Mentor Expectations Guide – Structural Analysis Group / ATG
A Companion to the Mentor Guide T73S03:
Perform High Temperature Fracture Assessments Using R5 Volume 4/5 and 7

Compiled by Rick Bradford, Last Update: 6th December 2011

These Expectations Guides are a record of what the author of the Mentor Guide had in mind in posing the questions in the Knowledge & Skills Acquisition Activity Section. They are not necessarily a definitive statement of the 'right' answer.

The references to R5 herein relate to Issue 3 (June 2003)

1.0 Define the creep fracture parameters C* and C(t) and explain their relevance

$C(t) = LIM_{\Gamma \to 0}\left[\int_\Gamma \left\{\tilde{W}_c dy - \sigma_{ij}\frac{d\dot{u}_i}{dx}n_j ds\right\}\right]$ where $\dot{u}$ represents displacement rates, and $\dot{\varepsilon}$ represents strain rates, and $\tilde{W}_c$ is defined by $\tilde{W}_c = \int \sigma_{ij} d\dot{\varepsilon}_{ij}^c$. The parameter C* is defined as $C^* = LIM_{t \to \infty}\{C(t)\}$. Since all secondary stresses will have relaxed in the long time limit, it follows that C* depends only upon the primary stresses. In contrast, C(t) depends upon the primary and the secondary stresses, and hence is time dependent whilst redistribution and/or relaxation are taking place.

The relevance of these parameters is that, with certain caveats, they control the near crack tip stress and strain-rate fields. Hence they can reasonably be claimed to control creep crack growth. See tutorial session 39 on this site.

1.1 State the contour integral definition of the creep fracture C(t), including suitable contours to employ in its evaluation.

See above. Unlike J, which is (with certain caveats) contour independent, C(t) is defined with reference to sufficiently small contours near the crack tip, i.e., within the region controlled by C(t). The reason is that one of the caveats on the contour independence of J is that stress reduction does not occur. This is almost always violated in creep due to relaxation/redistribution. Hence contour independence of C(t) is not expected (and a unique definition is obtained only by specifying a small contour). See tutorial session 39 on this site.

1.2 Draw a typical graph of C(t) versus time for: (a)primary loading only; (b)secondary loading only; (c)combined primary plus secondary loading.

See illustrations in tutorial session 39. The key features are, (a)that the asymptotic value of C(t) for sufficiently long times is C*; (b)if there is no primary loading this asymptote is zero (in theory, but in practice relaxation effectively ceases at some non-zero stress); (c)when there is secondary loading the initial C(t) is due to the combined primary and secondary stress and hence reduces over time due to relaxation of the latter; (d)even if there is only primary load, the initial C(t) exceeds C* and then diminishes due to redistribution; (e)plasticity can strongly ameliorate the initial C(t) by causing redistribution before creep starts; (f)primary creep can enhance the initial C(t) in all cases.

1.3 Describe algebraically, using the contour integral definition of J, why C(t) is not in general equal to dJ/dt.

This question is slightly unfortunate because the J in question is not the conventionally defined J of R6. What is meant is a time dependent J define by $J(t) = \int_\Gamma \left\{W_{epc}dy - \sigma_{ij}\frac{du_i}{dx}n_j ds\right\}$ where, $W_{epc} = \int \sigma_{ij} d\varepsilon_{ij}$ and $\varepsilon_{ij} = \varepsilon_{ij}^e + \varepsilon_{ij}^p + \varepsilon_{ij}^c$. Taking the time derivative of this J(t), those parts of the derivative of the integrand which involve the strain rate or displacement rate just reproduce the integrand in the definition of C(t),

$C(t) = LIM_{\Gamma \to 0}\left[\int_{\Gamma}\left\{\tilde{W}_c dy - \sigma_{ij}\frac{d\dot{u}_i}{dx} n_j ds\right\}\right]$. The remaining terms involve the time derivative of the stresses. During primary creep, or transient creep (redistribution or relaxation), the stresses do change, so their time derivatives are not zero. Consequently C(t) is not equal to dJ/dt. However, in the long time, steady secondary creep limit the stresses become constant and these terms vanish leaving only the terms equivalent to C(t) – and in this limit $C(t) \to C^*$. Hence,

$$C^* = LIM_{t \to \infty}\{C(t)\} = LIM_{t \to \infty}\left\{\frac{dJ}{dt}\right\}$$

But this is only true in the limit of steady secondary creep when all secondary stresses have relaxed. See tutorial session 39 on this site.

1.4 State the contour integral definition of the creep fracture parameter C*, and hence show that C* = dJ/dt. Discuss the implications of this for the possible contours to employ in a finite element calculation of C* and contrast with C(t).

Most of this has been addressed above. Note that C* = dJ/dt is only true for very lond times such that all secondary stresses are relaxed to zero – an idealisation which is unlikely to be realised in practice. In respect of the required contours, the relationship between C* and J suggests that C* evaluations might be much more forgiving than C(t), i.e., much larger contours may give good, contour independent results. Off hand I don't know if this is borne out in practice.

1.5 State the form of the crack tip stress and strain fields for power-law creeping materials in terms of C(t) (assuming a stationary crack and no plasticity).

These are the creep version of the HRR fields, i.e., $\sigma_{ij}(t) = \left[\frac{C(t)}{B(t)I_n r}\right]^{\frac{1}{n+1}}\hat{\sigma}_{ij}(\theta,n)$ and

$\dot{\varepsilon}^c_{ij}(t) = B(t)\left[\frac{C(t)}{B(t)I_n r}\right]^{\frac{n}{n+1}}\hat{\varepsilon}_{ij}(\theta,n)$ assuming a Norton creep behaviour with arbitrary separable primary creep: $\dot{\varepsilon}^c = B(t)\sigma^n$ (uniaxial), $\dot{\varepsilon}^c_{ij} = \frac{3}{2}B(t)\bar{\sigma}^{n-1}S_{ij}$ (multiaxial).

1.6 State the expression for C(t) in terms of J, and hence K, for sufficiently early times.

These are listed in tutorial session 39. They are,

No Plasticity

For secondary creep as t→0: $C(t) \to \frac{K^2_{TOT}}{(n+1)\phi E}\cdot\frac{1}{t} = \frac{J}{(n+1)\phi}\cdot\frac{1}{t}$

For primary creep as t→0: $C(t) \to \frac{(1-m)K^2_{TOT}}{(n+1)\phi E}\cdot\frac{1}{t} = \frac{(1-m)J}{(n+1)\phi}\cdot\frac{1}{t}$

With Plasticity

As $t \to 0$: $C(t) \to \frac{\varepsilon^{ep}_{ref}\dot{\varepsilon}^c_{ref}(t)}{\varepsilon^p_{ref}\sigma_{ref}}K^2_{TOT} \approx \frac{\dot{\varepsilon}^c_{ref}(t)}{\varepsilon^p_{ref}}EJ$

However, if the plastic strain is far larger than the elastic strain then this becomes, As $t \rightarrow 0$ and if $\varepsilon_{ref}^{p} >> \varepsilon_{ref}^{e}$: $$C(t) \rightarrow \frac{\dot{\varepsilon}_{ref}^{c}}{\sigma_{ref}} K_{TOT}^{2}$$

See tutorial session 39 for an explanation of the terms. The limit $t \rightarrow 0$ means $\varepsilon_{ref}^{c} << \varepsilon_{ref}^{ep}$. Note that assessments do not commonly use these short-time expressions. The C(t) estimates which are more commonly employed are addressed in later sessions.

For Questions 1.0 to 1.6 see http://rickbradford.co.uk/T73S03TutorialNotes39.pdf

1.7 State the main mechanisms which might lead to creep crack initiation in BE plant.

Cracks may initiate due to the following processes involving creep,

(a) Reheat cracking;

(b) Type IV cracking (ferritic weldments);

(c) Coarse HAZ cracking in ferritic weldments;

(d) Creep-fatigue, where load cycling is significant.

In addition, the following non-creep mechanisms of crack formation may lead to a crack which subsequently grows by creep,

- Original sin of many kinds which lead to sharp features, especially welding defects (e.g., lack of fusion, sharp toe features, hydrogen cracking, etc);
- High-strain fatigue due to service cycles;
- High-cycle fatigue, e.g., due to vibration;
- Thermal fatigue of several types,
    - TTIBC / thick-section thermal fatigue
    - Header ligament cracking
    - Small bore condensate refluxing
- Defects due to IGA (intergranular attack) - aqueous
- Defects due to SCC (stress corrosion cracking) – aqueous or wet steam
- Other corrosion morphology (e.g., pits) – aqueous or damp gaseous
- Intergranular oxide fingers – gaseous (air, CO_2, anything oxidising)
- Fretting damage

1.8 Define what is meant by “Type IV” cracking in low alloy ferritic weldments. State the key factors leading to Type IV cracking. State the best means of mitigating against Type IV cracking.

Type IV cracking is defined as cracking in the inter-critically refined HAZ of low alloy ferritic weldments. It is (one of) the end-of-life creep mechanisms of such weldments. It is generally associated with large system stresses, particularly in systems which have had repairs without care to maintain the proper cold pull. Mitigation is to ensure system loads are not excessive via correct design, maintenance of pipework supports, and correct restraining and heat treatment procedures when carrying out repairs to the system.

1.9 Describe the reheat cracking mechanism and the key contributing factors to its occurrence. Compare and contrast the reheat cracking threat for ferritic and austenitic weldments. State the phase of operating life in which the initiation of reheat cracking is most likely for both ferritic and austenitic materials under AGR plant conditions. State the best means of mitigating against reheat cracking.

Reheat cracking is defined as creep cracking which occurs on being raised to creep temperatures some time after welding and which is driven predominantly by welding residual stresses. It can occur in service only if the weld was not stress relieved. Alternatively a badly conducted heat treatment can itself cause reheat cracking (though it might then be called something else).

Reheat cracking can occur in both ferritic steels and austenitic steels. However it has been rare in ferritics since the late 1970s because design codes call for heat treatment of ferritic weldments. In contrast, the codes frequently (still) permit austenitic welds to enter service without heat treatment. This is the reason why it has been austenitic materials which have been associated with reheat cracking over the last 20 years – not necessarily because they are intrinsically more prone to reheat cracking.

Reheat cracking is an early to mid-life phenomenon. After sufficient time at temperature in the creep regime the initial welding residual stresses will have relaxed and the threat of cracking, if it has not already happened, recedes. The time after which the threat becomes low depends, of course, on the temperature.

Proper post-weld heat treatment reduces the threat of reheat cracking to essentially zero.

1.10 State what is meant by ‘creep-fatigue initiation’. State under what conditions a creep-fatigue crack is likely to initiate.

Creep-fatigue is the mechanism which results from a synergy between creep and fatigue. The principal deleterious feature is that load cycles result in elastic-plastic stress-strain hysteresis loops which cause the stress during steady operation to be re-set to a high level despite creep relaxation. Each cycle therefore involves a renewed period of creep relaxation and associated creep damage. The creep fatigue mechanism is most serious when the structure is outside of strict shakedown, so that plasticity occurs on every cycle. This will be exacerbated by poor creep ductility and/or a large number of cycles.

1.11 Describe the threat from thermal fatigue cracking, for BE and conventional power plant, in respect of: (a)the bore of main steam pipework; (b)the ligaments of superheater headers; (c)thick section components such as steam chests, turbine casings, valve bodies and tubeplates; (d)small bore branches on steam pipes or headers. State the best means of mitigating against these threats in each case.

TTIBC: mitigation would be to (a)reduce the severity of the thermal transients; (b)reduce the number of load cycles; (c)reduce the operating temperature. Conventional power plant relies on (a) because (b) is constrained by the requirement to two-shift, whilst (c) is undesirable due to the reduced power output (though possible). For AGR plant, (b) and (c) are both benign and hence TTIBC is not a problem. For conventional plant TTIBC has lead to the need for very widespread weld repairs.

Header Ligament Cracking: Mitigation is the same as for TTIBC. There is a theoretical problem for AGRs, but probably not real (due to conservative assessment of the creep component of damage). On conventional plant, many main steam headers have been replaced. (Often using P91 – out of the frying pan into the fire?).

Steam Chests, etc.: Cracking common on conventional plant, but often self-limiting so no need to replace. Unlikely to be a problem on AGRs.

Small Bore Condensate Reflux Cracking: I do not know whether conventional plant has suffered from this (though I don’t see why not). On AGRs there have been quite a few instances in the past, especially at DNB in the early 90s. But also a few isolated instances more recently at other Stations. Mitigation is to re-run the small bore lines under the main line lagging to keep them hot, and/or to ensure that valve configurations prevent refluxing.

1.12 Discuss other fatigue crack initiation mechanisms and the applicability and limitations of R5 to their prediction and/or assessment.

High-strain fatigue – R5 is applicable

High-cycle fatigue – R5 is not applicable – use R2

1.13 State the prescription within R5 Volume 4/5 for determining whether creep is significant

For cracked structures, the (in)significance of creep depends upon the crack depth and the loading. The criterion differs from the criterion for uncracked structures. The criterion is that creep is insignificant for a period of time t_m defined as the time to accumulate a strain equal to $1/50^{th}$ of the creep ductility (capped at 10%) at the relevant ***reference*** stress and operating/assessment temperature. (In addition, t_m is limited to the LOIC time for the uncracked structure). The use of the reference stress in the definition of t_m is what causes the crack size dependence.

Hence, unlike the uncracked LOIC, t_m depends in general upon the loading of the structure as well as the crack size. However, for 304ss and 316ss, Figures A6.6 and A6.7 in R5V4/5 Appendix A6 give load independent versions (essentially generalisations of LOIC to the cracked case).

1.14 Describe the conditions required by R5 for cyclic loading to be considered as insignificant, both as regards the uncracked ligament and the crack tip region.

There are six criteria, all of which must be met if cyclic loading is insignificant in R5V4/5:-

[1] The greatest elastic Mises stress range, $\Delta\bar{\sigma}_{el,\max}$, is less than the sum of $K_S S_y$ at the two ends of the cycle;

[2] The structure is within strict shakedown;

[3] The elastically based fatigue damage is less than 0.05;

[4] Creep behaviour is unperturbed by cyclic loading.

[5] The fatigue crack growth does not exceed 10% of the creep crack growth, and,

[6] The cyclic plastic zone at the crack tip is small compared with the characteristic dimensions (i.e., the crack size, the ligament size and the thickness).

1.15 State the conditions under which it is necessary to apply fatigue crack growth data obtained from tests including creep dwells.

Fatigue crack growth data from tests including creep dwells must be used if creep is perturbed by cyclic loading but the fcg is less than 10% of the ccg.

In addition, it may be necessary to adjust the fcg law used if propagation is through material subject to heavy prior creep damage.

1.16 State how the stability of the crack, e.g. against fast fracture, should be determined.

Using R6.

For Questions 1.7 to 1.16 see http://rickbradford.co.uk/T73S03TutorialNotes40A.pdf

1.17 Discuss the inputs required for an assessment (including: effective historical creep temperature; future temperature; rate of cycling; assessment period; stress classification; defect idealisation; relevant materials/zones to be assessed, etc)

This is covered in http://rickbradford.co.uk/T73S03TutorialNotes40A.pdf.

- The historical temperatures, most conveniently expressed as an historic MECT (generally a best estimate);
- The projected future operating temperature, also most conveniently expressed as an MECT (generally a best estimate with a slight conservative bias);
- Normal operating loads (for creep);
- The peak normal operating loads (maximum and minimum) defining the fatigue cycles;
- Fault loads for the crack stability (R6) assessment;
- Past and projected operating hours;
- Past and projected cycling rate;
- Load categorisation (primary or secondary);
- Defect size, shape, position and orientation (actual or hypothesised);

- Material/weldment zones in which cracks occur or are to be postulated;
- Elastic follow-up factor(s), Z.

1.18 Define the elastic follow-up factor, Z, and state two ways in which the value of Z for a crack growth assessment to R5V4/5 may differ from that for an initiation assessment to R5V2/3.

The usual definition of Z is $Z = \frac{\bar{\varepsilon}_c}{|\Delta\bar{\varepsilon}_{el}|}$, but actually a better definition is $Z' = \frac{|\bar{\varepsilon}_c - \bar{\varepsilon}^R_{c,ref}|}{|\Delta\varepsilon_{el}|}$ where $\bar{\varepsilon}^R_{c,ref}$ is the primary creep strain at the rupture reference stress. This definition is consistent with the recommended relaxation equation, $\frac{Z'}{\bar{\bar{E}}} \cdot \frac{d\bar{\sigma}}{dt} = -\left(\dot{\bar{\varepsilon}}_c(\varepsilon_c, \bar{\sigma}, T) - \dot{\bar{\varepsilon}}_c(\varepsilon_c, \sigma^R_{ref}, T)\right)$.

There are two (potentially) significant differences between the Z used in R5V2/3 and that used in R5V4/5:-

[1] The R5V2/3 Z refers to the stresses and strains at the point being assessed for crack initiation, e.g., a surface point. In R5V4/5 the Z is used in the equation specifying the relaxation of the reference stress. Hence the relevant Z in R5V4/5 relates to the gross section, i.e., the reference stress.

[2] The R5V2/3 Z refers to the uncracked structure whereas the R5V4/5 Z refers to the cracked structure. The presence of the crack will generally increase the effective Z (at least for points near the crack tip, but this is not so clear as regards the gross ligament).

In the absence of better information, R5 Issue 3 (2003) advises that the uncracked Z be increased by 1 for an R5V4/5 assessment.

However, the current view is that in many cases the Z to be used in R5V4/5 need not exceed that which would be used in R5V22/3. In fact, I would argue, that if there is a surface stress raiser which elevates the value of Z relevant to a crack initiation assessment, then the Z appropriate in R5V4/5 might actually be smaller.

1.19 Itemise the key materials data required in an R5 creep-fatigue crack growth assessment

[1] Elastic moduli, E, ν;

[2] The lower bound 0.2% proof strength and UTS (for R6 and for the shakedown assessment), and the whole monotonic stress-strain curve if the sigma-d incubation procedure is used;

[3] Fracture toughness;

[4] The shakedown factor, Ks;

[5] A cyclic stress-strain curve (to determine the cyclic plastic zone size around the crack tip as well as for constructing the hysteresis cycle, if relevant, and also potentially required in a sigma-d incubation assessment). The distinction between the cyclic and monotonic stress-strain curves is discuss in http://rickbradford.co.uk/T73S04TutorialNotes31.pdf;

[6] Creep rupture data/equation;

[7] Creep deformation data/equation, including the creep index, n;

[8] Creep ductility, including its dependence on strain rate and stress triaxiality, and possibly dwell stress (to assess ligament rupture via ductility exhaustion and possible for a Method II creep-fatigue crack growth law, which uses D_c at the surface);

[9] For incubation assessments, either (i)critical incubation CTOD; or, (ii)creep toughness if the HTFAD is used (though this can be approximated from the ccg law); or, (iii)fatigue endurance if sigma-d is used (in addition to creep rupture).

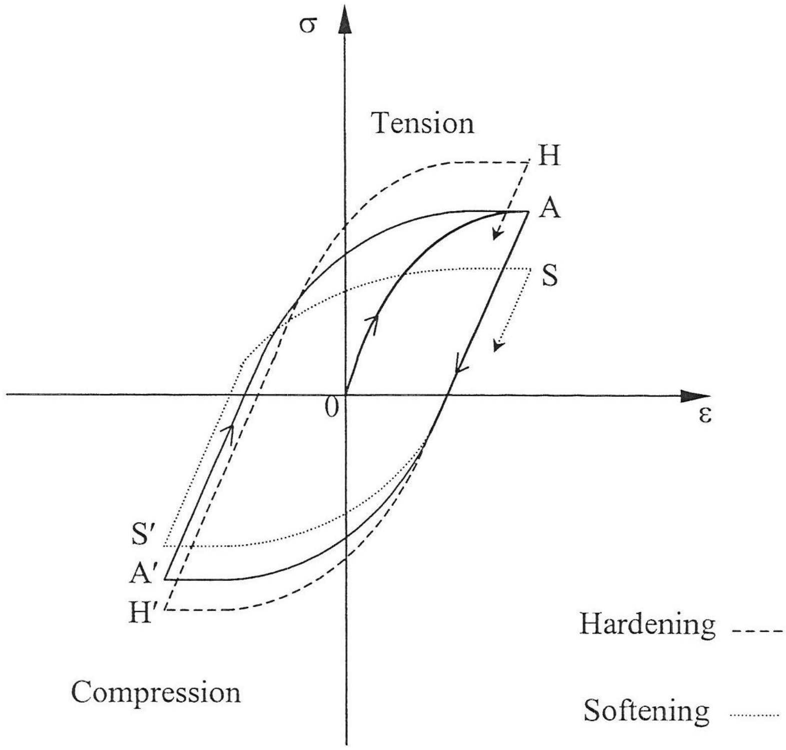
[10] Creep crack growth law;

[11] Fatigue crack growth law (Paris Law or small crack law, as appropriate);

1.20 Describe the cyclic stress-strain behaviour of structural metals. State how this behaviour might change due to (a) repeated cycling, or, (b) prolonged exposure to high temperatures.

When a material is taken around a load cycle involving yielding in both the tensile and compressive senses, the stress-strain cycles do not immediately over-plot. It takes at least several cycles (maybe many cycles) to shakedown to the stable cyclic state so that the hysteresis loops overplot. When they do, the shape of these loops is not the same as the monotonic stress-strain curve – as illustrated by Figure 1. During the transient period before the steady cyclic state is attained, the hysteresis loops may either move to higher stresses or lower stresses, as illustrated in Figure 2. This is cyclic hardening or cyclic softening respectively.

Figure 1



Long dwell times at high temperature will tend to reduce the degree of cyclic hardening. Advice on this is included in R66.

1.21 Define "strict shakedown" and "global shakedown". Discuss how these might influence creep-fatigue crack growth, and how this is incorporated into the R5 procedure

Strict shakedown refers to a structure which, possibly after some initially plasticity and possibly after some further plastic straining over the initial load cycles, eventually settles down to behaving purely elastically during load cycling.

For a structure which does not strictly shakedown, global shakedown refers to the establishment after some initial cycling of a stable elastic-plastic hysteresis cycle. Subsequent load cycles cause any given point of the structure to follow the same stress-strain hysteresis loop repeatedly with no net accumulation of plastic distortion. Global shakedown is the logical negative of ratcheting.

Regions of a structure which are outwith strict shakedown and hence subject to elastic-plastic cycling will have their creep dwell stress reset to the same starting level on each load cycle. The benefit of stress relaxation is therefore confined to a single cycle. This is the essence of the creep-fatigue mechanism. Moreover, plastic cycling may also enhance creep rates at a given creep strain. Consequently structures outwith strict shakedown will be subject to much more onerous conditions, as regards both crack initiation and crack growth.

However, one benefit of plastic cycling on creep crack growth is that plastic strains will suppress the magnitude of $C(t)$.

1.22 Identify the provisions within R5 specific to displacement controlled loading.

Advice on displacement controlled load can be found in R5V4/5 Appendix A3, §A3.5.3, and also in R5V4/5 Appendix A4, §4.4.3.1 for transition joints. However, it is likely that the more recent advice of Ainsworth, Dean & Budden E/REP/BDBB/0059/GEN/04, Rev.003, could now be used for displacement controlled load since this incorporates load reduction due to cracking and follow-up effects.

1.23 Discuss which material properties may be affected by prolonged exposure to high temperatures.

The following may be affected by thermal ageing, possibly exacerbated by environment,

- Creep rates (thermal ageing at lower stress)
- The tensile strength (ferritics tend to soften),
- The fracture toughness (adverse effect on austenitics, especially weld),
- The cyclic stress-strain curve,
- The fatigue endurance (ferritics),

1.24 Discuss qualitatively the distinction between creep-brittle and creep-ductile behaviour with respect to the characteristics of how cracks form and grow.

Creep brittle materials will have very low creep ductility and fast creep crack growth rates. Cracks will grow with little or no apparent non-linear strains, hence tight cracks with sharp tips.

For Questions 1.17 to 1.24 to see http://rickbradford.co.uk/T73S03TutorialNotes44B.pdf

1.25 Describe the "critical crack opening displacement" method for calculating the incubation time of a crack.

This method works by exploiting a relationship between the reference creep strain and the crack tip opening displacement, CTOD. It is assumed that incubation occurs at a critical value of the CTOD, δ_i, which must be obtained from experiment for the material in question. Formulae are given in R5V4/5 which allow this incubation CTOD to be converted into a incubation reference strain. The time at which the reference strain equals this is the incubation time.

The drawback of the method is that the User must have data for δ_i, which is often not available in practice.

1.26 Define how a Failure Assessment Diagram may be devised for creeping conditions, and outline how the creep toughness may be found. Hence explain how this approach may be used to calculate the incubation time.

The cop-out answers are, "see R5V4/5 Appendix A5" or the session 40B notes at http://rickbradford.co.uk/T73S03TutorialNotes40B.pdf. Very briefly the key points are:-

The High Temperature Failure Assessment Diagram (HTFAD) extends the FAD approach of R6 to creep. It can be used to assess both incubation and creep crack growth. In place of the 0.2% proof stress from short-term tensile tests, the stress $\sigma_{0.2}^c$ to produce 0.2% inelastic (plastic+creep) strain is used to define the Lr parameter. The HTFAD is defined as $K_r = \left\{ \frac{E\varepsilon_{ref}^c}{L_r \sigma_{0.2}^c} + \frac{L_r^3 \sigma_{0.2}^c}{2E\varepsilon_{ref}^c} \right\}^{-1/2}$, just as in R6, but where ε_{ref}^c is the total reference strain from the mean isochronous creep curve at a stress of $L_r \sigma_{0.2}^c$ and for the time and temperature being assessed. The Kr parameter is defined using a creep toughness, rather than the usual low toughness. This is essentially an extension to the concept of the J_R torn toughness, but now the tearing is actually creep crack growth. Hence, The "creep toughness" is defined via ccg tests by $K_{mat}^c = \sqrt{E'J_{ep} + EJ_c}$ where J_{ep} is the usual elastic-plastic J for the specimen and J_c can be defined via the same J-integral but in which the strains are all creep strains. In practice J_c is found experimentally using

$J_c = \eta\left(\frac{n}{n+1}\right)\frac{P}{B_n(w-a)}\Delta_c$, where Δ_c is the load line displacement due to creep. Hence $C^* = \frac{dJ_c}{dt} = \eta\left(\frac{n}{n+1}\right)\frac{P}{B_n(w-a)}\dot{\Delta}_c$ is the usual empirical formula for C^*. The creep toughness depends upon time and temperature and also upon the crack growth, Δa. The (L_r, K_r) assessment point is plotted on the HTFAD. If it lies within the diagram then the crack growth is less than the value Δa assumed in the above calculations. If it lies outside then the growth is greater than Δa. An incubation assessment is carried out using the HTFAD method by setting Δa to some suitably small value, e.g., 0.2mm.

1.27 Explain the σ_d method for calculating the incubation time of a crack under creep-fatigue loading. Contrast the value of 'd' with the conceded crack increment.

The cop-out answers are, "see R5V4/5 Appendix A6" or the session 40B notes at http://rickbradford.co.uk/T73S03TutorialNotes40B.pdf. Very briefly the methodology is a s follows. Incubation is conceded if an element of material at a characteristic distance, d, ahead of the crack tip is assessed to 'rupture'. The distance, d, is usually taken to be 50 microns. The stress at this point is estimated from the LEFM stress given by $K/\sqrt{2\pi d}$, but Neuberised to account for the stress reduction due to plasticity. (The full procedure includes several refinements, but this is the overall concept). This results is the stress σ_d which is entered into the uniaxial rupture equation. The time to rupture is identified as the incubation time (lower bound rupture giving lower bound incubation).

For Questions 1.25 to 1.27 see http://rickbradford.co.uk/T73S03TutorialNotes40B.pdf

1.28 Describe the basic experimental arrangement used in creep crack growth tests and the raw data measured.

The specimens used are broadly similar to those used in low temperature fracture toughness J-testing, e.g., compact tension specimens, but the load applied is not sufficient to cause plastic stable tearing. However the load is held constant for a long duration, perhaps tens of thousands of hours, during which time the crack grows due to creep. The key data that is collected is,

- Load;
- Load line displacement;
- Crack length increment.

The displacement is generally measured using a capacitance gauge. The crack growth is monitored in real time, usually using DCPD.

1.29 State how the creep fracture parameter C* is estimated from the raw data measured in a crack growth test. Discuss the errors to which this estimate is subject.

The intention is derive a growth law in the form $\dot{a} = AC^{*q}$, so the objective is to measure both $\dot{a}$ and C^*. The former is provided by the slope of the crack growth versus time curve obtained from DCPD. To a first order approximation C^* is estimated using,

$$C^* \approx \eta \frac{P\dot{\Delta}}{A}$$

where, P is the (constant) load, A is the net section area, $A = B_n(w-a)$, and $\dot{\Delta}$ is the displacement rate. There can be refinements of this estimation formula, such as subtraction of the elastic component of displacement rate and a material dependent factor, H. Hence a sequence of points on an $\dot{a} - C^*$ plot is obtained as time increases. In the regime where the growth obeys the law $\dot{a} = AC^{*q}$ then this trajectory will be linear on a log-log plot, with slope q. Potential sources of error are the accuracy of the displacement and crack growth rate measurements. The instrumentation, its set-up and its calibration can introduce errors. However, perhaps the chief source of inaccuracy (in austenitics, at least) is caused by crack growth being discontinuous and the problem of estimating the correct elastic-plastic displacement rate to subtract from the total. These two problems may or may not be closely related.

1.30 Describe how the crack tip opening displacement (CTOD) is measured at any time during a creep crack growth test, and hence how the critical CTOD for crack incubation is defined.

CTOD cannot be measured directly in a non-destructive manner but only inferred indirectly. One way is to infer it from the crack mouth opening displacement, e.g., by assuming CTOD:CMOD is the same ratio as the respective distances from some pivot point roughly mid-ligament. A better way is to use a correlation of CTOD with J, where J is based on the total displacement (including the creep). Hence the critical CTOD can be estimated since the crack growth is being measured (e.g., by plotting CTOD versus Δa, as per a J_R curve).

1.31 State the validity requirements on specimen dimensions. Hence describe how an upper limit to the valid creep crack growth could be obtained.

ASTM E1457 does not specify an explicit size requirement in the same way that toughness testing standards do. Instead it requires that the time to achieve steady creep (C*) conditions be small compared with the test duration. This is ensured in EDF Energy practice (McLennon & Allport) via various criteria. These criteria require vetoing invalid data, such as data prior to steady C* controlled conditions being attained. This means that data before a certain time (the incubation or redistribution time) are ignored. It also means that data after a certain time, when the crack is growing too fast, are also ignored. This is based on an upper limit to the dimensionless crack velocity $\lambda = \frac{\dot{a}\sigma_{ref}^2}{EC_{ref}^*}$, namely 0.5. This might indirectly define an upper limit to crack growth, or such an upper limit would follow from the valid range of the SIF solution or the parameters in the C* estimation formula.

However, note also that R5V4/5 Appendix A1, §A1.4.5.2 recommends explicit size requirements for a CTS in direct analogy to J-toughness testing, i.e., that the key dimensions ($a_0, w - a_0, B_n$) be greater than 25 times the 'initiation' CTOD (defined at 0.2mm growth).

1.32 Explain what side-grooving is, how side-grooved specimen tests are interpreted, and why side-grooving may be desirable. Describe the variation in creep crack growth rates for progressively thicker or more deeply side-grooved specimens (at the same C*).

CT specimens invariably employ side-grooves. Usually this involves 2.5mm deep grooves with a Charpy V-notch profile on both sides of the specimen. A 25mm thick CTS is thus locally reduced to a net thickness of $B_n = 20$mm, only 80% of the gross thickness. The benefits of side-grooves are,

- The crack is constrained to grow along the ligament $(\theta = 0)$ rather than veering off to one side, making the interpretation more difficult;
- The crack front of a non-side-grooved specimen tends to adopt a "thumb-nail" shape, due to the greater constraint in the middle of the section compared with the free surfaces. This again makes interpretation difficult since there is no unique crack growth measure, Δa. The sidegrooves create high constraint along the whole of the crack front and promote a straighter crack front.

Because side-grooving promotes constraint, the crack growth rate may be higher for deeper side-grooves. The same is true for progressively thicker specimens.

1.33 Describe how the results of a creep crack growth test are presented graphically. Discuss how these results are used to derive a crack growth rate law. Describe the 'tails' in the graph, and explain how they arise with reference to the creep deformation behaviour of the material.

Results are generally presented in the form of an $\dot{a} - C^*$ plot, from which the parameters A and q in the growth law $\dot{a} = AC^{*q}$ are then derived. When the early data is plotted on the $\dot{a} - C^*$ plot it does not initially fall along the ultimate trend line described by $\dot{a} = AC^{*q}$. Instead the initial data most often lies at low $\dot{a}$ but *high* C*. This produces points which lie below the trend line and far to the right. As transient creep dies away, the $\dot{a} - C^*$ trajectory moves towards the trend line, with $\dot{a}$ increasing but with the value of C* derived from the empirical estimation formula decreasing (though, at this stage, this is not really C*). When the trend line is reached the trajectory changes direction to join the trend line, so that C* is now increasing. The initial trajectory off the trend line is known as the "tail". However, tails are very variable and can even occur above the trend line, particularly if test conditions are changed or the material is pre-conditioned in some way. The trend line is achieved when steady C* controlled creep is reached.

1.34 Indicate typical plant C* or C(t) values on a typical experimental graph of da/dt versus C*. Discuss the reliability of the implied extrapolation with reference to longer term creep crack growth tests, contrasting ferritic and austenitic material behaviour.

Experimental C* values are generally >10^{-6} MPa.m/hr, although recent longer term tests on 316 have achieved ~10^{-7} MPa.m/hr. This latter value has begun to bring the experimentally determined range within that assessed for plant (10^{-7} MPa.m/hr corresponding to an upper bound growth rate of ~1 mm/yr in 316, for example). However, more typically plant C(t) or C* values may be ~10^{-8} MPa.m/hr. Consequently extrapolation of the data is still required – and this generally assumes the straight line in log-log space implied by $\dot{a} = AC^{*q}$ is valid. Evidence to-date is that extrapolations to smaller C* values have proved non-conservative for austenitics but conservative for ferritics.

For Questions 1.28 to 1.34 see http://rickbradford.co.uk/T73S03TutorialNotes41.pdf

1.35 Define the effective stress intensity factor range, ΔK_{eff}, used in R5 fatigue crack growth assessments.

Putting $R = K_{\min} / K_{\max}$ and then defining,

$$q = 1 \qquad \text{for } R \geq 0$$

$$q = \frac{1 - 0.5R}{1 - R} \qquad \text{for } R < 0$$

The effective SIF range is $\Delta K_{eff} = q\Delta K$

1.36 Define when plasticity corrections to ΔK_{eff} are required. State the corresponding methodology.

If there is widespread yielding then ΔK cannot be expected to be adequate to parameterise fatigue crack growth, since it does not capture the plastic strain contribution. The relevant parameter is ΔJ, the range of the elastic-plastic fracture parameter, J, which takes the elevated reference strain range into account. The fcg law is then re-expressed in terms of ΔJ, i.e.,

$$\frac{da}{dN} = C\left(E'\Delta J\right)^{m/2}$$

The cyclic J-integral, ΔJ, can be found by replacing stress, strain and displacement in the usual J-integral by their ranges. A more practical tool for assessments is to use the reference stress formula, $\Delta J = \frac{\Delta\varepsilon_{ref}}{\Delta\sigma_{ref}}\Delta K^2$.

Here the reference strain is the elastic-plastic strain corresponding to the reference stress range $\Delta\sigma_{ref}$. For example, assuming a Ramberg-Osgood fit, $\Delta\varepsilon_{ref} = \frac{\Delta\sigma_{ref}}{E} + \left(\frac{\Delta\sigma_{ref}}{A}\right)^n$, where $n = \frac{1}{\beta}$. However, it is also necessary to take account of crack closure effects. This can be done conservatively using,

$$\Delta J = q\left[\frac{q}{E} + \frac{\left(\Delta\sigma_{ref}\right)^{n-1}}{A^n}\right]\Delta K^2$$

This is equivalent to R5V4/5 Equ.(A3.9). See R5V4/5, Appendix A3 for further details.

1.37 Define the ΔK_{eff} based method for calculating fatigue crack growth. State the criterion for this approach to be valid.

The Paris Law for fcg is,

$$\frac{da}{dN} = C\Delta K_{eff}^{m}$$

This is valid if the crack tip lies beyond the cyclic plastic zone and as long as ΔK_{eff} is less than the threshold, ΔK_0. There may also be an upper limit on ΔK_{eff} due to the range tested experimentally. However extending to $\Delta K \leq 0.7 K_{IC}$ for brittle materials or to $\sigma_{ref} \leq 0.7\sigma_{flow}$ for ductile materials is likely to be acceptable (see R66). This law is used if the crack extends beyond the cyclic plastic zone.

1.38 Discuss the threshold for fatigue crack growth.

Below a certain stress intensity factor range there is no fatigue crack growth at all. The ΔK which is required to produce non-zero growth is the fatigue crack growth threshold, ΔK_{th} or ΔK_0. A crack cannot advance by less than one atomic spacing. The fcg threshold ΔK_0 is effectively the SIF range which would produce a growth of one atomic spacing. Hence ΔK_0 is such that $C\Delta K_0^m \approx 2\times10^{-10} m$, which for experimentally determined upper bound values of C gives a lower bound threshold of $\Delta K_0 \sim 2MPa\sqrt{m}$. This is in good agreement with test data of the fcg threshold. A lower bound of $\Delta K_0 \sim 2MPa\sqrt{m}$ is generally used in practice. In truth such low values tend to occur only for high mean stresses. For small mean stresses ΔK_0 may be a factor of 2 or 3 larger.

1.39 Discuss the effect of creep dwells on fatigue crack growth rates and when creep-enhanced fatigue laws need be taken into account explicitly in assessments (see also 3.3).

Fatigue crack growth laws based on tests which include dwells at creep temperatures can be far more onerous than those based on continuous cycling tests (e.g., by about an order of magnitude – compare R66 Sections 10 and 12). In practice the fcg laws based on continuous cycling are more commonly used because the R5V4/5 assessment itself takes account of the ccg part separately.

However, R5V4/5 §9.3(i) specifies an exception. This is when creep is perturbed by cyclic loading but the fcg is less than 10% of the ccg. In this case the use of fcg data based on tests including dwells "relevant to the service application" is recommended. Given that service dwells are likely to be of the order of 1000 hours or more this will be problematical! However, the use of R66 Section 12, as a minimum, appears motivated.

1.40 Discuss the range of stress or stress intensity factors for which 'Paris law' fatigue crack growth formulations are valid.

See 6.3

1.41 Describe the method for calculating fatigue crack growth for cracks embedded within the cyclic plastic zone. State how the size of the cyclic plastic zone is determined.

If the crack lies entirely within the cyclic plastic zone of the uncracked body, r_p, then the 'small crack' fcg formula should be used. r_p is found using the methods of R5V2/3 (see for example R5V2/3 §7.1.4). r_p is that part of the section which is outside strict shakedown (and hence subject to plastic cycling). This r_p should not be confused with the cyclic plastic zone which occurs at the tip of the crack itself, r_p^{crack}. The small crack fcg law in R5 and R66 is,

$$\frac{da}{dN} = B'a^{Q} \text{ mm/cycle}$$

where a is the crack depth in mm. R66 provides recommendations for the parameters B' and Q for a range of materials. An upper bound for all these materials is given by,

$$Q = 1 \text{ and } B' = 26{,}100\Delta\varepsilon_t^{2.85}$$

for a total strain range of $\Delta\varepsilon_t$. This bounds data obtained at high temperatures (550°C and above).

1.42 State the basic reference stress formula for estimating C* under primary stressing alone.

$$C^* = \frac{\dot{\varepsilon}_{ref}^{PR}}{\sigma_{ref}^{PR}} K_{PR}^2$$

All quantities in this formula are based on primary loads alone.

1.43 Define "redistribution time", t_{red}, and how it is calculated.

The redistribution time is the time take for the stress and strain fields around the crack tip to reach their steady creep values. However this does not provide an easy numerical definition. In practice it is defined as the time for the reference creep strain to reach the elastic strain at the reference stress level, i.e., $\varepsilon_{ref}^c(t_{red}) = \varepsilon_{ref}^e$

1.44 Write down the C(t) estimation formula for primary loading alone, in terms of either time or strain. Hence describe how C(t) varies with time under primary stressing alone.

Including the effects of plasticity the C(t) estimation formula is,

$$C(t) = f(\tau) \cdot C^*, \text{ where, } f(\tau) = \frac{(1+\tau)^{1+n}}{\left[(1+\tau)^{1+n} - 1\right] + \frac{\varepsilon_{ref}^p}{\varepsilon_{ref}^{ep}}} \text{ and } \tau = \frac{\varepsilon_{ref}^c}{\varepsilon_{ref}^{ep}}.$$

The function $f(\tau)$ causes $C(t) > C^*$ at times before the redistribution time, and hence before the creep fields around the crack tip have achieved their steady conditions. This "C(t) spike" can be very marked and is assessed to cause rapid growth initially (whether this is actually true is another matter). The parameter τ is a dimensionless time, essentially time normalised by the redistribution time. For $\tau \geq 1$ we get $C(t) \approx C^*$.

1.45 Outline how the C(t) estimation formula is modified in the presence of significant plasticity and how this may be taken into account quantitatively within the R5 procedure.

Plastic strain is included in the above estimation formula. If the plastic strain is small compared with the elastic strain it makes little difference. However if the plastic strain is large compared with the elastic strain then it has the effect of strongly ameliorating the "C(t) spike", i.e., we get $f(\tau) \approx 1$ and hence $C(t) \approx C^*$ even at early times. Physically this is because the plasticity does the redistribution immediately. However, this prediction, and the above estimation formula, is really only valid if the plastic index is greater than or equal to he creep index.

For Questions 1.35 to 1.45 see http://rickbradford.co.uk/T73S03TutorialNotes42.pdf

1.46 Describe the R5 V4/5 Appendix A3 / Ainsworth, Dean & Budden procedure for calculating a relaxing reference stress under combined primary and secondary loading.

1.47 Describe in outline how the calculation of the relaxing reference stress from 1.46 is modified if the crack growth is a significant fraction of the remaining ligament.

The general formula for relaxation of the combined load reference stress, σ_{ref}, is,

$$\frac{d\sigma_{ref}}{dt} = -\frac{E}{Z}\left(\dot{\varepsilon}_{c,ref} - \dot{\varepsilon}_{c,ref}^{PR}\right) + \frac{da}{dt} \cdot \frac{\partial \sigma_{ref}}{\partial a}$$

Where the combined load reference stress, σ_{ref} , can be estimate either by using $\sigma_{ref} = \frac{K_{TOT}}{K_{PR}}\sigma_{ref}^{PR}$ or by inserting the total (primary + secondary) load resultants in a reference stress solution of the form $\sigma_{ref} = f\left(N_t, M_t, N_h, M_h, a\right)$. The above expression for $\frac{d\sigma_{ref}}{dt}$ includes creep relaxation via the first term on the RHS and also the effects of crack growth via the second term.

1.48 Write down the R5 V4/5 Appendix A3 / Ainsworth, Dean & Budden estimation formula for C(t) in terms of the relaxing reference stress under combined primary and secondary loading. Identify the physical meaning of the two factors in this expression with reference to the estimation formulae from 1.42 and 1.44.

1.49 Describe how the C(t) estimation formula in 1.48 is changed when account is taken of plasticity.

The estimation formula recommended for general use, and including the effects of plasticity, is,

$$\frac{C(t)}{C^*} = \left(\frac{\sigma_{ref}\,\dot{\varepsilon}_{c,ref}}{\sigma_{ref}^{PR}\,\dot{\varepsilon}_{c,ref}^{PR}}\right)\left[\frac{\left(\varepsilon_{ref}/\varepsilon_{ref}^{0}\right)^{n+1}}{\left(\varepsilon_{ref}/\varepsilon_{ref}^{0}\right)^{n+1} - \left(\sigma_{ref}^{0}/E\varepsilon_{ref}^{0}\right)}\right]$$

The first term, $\left(\frac{\sigma_{ref}\,\dot{\varepsilon}_{c,ref}}{\sigma_{ref}^{PR}\,\dot{\varepsilon}_{c,ref}^{PR}}\right)$, accounts for the secondary stresses and their relaxation. For primary loads alone (to which questions 7.1 & 7.3 relate) this term would be unity.

The second term, $\left[\frac{\left(\varepsilon_{ref}/\varepsilon_{ref}^{0}\right)^{n+1}}{\left(\varepsilon_{ref}/\varepsilon_{ref}^{0}\right)^{n+1} - \left(\sigma_{ref}^{0}/E\varepsilon_{ref}^{0}\right)}\right]$, is the "C(t) spike" and hence models redistribution of both the primary and secondary stresses. In the case of primary loads alone this term reduces to the same formulae stated under questions 7.1 & 7.3.

Plasticity is included in the above formula for C(t) through the plastic strains which are included in $\varepsilon_{ref} = \varepsilon_{ref}^{e} + \varepsilon_{ref}^{p} + \varepsilon_{c,ref}$ and $\varepsilon_{ref}^{0} = \varepsilon_{ref}^{e0} + \varepsilon_{ref}^{p0}$. Hence the case with no plasticity follows by dropping the plastic strain terms. The effect of the plastic strains is to ameliorate the "C(t) spike". If $\varepsilon_{ref}^{e} << \varepsilon_{ref}^{p}$ the C(t) spike disappears altogether.

1.50 State the relationship between the power-law creep index n and the exponent q in the creep crack growth law $\dot{a} = AC(t)^q$. Explain why this is relevant in estimating C(t).

$q = \frac{n}{n+1}$. This may be derived from a continuum damage mechanics / ductility exhaustion model of creep crack growth (see session 42). The relevance of this relationship in evaluating C(t) is that it may be preferable to define the *n* which appears in the estimation formula for C(t) via *q* than to use a creep deformation based *n*. This is a matter of consistency since *q* will be used in the growth law itself.

1.51 Derive an expression for the creep crack growth in terms of K for sufficiently early times $(t << t_{red})$ starting from the law $a\ AC(t)q$. Discuss the temperature dependence of the resulting expression.

The derivation is given in http://rickbradford.co.uk/T73S03TutorialNotes44B.pdf

1.52 State the simplified C(t) estimation formula from R5 V7 applicable to primary plus secondary stresses. Explain the main differences between the R5V7 approach and that of R5V4/5A3 / Ainsworth, Dean & Budden. State the plant features to which the R5V7 approach is applicable.

R5V7 applies only to similar weldments in low alloy ferritic materials under steady loading (no cycles).

The R5V7 law differs from that of R5V4/5 in that,

- It's treatment of secondary stresses is much simpler;

- It does not include relaxation;
- It does not include plasticity;
- It includes allowance for CMV weldment zone off-loading (the k factors)

The R5V7 estimation procedure is,

$$C(t) = f(\tau)\cdot C^*;\ \ f(\tau) = \frac{(1+\tau)^{1+n}}{\left[(1+\tau)^{1+n} - 1\right]};\ \ C^* = k\frac{\dot{\varepsilon}_c^{PR}}{\sigma_{ref}^{PR}}K_{PR}^2;\ \ \tau = \left(\frac{K_{PR}}{K_{TOT}}\right)^2 \frac{E\varepsilon_{c,ref}^{PR}}{k\sigma_{ref}^{PR}}$$

1.53 Define the datum of time or strain to be used in calculating C(t) for a service induced crack.

For Questions 1.46 to 1.53 see http://rickbradford.co.uk/T73S03TutorialNotes43.pdf

1.54 State the form of the creep crack growth law in terms of C(t)

$\dot{a} = AC(t)^q$

1.55 State how to obtain estimates of the creep crack growth law, in the absence of such test data, in terms of the creep ductility or the rupture time.

This is discussed in R5V4/5 Appendix A1, §A1.4.6. Growth rates in m/hr may be estimated using,

$$\dot{a} = \frac{0.003C(t)^{0.85}}{\varepsilon_f} \qquad \text{or} \qquad \dot{a} = \frac{0.0003C(t)^{0.85}}{\varepsilon_f(lowerbound)}$$

where ε_f is the absolute uniaxial creep ductility. Alternatively, in terms of the creep rupture life, t_r (hours), a scoping calculation may use,

$$\dot{a} = 0.005\left(\frac{K^2}{\sigma_{ref} t_r}\right)^{0.85}$$

In the above *K* is in MPa√m and *C(t)* in MPa.m/hr. A material-specific experimental $\dot{a} = AC(t)^q$ is preferable to either of these approximate methods.

1.56 State the criterion for the da/dt-C* correlation to be valid, and define the dimensionless crack velocity. Identify the approach to be used to assess creep crack growth if the C* correlation is invalid.

The dimensionless crack velocity is defined as $\lambda = \frac{\dot{a}(\sigma_{ref})^2}{EC(t)}$. For the da/dt-C* correlation to be valid the dimensionless crack velocity is required to be les than1 (or less than 0.5, R5 and Ainsworth, Dean & Budden give different limits). In the case of combined primary plus secondary loading the reference stress used to define λ should be the combined load reference stress.

For large dimensionless crack velocities ($\lambda >> 1$) R5 advises a correlation of creep crack growth rate with K (see R5V4/5 Appendix A2, Equs.(A2.28-29).

1.57 Describe the provisions within R5 V4/5 for taking account of enhanced crack growth rates prior to steady cyclic conditions being attained (in the case of significant cyclic loading).

The reference dwell stress on first loading is denoted $\sigma_{ref}^{cyc=1}$. It can be found using the elastic stresses for the operating condition followed by application of the Neuber construction to account for initial (not cyclic) plastic relaxation (see R5V4/5 A3.4.1).

R5V4/5 §10.6 gives guidance on calculating t_{cyc}, the time to establish steady cycling. It is estimated using

$$\varepsilon_c\left(\frac{\sigma_{ref}^{cyc=1}+\sigma_{ref}}{2}, t_{cyc}\right)=\frac{Z\left(\sigma_{ref}^{cyc=1}-\sigma_{ref}\right)}{E}$$

For times before the steady cyclic state is reached, $t < t_{cyc}$, an average C-parameter is employed. R5V4/5 §10.7.1.3 advises this to be,

$$\overline{C}^* = \frac{\sigma_{ref}^{cyc=1}+\sigma_{ref}}{2}\dot{\varepsilon}_c\left(\frac{\sigma_{ref}^{cyc=1}+\sigma_{ref}}{2}\right)R'$$

where $R' = (K^{PR} / \sigma_{ref}^{PR})^2$. This average crack parameter is plugged into the usual growth formula which is integrated over the dwell period to get the creep crack growth per dwell.

1.58 Describe the simplified means of accounting for the enhanced creep crack growth during redistribution when the overall assessment time exceeds t_{red}.

For times longer than the redistribution time $C(t) \approx C^*$. Consequently at such times C^* alone is adequate to calculate ccg. However it would not be correct to use C^* only if integrating total crack growth from $t = 0$, since $C(t)$ is initially larger than C^*. R5 §10.7.1.2 gives a simplified prescription in this case [if you want to avoid the bother of integrating $C(t)$]. This consists simply of doubling the growth rate prior to t_{red} , that is putting $\dot{a} = 2A\left(C^*\right)^q$ for $t < t_{red}$ and $\dot{a} = A\left(C^*\right)^q$ for $t > t_{red}$. This simplified method is valid only for assessment times $t > t_{red}$.

1.59 Describe the two methods for combining fatigue and creep crack growth. Explain how creep crack growth is taken into account for cracks within the cyclic plastic zone.

Method I uses the Paris Law for fcg and an $\dot{a} = AC(t)^q$ relation for ccg. It is valid to use Method I when the crack tip lies outside the cyclic plastic zone for the uncracked body. Otherwise Method II should be used. This uses the growth laws,

$$\frac{da}{dN}=\frac{1}{\left(1-D_c^{surface}\right)^2}\left(\frac{da}{dN}\right)_f \qquad \text{where,} \quad \left(\frac{da}{dN}\right)_f = B'a^Q \text{ mm/cycle}$$

Hence the creep crack growth is accounted for by factoring up the fatigue crack growth according to the value of the surface creep damage in the uncracked body, $D_c^{surface}$.

1.60 Discuss how the effects of prior creep damage may be taken into account in the assessments of fatigue and creep crack growth rates.

In principle the fcg and/or ccg rates can be accelerated through material previously damaged by creep [see R5V4/5 §9.3(ii)]. One school of thought is that this is relevant only for very heavy creep damage, i.e., if $D_c > 0.8$ (BS7910). Another is that the fcg and ccg laws should be factored by $1/\left(1-D_c\right)$ at all damage levels. In either case it is likely to most reasonable to us the best estimate of D_c for this purpose.

1.61 State the procedure within R5 for assessing defects which have initiated in-service.

The creep strain which enters the C(t) estimation formula is calculated from the time of initiation, t_d . This means that the peak of the "C(t) spike" is immediately after initiation. However relaxation of secondary stresses may be incorporated from the start of life (including before the crack initiates). Consistent with this, the total creep strain from the start of life should be used to evaluate strain hardening of the creep rate. An incubation period may be justifiable for non-creep induced defects in which case the effects of the "C(t) spike" will be ameliorated.

For Questions 1.54 to 1.61 see http://rickbradford.co.uk/T73S03TutorialNotes44A.pdf and also session 42.

1.62 Describe the different microstructural regions in a ferritic weldment and state their relevance in calculating local reference stresses

The ferritic weldment zones are described here, http://rickbradford.co.uk/T73S06TutorialNotes26.pdf.

In an R5V7 assessment, the distinction between the various ferritic weldment zones is addressed via the *k* off-loading factors. However these make no difference to the reference stress. The same primary reference stress is used in the estimate of C*, though C* itself is factored by *k*,

$$C^* = k\frac{\dot{\varepsilon}_c^{PR}}{\sigma_{ref}^{PR}}K_{PR}^2$$

Note in particular that the off-loading factor *k* is ***not*** used to factor the stress when determining the strain rate used in C*. The weldment zone used to calculate the strain rate is as follows,

- For hoop dominance the parent creep deformation should always be used (whatever weldment zone is being assessed);
- For axial dominance the creep deformation appropriate to the weldment zone being assessed should be used (but *k* is, of course, 1 for all zones).

So the strain rate used to find C* never depends upon *k*. However the dimensionless time used to find $f(\tau) = C(t)/C^*$ depends upon *k* through,

$$\tau = \left(\frac{K_{PR}}{K_{TOT}}\right)^2 \frac{E\varepsilon_c^{PR}}{k\sigma_{ref}^{PR}}$$

For Question 1.62 see http://rickbradford.co.uk/T73S06TutorialNotes26.pdf

1.63 State what tests can be used to confirm whether residual welding stresses are significant, (a)from R5 V4/5 A4; (b)from R5 V7.

R5V4/5 App.A4, §4.3.3 gives the following criterion for insignificant welding residual stresses (or, more generally, the insignificance of any secondary loads),

$$\frac{\overline{\sigma}_{\max}^{secondary}}{E} < 0.1\left(\frac{\delta_i}{R'}\right), \qquad R' = \left(\frac{K_{PR}}{\sigma_{ref}^{PR}}\right)^2$$

Here δ_i is the incubation CTOD. If this criterion is obeyed then residual stresses can be neglected in the calculation of creep crack growth.

The R5V7 criterion relates to the assessment of gross ligament creep rupture only. For low alloy ferritic similar metal weldments the effect of residual stresses on rupture may be ignored if EITHER of the following apply,

- A stress relief heat treatment to an appropriate procedure was carried out, leading to a high degree of HAZ refinement (microstructural parameter $\alpha \le 1.5$); OR,
- $\frac{k\sigma_{ref}^{PR}}{E}\left(\frac{K_{TOT}}{K_{PR}}\right)^2 < 0.1\varepsilon_f$.

For "appropriate" PWHT procedures see R5V7 App.A2, though conformance to a modern design code is sufficient. Here ε_f is the creep ductility.

R5 is not explicit about the applicability of the above criteria to austenitic welds but the second of the above criteria is probably applicable. Design codes still do not generally require PWHT for austenitic materials, so the first criterion is not well defined. A full solution heat treatment (probably at $\geq 1050^o C$) is usually taken to render the residual stresses negligible.

1.64 State the main features in a creep-fatigue crack growth assessment which are specific to a dissimilar metal joint.

1.65 State the main features in a creep-fatigue crack growth assessment which are specific to a graded transition joint

Rupture and deformation will generally be TJ specific.

Rupture data should be that from cross-weld tests. For the rupture of the remaining ligament use the more onerous of the homogeneous or the TJ specific reference stresses (the latter being specified in R5V6).

Deformation data for the 'reference material' (where cracks are likely to form) are TJ specific. For conventional TJs a methodology is given in R5V4/5 App.A4 using the cross-weld rupture to estimate the deformation behaviour. A specific formulation is given also for Jessop-Saville deformation.

However, the crack growth law would generally be that for the ferritic material.

1.66 State the two alternative procedures for assessing the remaining ligament life based on rupture data and under steady creep conditions.

1.67 State the procedure for assessing the remaining ligament life when cyclic loading is significant and/or under combined secondary and primary loading.

I think 10.1 is worded badly. I don't think there are two methods both based on creep rupture data. However, there are two methods: one based on creep rupture (time fraction damage) and one based on ductility exhaustion (strain fraction damage). The former is sanctioned in R5 if secondary loads are insignificant according to the criterion of R5V4/5 App.A4, §4.3.3. The time-fraction based definition of creep damage is $D_c = \int \frac{dt}{t_{rup}}$.

Otherwise R5 requires that a ductility exhaustion definition of creep damage be used. In R5V7 App.A4, §A4.3.2, this is expressed as the usual strain-ratio damage for the primary part plus a flat allowance for the secondary stresses,

(My paraphrasing)
$$D_c = \int \frac{d\varepsilon_c^{PR}}{\varepsilon_f} + \frac{k\sigma_{ref}^{PR}}{E\varepsilon_f}\left(\frac{K_{TOT}}{K_{PR}}\right)^2$$

However, I suggest that a less conservative method would be the usual ductility exhaustion approach in which the stress relaxes over time, i.e.,

$$D_c = \int \frac{d\varepsilon_c^{tot}}{\varepsilon_f}$$

I advise that ε_f be interpreted as the creep ductility relevant to the state of stress, i.e., allowing for triaxiality, though R5V7 is not explicit.

Actually the time-fraction method, $D_c = \int \frac{dt}{t_{rup}}$, can also be used for combined primary-plus-secondary loads so long as the rupture time is based upon the relaxing stress. This has been used in assessments though not sanctioned in R5.

I believe that R5V4/5 does not call for any allowance for the influence of cyclic loading on gross ligament creep rupture. If the User considers this to be a shortcoming then refer to R5V2/3 §7.5, and see, http://rickbradford.co.uk/T73S04TutorialNotes30.pdf.

1.68 State the procedures and sources of materials data for assessing the remaining ligament life for, (a)a similar metal weldment, (b)a dissimilar metal weldment, (c)a graded transition joint.

The methodologies are as above, with the following TJ specific inputs:-

I read R5V4/5 App.A4, §A4.4 to mean that you should use the larger of the usual homogeneous primary reference stress and the TJ specific reference stress given in R5V6 App.A2.

Cross-weld rupture data from representative TJ tests should be used.

For Questions 1.63 to 1.68 see http://rickbradford.co.uk/T73S03TutorialNotes45.pdf

1.69 State the combinations of materials data bounds that must be employed for creep strain rate and creep crack growth law parameters, for (a)ferritic materials, (b)austenitic materials.

Ferritic Materials

R5V4/5 §11.1 recommends a base case using BE / BE and sensitivity studies addressing LB / UB and UB / LB combinations only.

Austenitic Materials

The R5 advice referred to above is not material specific. Hence the combinations BE / BE, LB / UB and UB / LB should be assessed and reported. However, in the case of 316ss, E/REP/BDBB/0040/GEN/03 has advised that the combination UB(ccg) / BE(deformation) also be assessed and reported. In practice this is generally the bounding case. Whilst E/REP/BDBB/0040/GEN/03 is specific to 316ss, it is generally taken as implying that the UB/BE combination should be considered for all austenitic materials. (The main reason why the requirement has been recognised for 316ss is simply because this material has been subject to long term ccg testing).

1.70 Discuss best practice in terms of what results should be presented, what sensitivity studies may be desirable, and the relevance of validation evidence to the reliability of the results.

Cfcg assessments require BE/BE, UB/LB and LB/UB combinations of deformation/ccg data. For austenitics, BE/UB is also required. For Validation see R5V4/5 Appendix A9 (though there will have been additional validation in the 8 years, since R5 was last issued).