5.2, §A7.5.3.1 , §A7.5.4, §A7.5.6.1, §A7.5.6.2. I found this rather confusing. I recommend the tutorial notes which specify the exact equations to use at each step.

## 1.21 State the procedure for finding the total strain range in the absence of creep

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

This is covered for insignificant creep by Section A7.3. Candidates should know that the total strain range in this case is the sum of the elastic, plastic and volumetric correction parts. They should know that the elastic strain uses $\overline{E}$ rather than $E$ . There is no point in candidates memorising the formulae for the volumetric strain, but they should be aware that it depends upon $\nu$ and the secant modulus, and what the latter is.

Most importantly, candidates must know that the plastic strain is derived via the Neuber construction, and what that is. Mentees should be familiar with Equations (A7.13) and (A7.14), which are the general formulation of the Neuber construction. For severe loadings, Mentees should appreciate that it is the plastic strain range that becomes dominant (i.e., compared with the elastic, creep or volumetric strain ranges). Fig.A7.4 is unrepresentative of severe loadings in this respect.

Candidates should also know that the creep strain may need adding *or subtracting* from the total, as per A7.5.6.2 and A.7.5.6.3.

## 1.22 Comment on the assumptions implicit in the use of the Neuber construction

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

and http://rickbradford.co.uk/T73S04TutorialNotes34.pdf.

OK this is a bit of a hobby horse of mine. It refers to the fact that there is great play on using the correct Z for the creep dwell, but no such demand for the plastic behaviour. In using the R5 procedure, most people are likely to be unaware that it contains an implicit assumption regarding the value of Z in plasticity. But they *should* be aware of it. Real structures do not necessarily behave as per the Neuber construction, as FEA will generally reveal. Behaving as per Neuber is equivalent to a follow-up factor in plasticity of Z = (2 – x) / (1 – x), where $x = \Delta\sigma / \sigma_0$. So, Z ~ 2 for very small plastic corrections to the stress (benign loadings), but Z is unboundedly large for large reductions to the elastic stress (the more usual case in 'challenging' applications). So, it is some comfort that the implicit Z is reasonably (or even unreasonably) large, and hence likely to be conservative.

However, Neuber really applies for stress-strain fields local to notches. Candidates should be aware of this because their geometry may not be notch-like at all.

There is an interesting discussion point here: why should Z be different in plasticity and creep? The R5 V2/3 procedure implicitly assumes they *are* different. But I suspect they must really be the same (for the same initial stress and relaxation).

## 1.23 Describe the simplified method for enhancing the strain range due to creep at the hysteresis loop tip

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

This is covered in Section A7.4, for cycles illustrated in Fig.7.1(a). The main thing is that candidates know that the effective elastic stress range gets enhanced by the stress drop due to creep. Candidates might be expected to appreciate the relevant parts of the Status notes (e.g. A7.7.4).

## 1.24 Describe the overall approach taken in R5 V2/3 Appendix A7 to constructing the hysteresis cycle (intermediate dwell)

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

The candidate should be able to summarise the broad approach as follows:-

- The two half-cycles, with and without the creep dwell, are considered separately;
- The half-cycle without creep is considered first, the elastic-plastic stress range and strain range being determined (say, from hot peak to 'cold' peak);
- The strain range is corrected for volumetric strain;
- Next, the absolute position of this half-cycle on the stress axis is found;
- The half-cycle-with-creep is next considered, finding the stress range and strain range from the 'cold' peak to the start of the dwell. This provides the dwell stress;
- Next the creep stress drop and creep strain are found;

- Finally, the elastic-plastic stress range and strain range for the whole of the half-cycle-with-creep are found, from the cold peak to the hot peak. This has to take account of the creep dwell in affecting the stress range and strain range input to the Ramberg-Osgood curve. Also a different Ramberg-Osgood curve is used than for the half-cycle without creep.
- The strain range is corrected for volumetric strain and creep strain.
- The larger of the strain ranges evaluated for either half-cycle is used in the assessment of fatigue damage, recalling that the volumetric strain correction must be added, and the creep strain must be added or subtracted as appropriate.

## 1.25 Define the details of the construction of the half-cycle without creep

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

The key aspects are:-

- The relevant elastic stress range that is the main input to this procedure is the full hot-peak-to-cold-peak range;
- Candidates must know that the Neuber construction is used to find the elastic-plastic stress & strain ranges. I would expect them to be able to write down Equ.(A7.13). The aspects of this key equation they should appreciate include…
  - $\overline{E}$ rather than E;
  - Understanding the various options for A* and $\sigma_D$ depending upon how the cyclic behaviour has been chosen to be represented, as defined in A7.5.2
  - BUT in this step the cyclic material Ramberg-Osgood parameter (A) is called for;
- The example construction in the session 33 tutorial may be helpful in making this more concrete by specifying the exact equations to be solved.
- The absolute positioning in stress of the half-cycle is important to the eventual value of the dwell stress (which is important because creep damage often dominates). Candidates should be aware of the three possibilities, as listed in A7.5.3.2:-

  (1) Stress range outside $(K_S S_y)_{peak1} + (K_S S_y)_{peak2}$ so symmetrise with respect to the 'stress centroid', i.e. $\left[(K_S S_y)_{peak1} - (K_S S_y)_{peak2}\right]/2$.

  (2) Stress range within $(K_S S_y)_{peak1} + (K_S S_y)_{peak2}$ and hence the datum position is 'up against the ceiling' $(K_S S_y)_{peak1}$ or 'down on the floor' $(K_S S_y)_{peak2}$ according to the development/history.

  (3) Pinned by primary stress: If creep causes the stress to relax down to the primary rupture reference stress, then this provides an enforced location along the stress axis.

  [NB: "peak1" is the tensile, or 'hot' peak, and "peak2" is the compressive or 'cold' peak].

- The absolute positioning establishes the reverse stress datum, $\sigma_D$, and the first estimate of the forward stress datum, $\sigma_F$.

## 1.26 Define the details of the construction of the half-cycle with creep

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

As a minimum the candidates should appreciate the following;

- The part of the half-cycle from peak 2 to the dwell is considered first;
- The relevant elastic stress range in this step is therefore peak2-to-dwell, not the whole

peak-peak range;

- Solve the Neuber construction to estimate the elastic-plastic stress range and strain range from peak 2 to dwell;
- In this step the Ramberg-Osgood parameter called for is different from (4.6), namely the cyclic parameter modified to represent the shape of the hysteresis cycle (i.e. using A/2 in place of A, and the stress datum is zero rather than stress range);
- Hence, determine the start-of-dwell stress (usually by subtracting the reverse stress datum, $\sigma_D$, from the peak2-to-dwell range).
- The creep strain may need adding *or subtracting* from the total, as per A7.5.6.2 and A.7.5.6.3.
- Finally the elastic-plastic stress range and strain range for the whole of the half-cycle-with-creep are found, from peak2 back to peak1. The modified Ramberg-Osgood curve (using A/2) is used again here. A7.5.6.1-3 discusses various possibilities which arise.

Again the example construction in the session 33 tutorial may be helpful in making this more concrete by specifying the exact equations to be solved at each step.

## 1.27 Discuss whether the stress-strain hysteresis cycle would be expected to be closed

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes33.pdf.

People should realise that the R5 V2/3 App.A7 construction is unlikely to produce a closed loop simply because it is only approximate. This does not imply that ratcheting is occurring! However, people should also realise that the true hysteresis cycle *should* be closed if the same loading cycle repeats sufficiently often – unless there really is ratcheting, in which case the assessor has a problem. Ratcheting is dealt with in other questions.

However, in truth the loading cycles on plant will not all be identical. Each cycle will differ from the last. In this case the hysteresis cycles will not be closed even in principle. To deal with this requires an interacting cycle methodology which goes beyond the current R5V2/3 procedure. An unapproved example of such a procedure can be found in this presentation, http://rickbradford.co.uk/R5V23ProbabilisticPresentationDec12.ppt

## 1.28 State the two different types of materials data that may be used to estimate the stress drop during the creep dwell

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes34.pdf.

What I had in mind was relaxation data and forward creep data suitably integrated. Candidates might be expected to know how relaxation data is presented (Feltham equation). However, the Feltham fits in R66 are now regarded as unreliable except in quite a narrow range of stresses and temperatures [see, for example, M.W.Spindler, "CR356600 Internal Stress Values in Section 4 of R66 Are Not Realistic", letter to Chris Hamm (R66 editor) dated 15th February 2007, referenced in the R66 User Queries database, unique number Q4.10]. Consequently knowledge in this area is probably no longer required.

However, Mentees *must* know how to formulate the relaxation problem in terms of a forward creep law. Given its importance, I suggest that they should be familiar with both forms of the relaxation equation, i.e.,

$$\frac{Z}{\overline{\overline{E}}}\cdot\frac{d\overline{\sigma}}{dt}=-\dot{\overline{\varepsilon}}_c(\varepsilon_c,\overline{\sigma},T)\ \text{as well as}\ \frac{Z}{\overline{\overline{E}}}\cdot\frac{d\overline{\sigma}}{dt}=-\left(\dot{\overline{\varepsilon}}_c(\varepsilon_c,\overline{\sigma},T)-\dot{\overline{\varepsilon}}_c(\varepsilon_c,\sigma_{ref}^P,T)\right)$$

The Mentee should understand why these equations are consistent, despite appearances (namely that they refer to different Z values). The Mentee should also appreciate the advantages of the second form of relaxation equation, which is really to be preferred. These are that, (i) it ensures that relaxation below the rupture reference stress (which is not permitted) cannot occur, and, (ii) a relaxation curve which is asymptotic to the rupture reference stress is obtained even for a constant value of Z, whereas the first form of relaxation expression requires a varying Z to be imposed by the User.

It is crucial to note that the creep strain at which *both* strain rates in $\frac{Z}{\overline{E}} \cdot \frac{d\overline{\sigma}}{dt} = -\left(\dot{\varepsilon}_c(\varepsilon_c, \overline{\sigma}, T) - \dot{\varepsilon}_c(\varepsilon_c, \sigma^P_{ref}, T)\right)$ are evaluated are the same, and that this accumulating creep strain can be found only by integrating (time-stepping) the complete RHS. The two terms, when integrated, can be thought of as giving the total creep strain increment and the primary (forward) creep strain increment respectively. However, these two quantities cannot be integrated separately because they both depend upon the common $\varepsilon_c$. You have been warned - this is very easy to get wrong when writing code to carry out the relaxation integrals.

A good exercise is to ask the Mentee to solve for the relaxed stress at time t for power law creep and a constant follow-up factor Z. By this means explore the sensitivity of the creep strain, and hence the creep damage, to Z. (The homework for tutorial session 24 is an example of this type of exercise).

Another exercise is to specify that the relaxation per dwell is very small compared with the dwell stress – and hence to determine the sensitivity of the creep damage over many cycles to Z in this case.

## 1.29 State how the creep strain is found from the stress drop during the dwell.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes34.pdf.

Oops! I got this wrong myself in the original version of these notes. I said: "This is a gift., $\Delta\varepsilon_c = Z|\Delta\sigma|/\overline{E}$". This is NOT correct in general, because it ignores the creep strain due to the primary, hence non-relaxing, component of stress. In the extreme, if the dwell stress equals the (primary) rupture reference stress, then $\Delta\sigma = 0$ but creep strain accumulates due to forward creep. So the correct expression for the increment of creep strain during a dwell is $\Delta\varepsilon_c = \Delta\varepsilon_c^P + Z|\Delta\sigma|/\overline{E}$ where $\Delta\varepsilon_c^P$ is the creep strain derived by integrating the creep strain rate evaluated at the (constant) rupture reference stress. Note that $\Delta\varepsilon_c^P$ cannot be found independently of the relaxation integral because the primary strain rate $\left(\dot{\varepsilon}_c(\varepsilon_c, \sigma^P_{ref}, T)\right)$ depends upon the *total* $\varepsilon_c$.

## 1.30 Describe the options for estimating the elastic follow-up factor, Z.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes34.pdf.

This is *mostly* covered by R5 V2/3 Section 7.3 and Appendix A8. Candidates should know that three options are included:-

(1)Use Z = ∞. Not terribly helpful, it seems to me.

(2)Use Z = 3, based on a cantilever analysis if the primary stresses are sufficiently small. Much more helpful, but the justification escapes me, to be honest.

(3)Do FEA. (Thanks!).

Candidates should be aware of the definition of Z for multiaxial conditions, via Equs.(A8.4-6). Note that the equivalent strain quantities are subject to the definition discussed in (3.2), and this is not the conventional definition in the case of elastic strain. (Equivalently, note the use of the modified Young's modulus in the definition). However the prescription for Z from Equs.(A8.4-6) is rather complicated and this is a consequence, I think, of using the 'wrong' definition for Z, namely $\frac{Z}{\overline{E}} \cdot \frac{d\overline{\sigma}}{dt} = -\dot{\varepsilon}_c(\varepsilon_c, \overline{\sigma}, T)$. If $\frac{Z}{\overline{E}} \cdot \frac{d\overline{\sigma}}{dt} = -\left(\dot{\varepsilon}_c(\varepsilon_c, \overline{\sigma}, T) - \dot{\varepsilon}_c(\varepsilon_c, \sigma^P_{ref}, T)\right)$ were used instead one could hope to fit a constant Z value to the computed relaxation curve

Appendix A8 rather unhelpfully does not include the advice on Z for welding residual stressing which is included in Appendix A4 – and which refers out to Baikie, Bradford et al (item #12 on the recommended reading list in the Mentor Guide).

Candidates may like to offer their own estimation methods for Z (in view of those in R5 being rather inadequate, in my view). Here's two from me:-

(4)Use the same Z as is implicit in the Neuber construction, i.e., Z = (2 – x) / (1 – x), where $x = \Delta\sigma / \sigma_0$ is the fractional stress drop. This gives Z ~ 2 for small stress drops, so may err on the non-conservative side. Treat with caution!

(5)If the stress can be considered as the sum of a primary stress, $\sigma_p$ (with Z = ∞) and a purely secondary stress, $\sigma_s$ (i.e. with Z = 1), then I believe the combined effect is a stress $\sigma_p + \sigma_s$ with a follow-up factor of $Z = \frac{1}{1-\xi}$ where $\xi = \left(\frac{\sigma_P}{\sigma_P + \sigma_S}\right)^2$. This is justified by a two-bar model. See http://rickbradford.co.uk/ZforPrimaryPlusSecondaryLoads.pdf for the derivation.

## 1.31 Write down the general expression for calculating the creep damage per dwell

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes34.pdf.

Creep damage is covered in Section 8.3 and Appendix A11. The equation expected is A11.1. Candidates should be aware of the effect of both strain rate and stress state on the creep ductility. They should be aware of the importance of both these factors in explaining austenitic reheat cracking.

Mentees should also appreciate that the strain rate will exhibit strain hardening. They should appreciate the distinction between time hardening and strain hardening.

## 1.32 State the procedure for correcting laboratory fatigue endurance data for the required initiation crack size.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

This is defined in Section 8.2 and Appendix A10. The key thing is the correction for the assumed initiation crack size cf the specimen size used to derive the endurance data. As part of this the candidate would be expected to make intelligent noises regarding the choice of initiation crack size, $a_0$. An essential part of this correction procedure is the splitting of the total endurance (obtained from lab test data) into an incubation phase and a crack growth phase. The former is generally taken as resulting in a micro-crack of depth 20 microns. The growth phase covers growth from 20 microns to the nominal 'initiation' depth declared in the assessment, $a_0$. If parent endurance data is to be used to assess a weldment, the number of cycles to incubation should be dropped, using only the growth phase. This is referred to as the WER (weld endurance reduction). However, if fatigue endurance data for a representative weldment is available (it generally isn't) then no WER correction is required.

## 1.33 Define the fatigue damage for a number of different cycle types.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

Miner's Law, Equ.(A10.2)

## 1.34 State which equivalent stresses should be used in which parts of the procedure for fatigue damage under multiaxial stressing

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

This is covered in A10.2. Both Tresca and Rankine are used in different parts. They differ for shear loading. Unfortunately the advice in R5V2/3 Appendix A10 only covers surface points, i.e., biaxial stressing. I suspect Mises strain range is actually used by most people, rightly or wrongly.

1.35 Discuss the influence of cycling frequency and cycle sequence on fatigue endurance.

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

These are discussed in A1.5 and A10.3. The effect of cycle sequence can be significant if the cycles differ substantially in severity. Unfortunately there is no easy way to assess this.

1.36 State how creep and fatigue damage are combined in R5

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

A gift, but important – linearly! Implicit in this is that the candidate would be expected to know that other procedures use some form of interaction diagram, which is another way of saying that the combined effect is non-linear, i.e. worse than linear. The candidate should be able to sketch the appearance of the creep-fatigue interaction diagram used in ASME NH, for example. This might provoke a discussion about why R5 is different – to which I am no longer confident that I know the answer.

1.37 Discuss what procedures may be relevant in assessing high cycle fatigue

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes35.pdf.

This is beyond the scope of R5 – but people should *know* this! Candidates should be expected to be able to quote R2 as a suitable procedure. They should also have some knowledge of the Goodman diagram, i.e. the importance of mean stress in reducing endurance to high frequency cycles. More detailed knowledge not necessary.

The sequence of questions 1.38 to 1.46 was originally written with R5 Issue 3 (2003) in mind. The guidance given below has now been extensively revised to be consistent with the draft replacement of R5 V2/3 Appendix A4 which is expected to be issued as part of R5 in 2013. This has required some creative re-interpretation of the questions.

1.38 Define the three Weldment Types in R5 Volume 2/3

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

Defined in A4.2

1.39 Define what is meant by a Fatigue Strength Reduction Factor (FSRF) and discuss the recommendations regarding FSRFs for weldments in R5 and how they vary with material, weldment class and condition of the weldment. *This question can now be re-interpreted by requiring discussion of the WSEF and the WER instead of the FRSF.*

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

The FSRF is no longer used in the revised procedure. Nevertheless candidates should know what a FSRF is, if only because it is extensively used in other codes/procedures. The FSRF is a factor (>1) applied to the strain range to account for the weakening effect of a feature, such as a weld, on the fatigue endurance. It is *not* applied to the stress range or the number of cycles, but to the strain range used to find the fatigue endurance from a standard endurance curve.

The FSRF has been replaced in the revised procedure by two factors: the WSEF and the WER, which are, WSEF = Weld Strain Enhancement Factor: this is used in the same way as the old FSRF, i.e., to factor up the strain range, but accounts only for the geometrical effects on fatigue endurance. Hence $1 < WSEF < FSRF$ .

WER = Weld Endurance Reduction: The WER is defined as the ratio of the number of fatigue endurance cycles with and without the nucleation cycles included. In practice, the WER is not determined explicitly but is incorporated into an assessment by lowering the parent material fatigue endurance curve by removing the nucleation cycles. The details of this procedure can be found in the tutorial session 37 notes.

## 1.40 Discuss the requirement to include or exclude the local peak F-stresses in R5 fatigue assessments for dressed and undressed weldments

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

This question was apposite for the R5 Issue 3 (2003) procedure, because the answer differed for dressed and undressed weldments. It is now much simpler. In the revised procedure the peak (F-)stresses are not used for either dressed or undressed weldments. Both are assessed using linearised stresses.

## 1.41 Discuss the influence of welding residual stresses on an R5 creep-fatigue initiation assessment

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

A contribution to creep damage from residual stress relaxation should be included in general, see §4.5.2 and §4.6.1.3.

Candidates should be aware of the threat of reheat cracking, in either austenitic or ferritic materials. They should be aware of the particular threat for austenitic materials as a consequence of the fact that ASME, BS and Eurocodes do not generally require PWHT for austenitics. Candidates should understand the (engineering-level) mechanism of reheat cracking. Namely the reduction of creep ductility sub-surface by triaxial stressing and low strain rate. This is exacerbated by elastic follow-up (Z is at least 2 for welding residual stresses, and can be much larger if there is a local SCF, e.g. due to a thickness mismatch, see Item #12 on the recommended reading list in the Mentor Guide). Creep damage is defined in the same way as for ‘cyclic’ creep damage.

Candidates should also appreciate the interaction between the initial welding residual stresses and the cyclic loading in service. The latter could be beneficial in ‘washing out’ the former – but an allowance for a period of transient damage would be required. (Section A.4.6.1.3).

## 1.42 Itemise the key features of an R5 creep-fatigue initiation assessment of a dressed weldment which differ from that for a parent material feature or that of an undressed weldment

## 1.43 Itemise the key features of an R5 creep-fatigue initiation assessment of an undressed weldment which differ from that for a parent material feature or that of a dressed weldment

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

These questions are treated together for convenience. In the revised Appendix A4, the treatment of dressed and undressed weldments has been unified (in contrast to the 2003 version of R5). However some differences do remain - and should remain since undressed weldments can be expected, in general, to initiate cracks more readily.

For both dressed and undressed welds the WSEF takes the place of the FSRF in the construction of the hysteresis cycle (and hence dwell stress). Previously (in R5V2/3 Issue 3) there was no such factoring of the strain range (with corresponding implications for the dwell stress) for dressed welds. Consequently, whilst the revised procedure will most often be less onerous for undressed weldments, for dressed weldments it may be *more* onerous than

R5V2/3 Issue 3.

Despite the unified methodology adopted for dressed and undressed weldments in R5V2/3 Issue 3 Revision1 Appendix A4, some differences will remain. I cannot be definitive about what these will be because, at the time of writing, the revised Appendix A4 has not been finalised. However I expect the following differences between dressed and undressed weldments,

(i) They may differ in the linearised stresses which are used, due to differing advice regarding the degree of geometrical refinement employed in an FEA;

(ii) A weld cap SCF recommended originally by O'Donnell may be retained for undressed weldments, but not for dressed weldments (not yet clear);

(iii) The WSEF for undressed weldments requires a thickness adjustment, but this is not required for dressed weldments.

There may be more differences in the final version.

However, a weldment assessment differs much more significantly from a parent feature assessment. Key differences are,

- It is not recommended that the fine details of a weldment be modelled when determining the elastic stresses, and the stresses input to the weldments procedure are the linearised values. This contrasts with the parent procedure for which local peak values are used. The reason for the difference is that the WSEF is taken to incorporate the local geometric stress concentration effects for a weldment.
- The WSEF is used to factor the strain range initially calculated by the R5 V2/3 Appendix A7 hysteresis loop construction for the parent stress-strain curve. In this way a strain range is found for the weldment. The corresponding stress range is found from the parent cyclic stress-strain curve. Hence a hysteresis loop for the weldment is constructed, including a new dwell stress (which is often substantially higher than the parent dwell stress).
- For assessment points in weld material, the start-of-dwell stress should be factored by the ratio of the weld:parent yield stresses (cyclically conditioned values, and in the state of residual stress that prevails); *[HAZ is not explicitly mentioned that I can see, but logic suggests the same factoring should apply];*
- The fatigue endurance assessment uses not just the above weldment strain range but also applies the WER, a further endurance reduction. This consists simply of ignoring the cycles to incubation (see 1.32 and http://rickbradford.co.uk/T73S04TutorialNotes35.pdf). However, if fatigue endurance data for a representative weldment is available (it generally isn't) then no WER correction is required.

I flatter myself that the session 37 tutorial notes are the most explicit procedural guidance on constructing a weldment hysteresis cycle.

## 1.44 Discuss the requirement, or otherwise, for multi-material stress analyses, as opposed from homogeneous models

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

Multi-material FEA is not required. R5V2/3 App.A4 assessments are generally based on homogeneous (parent) models. However, unlike previously in R5 Issue 3, multi-material models are sanctioned as a possibility in the revised procedure. §4.3.3 says, "*Where multi-material inelastic analysis is carried out, the WSEF is not required to be applied to the calculated strain ranges (since this strain enhancement effect is determined from the analysis, although the WER is still necessary in the fatigue assessment). However, for undressed weldments, the effects of local geometric stress concentrations should be taken into account either in the modelling of the weldment surface or by applying an appropriate strain concentration factor*".

Note the difference between multi-material modelling and homogeneous modelling for undressed weldments. When using multi-material modelling, the local stress raisers should be included and WSEF not included in the assessment. For homogeneous modelling, the local stress raisers should *not* be included but the WSEF *is* included in the assessment.

There is an issue here in that any sharp corner feature, e.g., a weld toe, will generate an arbitrarily high stress and strain concentration as the mesh refinement is increased. R5 currently offers no guidance on the degree of refinement which correctly captures the WSEF. Too coarse a mesh will under-estimate the WSEF effect, whereas too refined a mesh will over-estimate it. The mesh needs to be 'critically refined'. My personal (unvalidated) guidance is to use elements at the singularity with a Gauss point spacing comparable with the grain size. The question will then arise as to whether a single Gauss point reaching D = 1 is sufficient to imply crack initiation, or whether the cracking criterion should be multiple Gauss point failure. Good luck.

## 1.45 Discuss how the precise location of the assessment point in the vicinity of a weldment may be determined

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

Who knows? Use some judgement, but mostly assess several candidate points. There's no alternative that I can see. In particular, include sub-surface points because, even though the stresses may be less, the ductility may be *far* poorer.

## 1.46 Discuss recent developments in the methodology for initiation assessments of weldments

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes37.pdf.

This question is now void since the revised procedure is all you need consider. You need not know the R5V2/3 App.A4 Issue 3 procedure. However some appreciation of what difference the new procedure might be expected to make is desirable. Without having done any detailed comparisons my expectation is as follows: If an assessment is fatigue dominated then the results of using the revised procedure will probably not be dramatically different from that using the old procedure (roughly speaking, FSRF is equivalent to WSEF x WER). However, for creep dominated cases the assessment of undressed welds is expected to be very considerably less onerous using the revised procedure. It was the excessive conservatism of this case that was the motivation for the revision. Unfortunately it may be that the revised procedure is *more* onerous than the old for dressed weldments - but this depends upon the final recommendations.

## 1.47 Discuss the major factors influencing the outcome of a finite element analysis of a structure beyond strict shakedown

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes38.pdf.

Candidates should be well aware that an FE analysis of a structure undergoing hysteresis cycles is in a very different category from a monotonic loading analysis. They should appreciate that the reliability of the computer results is limited essentially by our poor knowledge of material constitutive behaviour. Candidates should be able to describe qualitatively isotropic and kinematic hardening. They should appreciate that these cases are extremes and that real materials tend to be intermediate. They should appreciate in what respects these hardening assumptions are conservative or non-conservative. Candidates should appreciate that materials may cyclically harden or soften, and give examples. Candidates should understand why 'plastic strain' becomes potentially an unhelpful quantity under cyclic conditions.

The formulation of creep deformation equations should have been covered in the "creep rupture" SQEP area (T73S06), but could usefully be reprised. More importantly, candidates should appreciate that there is an interaction between plasticity and creep. They should be able to explain in qualitative, physical terms why ignoring this interaction leads to problems (e.g. hysteresis cycles with creep dwells will not be closed). Candidates should be able to quote ORNL and FRSV (or R5SV) as examples of available constitutive models, and perhaps make some intelligent noises about them – but without detailed knowledge of the equations. They should appreciate the limitations of the available models and assumptions – as summarised in R5 Appendix A12, Table A12.1.

The Mentee might be asked about the status of FE technology in respect of calculating ratchet strains.

## 1.48 Discuss what options may be available for a structure which is outside the R5 global shakedown limit

Relevant Tutorials [http://rickbradford.co.uk/T73S04TutorialNotes38.pdf](http://rickbradford.co.uk/T73S04TutorialNotes38.pdf).

The main expectation is that the candidate has some familiarity with the Manus O'Donnell report E/REP/BDBB/0026/AGR/03, Required Reading Item #4 in the Mentor Guide. There are broadly two areas of interest: Either, (a) methods to demonstrate that there is no ratcheting (i.e. gross shakedown occurs) despite not meeting the R5 global shakedown criterion, or, (b) methods to evaluate the amount of ratcheting and assess its acceptability. In the case of (a), the assessment would continue via the R5 initiation route. Case (b) is outwith R5 but it may still be possible to make an integrity case.

Candidates should be able to make intelligent noises about the sequence of possible FE methods of escalating complexity (elastic; elastic with plastic bits given a very low E; unsophisticated elastic-plastic; elastic-plastic with advanced constitutive models). Various checks on the results, e.g. that the apparent ratchet strain per cycle is reducing; that the total ratchet strain over life is within some sensible limit; that the plastic zone is localised and not increasing in size significantly; that the Neuber method gives a reasonable estimate of strain (the latter as a check on excessive follow-up). Candidates should appreciate that this amounts to a potential relaxation of the '20%' rule in R5's global shakedown criterion.

For 316 steel, REP/0026 has suggested (equivalent) ratchet strain limits of:-

- 5% in parent (peak); 2.5% in weld (peak)
- 2% in parent (averaged over section); 1% in weld (averaged over section)

Plus, checks that dimensional changes are not functionally unacceptable.

REP/0026 implies that the above limits *may* be appropriate for other materials also.

However, the whole strategy may be compromised if the technology does not exist to calculate the ratchet strains (e.g. due to shortcomings in available constitutive models). Is a post-ratchet assessment reliable?

## 1.49 Discuss what alleviations in the derivation of the creep ductility of materials may be available to reduce levels of conservatism (e.g. for 316 or 304 steels)

Relevant Tutorials [http://rickbradford.co.uk/T73S04TutorialNotes38.pdf](http://rickbradford.co.uk/T73S04TutorialNotes38.pdf).

What I have in mind is Mike Spindler's stress-dependent formulation of ductility, as in Required Reading Items #6 & #7 and the more recent E/REP/BBGB/0016/GEN/07 (Feb.2009). . The formulation of the stress-dependent ductility with its associated multi-axial dependence is different from that in R5 V2/3 Issue 3, hence this counts as an alternative technique (though it may be incorporated into R5 ultimately). Candidates should appreciate that this may be helpful in avoiding excessive conservatism for creep-fatigue hysteresis cycles with intermediate dwells.

These same references, together with #8 & #9, also discuss the important issue of the use of total strain at failure rather than just the creep strain at failure as the definition of creep ductility for parent 316. However, I have my doubts about this now. I suspect the creep strain at failure should always be used – but consult the experts.

## 1.50 Discuss stress-rupture formulations which take account of multiaxial states of stressing

Relevant Tutorials [http://rickbradford.co.uk/T73S04TutorialNotes38.pdf](http://rickbradford.co.uk/T73S04TutorialNotes38.pdf).

Possibly this should be in the “creep rupture” Mentor Guide, though it is not actually part of the R5 procedure. However it fits in here more naturally because this is where multiaxial effects feature most.

Of course, one such formulation is R5 V2/3 via its $\chi$ factor method. However, this depends only on the ratio of the Mises stress to the reference stress. It is recognised in the literature that creep rupture also depends upon the hydrostatic stress and the maximum principal stress in addition to the Mises stress. This is easily discernable by looking at tension-torsion and pressure-tension rupture results in comparison with uniaxial results. Hence, the R5 V2/3 method is rather over-simplified. (Actually non-conservative in the case of significant hydrostatic tension, it seems to me). Candidates should perhaps have heard of the Huddleston formulation (1985 & 1993). But Baker has provided an alternative for 316H (Required Reading Item #10) which employs the same triaxiality function as in Spindler’s stress-dependent ductility formulations (Items #6 & #7).

Candidates should appreciate that, in terms of the time to rupture, these effects can be very marked indeed (orders of magnitude).

### 1.51 Describe the metallurgical mechanisms underlying creep deformation and creep failure

Relevant Tutorials http://rickbradford.co.uk/T73S04TutorialNotes36.pdf.

See also http://rickbradford.co.uk/T73S06TutorialNotes23.pdf.

It’s debatable whether this should be included since it forms no part of any assessment procedure. My view is that SQEPs should have at least some idea of what is happening physically during creep, but a lenient attitude could be taken as to the details. The three main features are:-

1) Creep deformation, like plastic deformation, is due to the movement of dislocations. Consequently, hardening, or reducing strain rate, will often be due to mobile dislocations becoming scarcer (e.g. because many have already got pinned to inclusions, or entangled together, by previous straining).

2) The approach to creep failure in creep ductile materials (especially ferritics) is the formation of the cavities with which we are familiar from CMV Type IV region cavity counting. Failure proceeds via alignment and inter-linking of said cavities. The cavities are big enough to be seen by optical microscopy. The cavities may form by a ductile mechanism, i.e., by dislocation movement induced strain. (Can vacancy diffusion contribute also? I don’t know). The cavities generally form on the grain boundaries.

3) The mechanism of creep failure in austenitic steels with low creep ductility is also generally assumed to be due to cavities nucleating and growing on the grain boundaries. The mechanism by which the cavities grow is vacancy diffusion or vacancies hitching a ride on a passing dislocation. Pure vacancy diffusion under conditions of interest to us will be dominated by ‘pipe diffusion’ down dislocation tangles. Vacancies within the material (single displaced atoms) diffuse due to thermal effects in a direction dictated by the stress gradient (seeking to minimise the free energy). The cavities are generally about 2 microns in diameter when they become large enough to link along the grain boundary and create a micro-crack. Thereafter you have crack growth rather than rupture. The key factor determining the ductility is the spacing between cavity nucleation sites on the grain boundary. There are many variants of semi-empirical models based on cavity nucleation and growth which ‘explain’ the stress-state dependence of austenitic creep ductility (see Dean, Required Reading Item #11 for one such).

4) Alternatively, creep failure (tertiary creep) may not be due to cavities at all. The cavities may just be fellow travellers. The failure may be due to rapidly increasing matrix softness, i.e., just due to excessive strain.

### 1.52 Identify the items which should be included in the report of a creep-fatigue initiation assessment to R5

In addition to the obvious things which should go in any assessment report (purpose, plant description, geometry, loading, temperature, environment, materials, all material property values used, etc) the following should specifically be included:-

1) Specification of the exact procedure used, because there are many options within R5, and especially if variants on strict R5 are adopted;

2) Elastic stresses at each relevant condition/transient (e.g. schematic graph of elastic stress versus time);

3) Justification of insignificance of creep or fatigue, if this is claimed;

4) Margins against plastic collapse and creep rupture;

5) Sketch of stress-strain hysteresis cycles, showing the operational manoeuvres and conditions (e.g. temperature) relevant at each point;

6) Details of the quantitative development of the stress-strain cycle(s) from the elastic stresses;

7) The resulting start-of-dwell stress, stress drop and assumed Z;

7) The resulting strain range, and the components from which it is made up;

8) State the assumed initiation crack size, with justification of reasonableness;

9) Details of calculation of fatigue damage;

10) Details of calculation of creep damage (e.g. multiaxial effects and strain rate effects, method of numerical integration of the forward creep, strain or time hardening);

11) Satisfaction of the cyclically enhanced creep limit;

12) Margins against failure (which may be time or cycles based, as appropriate).

13) Sensitivity studies.

It is difficult to be definitive about what sensitivity studies may be advisable since cases need to be considered on their own merits. However it is often the case that creep damage is limiting and that this is sensitive to the start of dwell stress, which in turn may be sensitive to input data such as the ‘yield’ stress, or Ks, or the elastic stresses. Generally this sensitivity should be explored. The cyclic stress-strain curve assumed will probably be both uncertain and important to the outcome of the assessment, and should also be subject to a sensitivity study.

Both the stress drop and the creep ductility may be subject to very large percentage uncertainties. A crude probabilistic approach may be of interest to avoid combining several independent assumptions at bounding levels. (NB: Three 95% CLs give $10^{-4}$).

### 1.53 Discuss the validation data available to support the conservatism of R5 creep-fatigue initiation assessment methodology

Candidates should have at least a passing acquaintance with the contents of R5 V2/3 Appendix A14 and to be aware that, in some cases, even using best estimate data the results of an R5 assessment may be conservative by an order of magnitude. Other cases, however, align well.