# T73S06 (Creep Rupture) Tutorial Session 26 – CMV Weldments

Last Update 7/11/14

*Example rupture data; Effect of triaxiality on creep rupture, limitations of R5; Variable conditions: Robinson's Rule; MECT definitions based on rupture or deformation; CMV weldment zones and how they differ as regards creep rates and creep strength; Axial and hoop dominance; Mixed HAZ and the $\alpha$ parameter (and might it be misleading, e.g. drain pots?); k redistribution factors;*

Do not use these notes as a source of data in real assessments

These notes are UNVERIFIED – so there could easily be errors

Qu.: How are creep rupture data expressed for the assessor?

Rupture data can be plotted as stress against time to rupture, one curve for each temperature. An example is given in Fig.1 (for 316ss parent) – seen already in session 23. This is the so-called "Soviet" model SM1 fit from R66, which has the form,

$$\ln(t) = A + B\log(T) + C\log(\sigma_R) + \frac{D}{T} + E\frac{\sigma_R}{T} \tag{1}$$

where $T$ is the absolute temperature (K) and $\sigma_R$ is the rupture stress (MPa) for a rupture time of $t$ (hours). Note the use in R66 of the natural ln on the LHS but log to base 10 on the RHS in this type of fit.

| |
|---|
| WARNING: Though the "Soviet" model SM1 fit is still the equation which appears in R66 Rev.009 (at November 2014), a new model by Sarah Spindler has been endorsed by the SIRC for inclusion in the next issue of R66 and should be used in preference. The SM1 model used here is merely for illustration. |

However, many different parametric forms of data fit are used. A common type of 'master curve' is that used in PD6525,

$$\frac{\log(t) - F}{(\theta - G)^H} = a + b\log\sigma_R + c(\log\sigma_R)^2 + d(\log\sigma_R)^3 + e(\log\sigma_R)^4 \tag{2}$$

where $\theta$ is the temperature in $^{o}$C, and note that the log of time is now to base 10. R66 Rev.009 contains the fitting parameters to equ.(2) for a range of steels, including carbon and CMn steels, as well as nickel alloys and various other steels.

In R66 Rev.007 the CMV parent recommended rupture equation ***was*** of this form also. However improved fits to CMV parent, Type IV and 2.25%Cr1Mo weld rupture data now appear in R66 Rev.009.

Qu.: What is the recommended rupture equation for CMV parent now?

The improved fit to CMV parent rupture data now recommended in R66 Rev.009 is of the "AJB2" form,

(New CMV Parent) $$\ln(t) = A + B\log(\sigma_R) + C\sigma_R\log(\sigma_R) + \frac{D}{T} \tag{3}$$

See Ref.[8] or R66 Rev.009. This CMV parent fit should now be used.

Qu.: What is the recommended rupture equation for CMV Type IV zone now?

The position is more confused for the Type IV zone. An older recommendation, known as the "minimum Commitment model", has been retained in R66 Rev.009. This is of the form,

(Old CMV Type IV) $$\ln(t) = A + B\log(\sigma_R) + C\sigma_R + D\sigma_R^2 + ET + \frac{F}{T} \tag{4a}$$

This will be referred to for brevity as the "Old Type IV" rupture equation. However, this has been retained in R66 Rev.009 only pending resolution of the k-factor issue (of which more below). There is also a recognised improved fit (Ref.[7]), referred to as "AJB3", of the form, (New CMV Type IV) $$\ln(t) = A + B\log(\sigma_R) + \frac{C}{T} + D\frac{\sigma_R}{T} \tag{4b}$$

In the interim, both the "old" (minimum commitment) and "new" (AJB3) fits need to be addressed in assessments (discussed further below).

When I last revised these speaking notes in 2010, I felt comfortable with referring to Ref.[7], issued in 2009, as a "new" fit. I continue to refer to AJB3 as the "new fit" here, but it is disappointing that a single, consistent recommendation has not been forthcoming 5 years later.

Qu.: Have the CMV parent & Type IV fits got better or worse?

It varies with stress and temperature.

Figure 2 compares lower bound CMV parent and Type IV zone rupture, for the old and new data fits, at 525°C.

- The new parent rupture times are much smaller, less than half those for the old data at the modest stresses relevant to plant (at 525°C, at least).

Figures 3 and 4 compare the old and new lower bound Type IV data at 500°C and 540°C. These show that,

- There is virtually no difference in the two Type IV fits at 525°C;
- The new Type IV fit gives substantially shorter rupture times at 500°C (by around 33%);
- The new Type IV rupture times are slightly longer at 540°C.

Qu.: How is the lower bound rupture life found?

The data fits are generally presented to give you the best estimate rupture time for a given stress. To find the lower bound rupture time, the most common advice is to enter the relevant curve, Equs.(1-4), at a stress which is factored up. This factor varies between materials:-

- For 316H using Equ.(1) it is x1.333;
- For old CMV parent using Equ.(2), i.e., R66 Rev.007, it is x1.25;
- For new CMV parent using Equ.(3), i.e., R66 Rev.009, it is x1.307;
- For the old CMV Type IV data, Equ.(4a), there is a more complicated prescription rather than just a factor on stress (see R66 Rev.009, Equs.(6.7-9);
- For the new CMV Type IV rupture advice, Equ.(4b), the lower bound life is found from the mean life using $t_f^{LB} = 0.543 t_f^M$.

Qu.: How is the best estimate rupture stress found for a given rupture time?

The rupture expressions, e.g., Equs.(1-4), are convenient for finding the rupture time for a given stress. Unfortunately the only way of inverting this to find the rupture stress for a given time is numerically – either by iteration or using the Solve facility in Excel if that's your bag.

Qu.: How is the lower bound rupture stress found for a given rupture time?

In most cases the procedure is to first find the best estimate rupture stress and then simply to apply a knock-down factor given in R66 or the appropriate report. For example,

- For 316H using Equ.(1) the factor is x0.75;
- For CMV parent using Equ.(2), i.e., R66 Rev.007, the factor is x0.8;
- For CMV parent using Equ.(3), i.e., R66 Rev.009, the factor is x0.765;

These factors are just the reciprocals of those used to factor *up* the stress when finding the lower bound rupture life. R66 tends to specify the amount by which to reduce the mean rupture stress to get the lower bound rupture stress (e.g., 25% for 316H or 20% for the old CMV parent fit and 23.5% for the new fit).

A potential error trap is to find the lower bound rupture time for a fit in which the stated stress bound is (say) -20% by factoring the stress up by 20%, i.e., using a factor of x1.2. But it *should* be x1/0.8 = x1.25

- In contrast, the scatter in CMV Type IV rupture data is formulated by specifying the lower bound rupture time. In this case, the inversion is done with respect to the lower bound time, thus giving the lower bound rupture stress without having to first find the mean rupture stress.

Qu.: What if conditions of stress or temperature vary?

Suppose that during the i$^{th}$ time interval, $t_i$, the stress and temperature are $\sigma_i, T_i$. The rupture life, found from the rupture curve for these conditions, is $t_{rup}(\sigma_i, T_i)$. The fraction of the rupture life expired during the i$^{th}$ time interval is thus, $\frac{t_i}{t_{rup}(\sigma_i, T_i)}$. Hence, the life fraction expired over a sequence of time periods with differing conditions is,

$$D_c = \sum_i \frac{t_i}{t_{rup}(\sigma_i, T_i)} \qquad (5)$$

This is known as Robinson's rule, or alternatively as the time-fraction, or stress-rupture, definition of life fraction. Note that this is the same as 'creep damage' if, by 'damage', we mean the overall, gross ligament damage. But note that creep damage can also be defined as a local quantity (e.g., in R5V2/3).

**Figure 1: Example of Rupture Data (316H parent)**: *Stress against rupture time for a range of temperatures. This shows the 'Soviet model' SM1 fit from R66 (Equ.1).* ***NB: This is no longer the recommended 316H rupture model.***

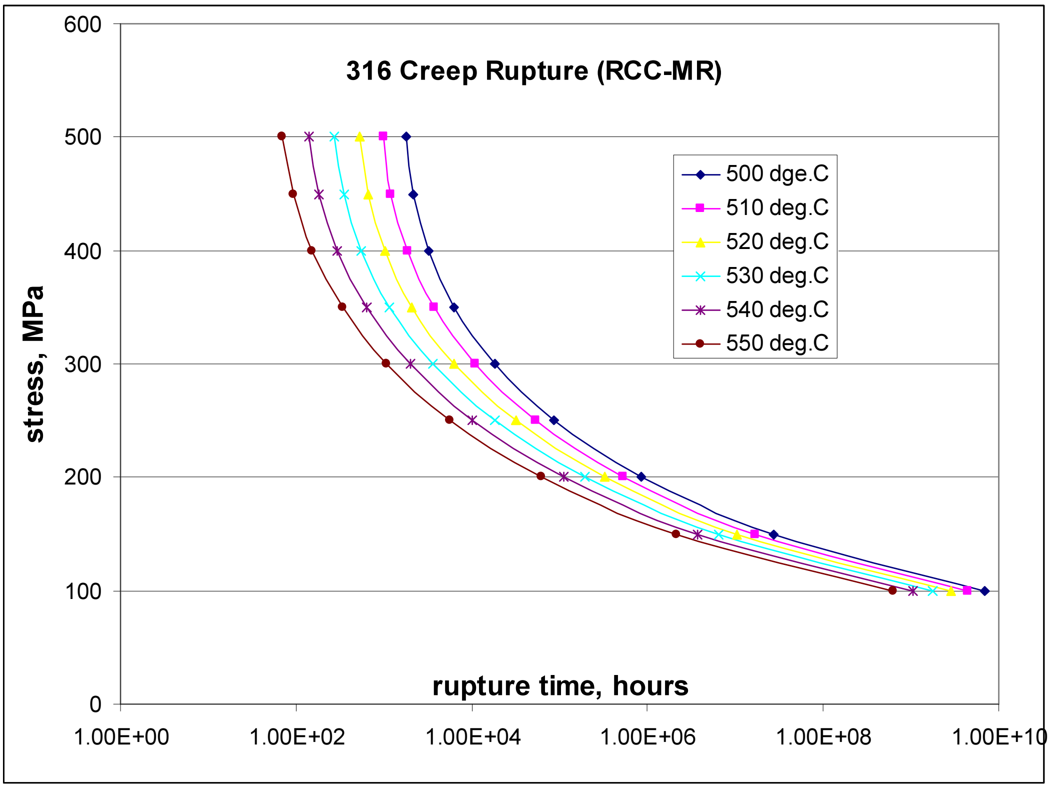



**Figure 2: Example of Rupture Data (CMV parent & Type IV)**: Rupture time against stress for CMV parent and Type IV zone at 525°C assuming k=1: Comparison of the old and new fits (see text for the sources).

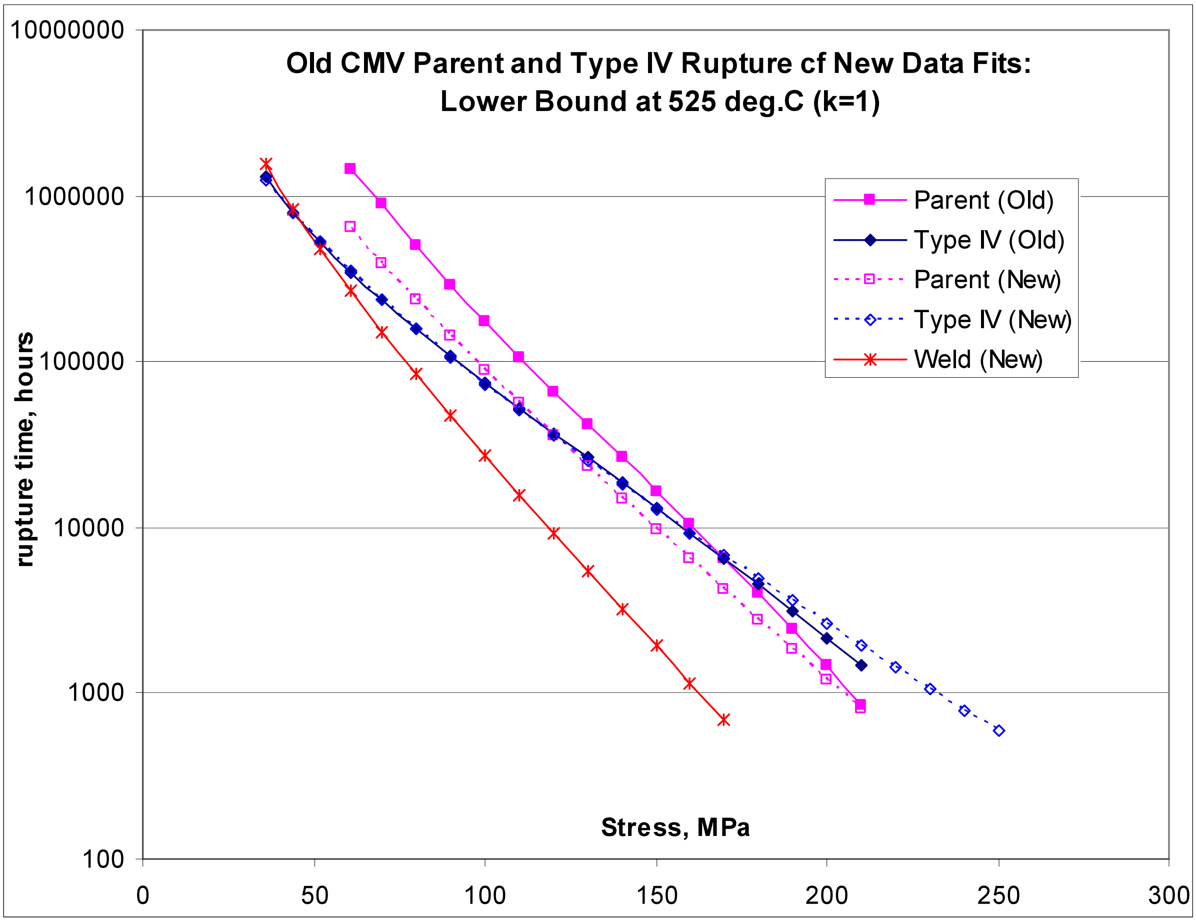


**Figure 3: Old cf New CMV Type IV Rupture Data at 500°C (k=1)**

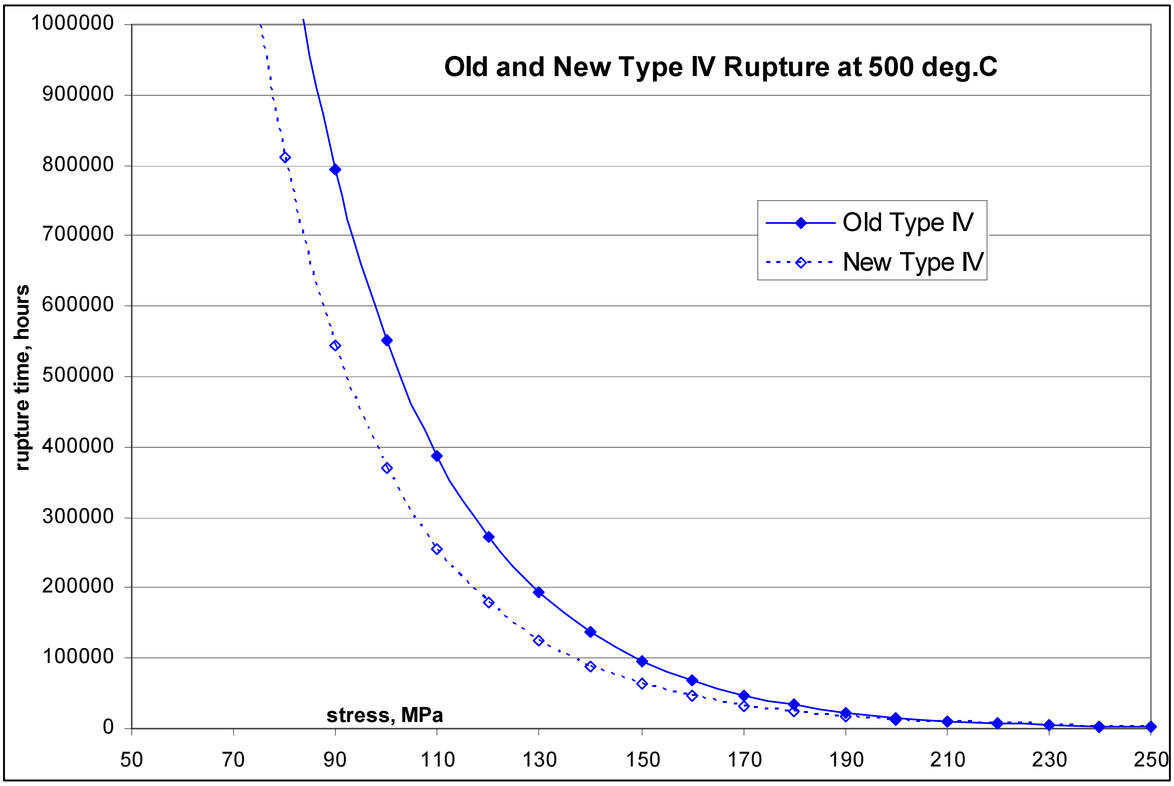
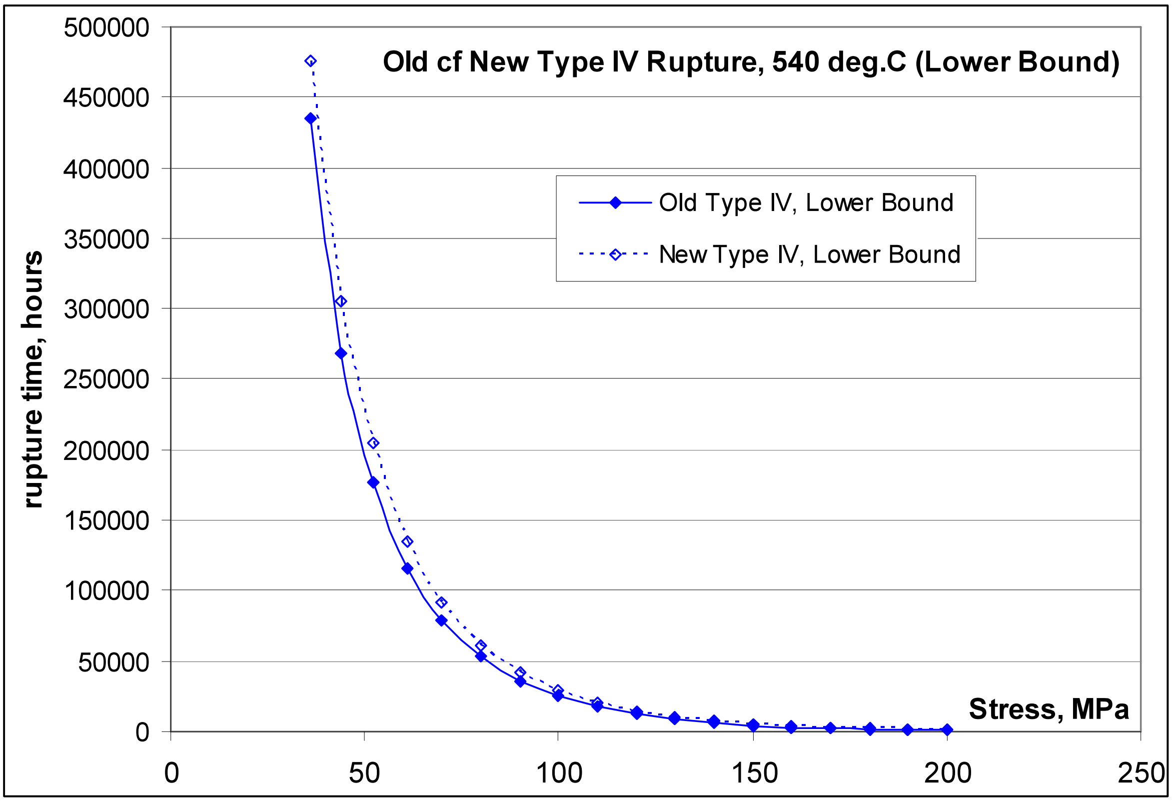



**Figure 4: Old cf New CMV Type IV Rupture Data at 540°C (k=1)**



Qu.: What is meant by "mean effective creep temperature (MECT)"?

Suppose there is a sequence of changing conditions as described above. It is sometimes convenient to define a single temperature, which, if constant over life, would produce the same creep rupture life fraction as the true history. This is the mean effective creep temperature (MECT). To be rigorous, the effect of varying stress would be built into this definition, i.e., $T_{MECT}$ is defined by,

$$\sum_i \frac{t_i}{t_{rup}(\sigma_i, T_{MECT})} = \sum_i \frac{t_i}{t_{rup}(\sigma_i, T_i)} \tag{6}$$

However, in practice the effect of varying stress is often ignored and the same, typical, stress level, $\sigma_{av}$, used for all time intervals giving,

$$\frac{\sum_i t_i}{t_{rup}(\sigma_{av}, T_{MECT})} = \sum_i \frac{t_i}{t_{rup}(\sigma_{av}, T_i)} \tag{7}$$

Qu.: What alternative definitions of MECT are there?

The above definition of MECT is based on creep rupture. This is natural since it is creep rupture which is the subject matter of this session (T73S06). However, the concept of an MECT is useful in other contexts, for example in R5V2/3 (crack initiation) or R5V4/5 (crack growth). In these cases it is the creep strain or strain rate which is the greater focus of attention, rather than rupture. Consequently an MECT can be defined based on reproducing the same total creep strain. Suppose the creep strain accumulated in the i$^{th}$ time interval is,

$$\Delta\varepsilon_i = \int_{t_{i-1}}^{t_i} \dot{\varepsilon}_c(\sigma_i, T_i, \varepsilon_c) \cdot dt \tag{8}$$

so the total strain up to the end of the n$^{th}$ time interval is $\varepsilon_n = \sum_{i=1}^{n} \Delta\varepsilon_i$. The deformation based $T_{MECT}$ is defined by requiring that,

$$\int_0^{t_n} \dot{\varepsilon}_c(\sigma_i, T_{MECT}, \varepsilon_c) \cdot dt = \varepsilon_n \tag{9}$$

As with the rupture based MECT, an approximation can be adopted in which the varying stresses, $\sigma_i$, are replaced by a constant, typical, stress, $\sigma_{av}$.

Note that the creep strain rate in a given time period is not uniquely defined by just the stress and the temperature. Some creep hardening parameter is also required – written above as strain hardening (but some other hardening law might be required). Because of this hardening law dependence, deformation based MECTs can require more work to implement.

Also note that, in general, the deformation-based MECT which results from a given set of stress and temperature conditions, $\{\sigma_i, T_i\}$, will depend upon their order. This contrasts with the simpler rupture-based MECT, which is order independent. However, the special case of strain hardening with equal time intervals produces an order independent deformation-based MECT (see session 24).

**Similar-Metal Ferritic Weldments (R5V7)**

Qu.: Why are low-alloy ferritic weldments treated specially in R5?

Because,

- Their heat affected zones (HAZ) are particularly complicated;
- Their various weldment zones are subject to specific failure modes (e.g. Type IV cracking and coarse HAZ cracking);
- They are commonly occurring in our plant;

Qu.: What are the weldment zones in low-alloy ferritic weldments?

In order they are,

[1] weld metal;

[2] coarse grained HAZ;

[3] refined HAZ;

[4] inter-critically transformed HAZ, commonly known as the Type IV zone;

[5] parent metal.

**Figure 5: Ferritic Weldment Zones**

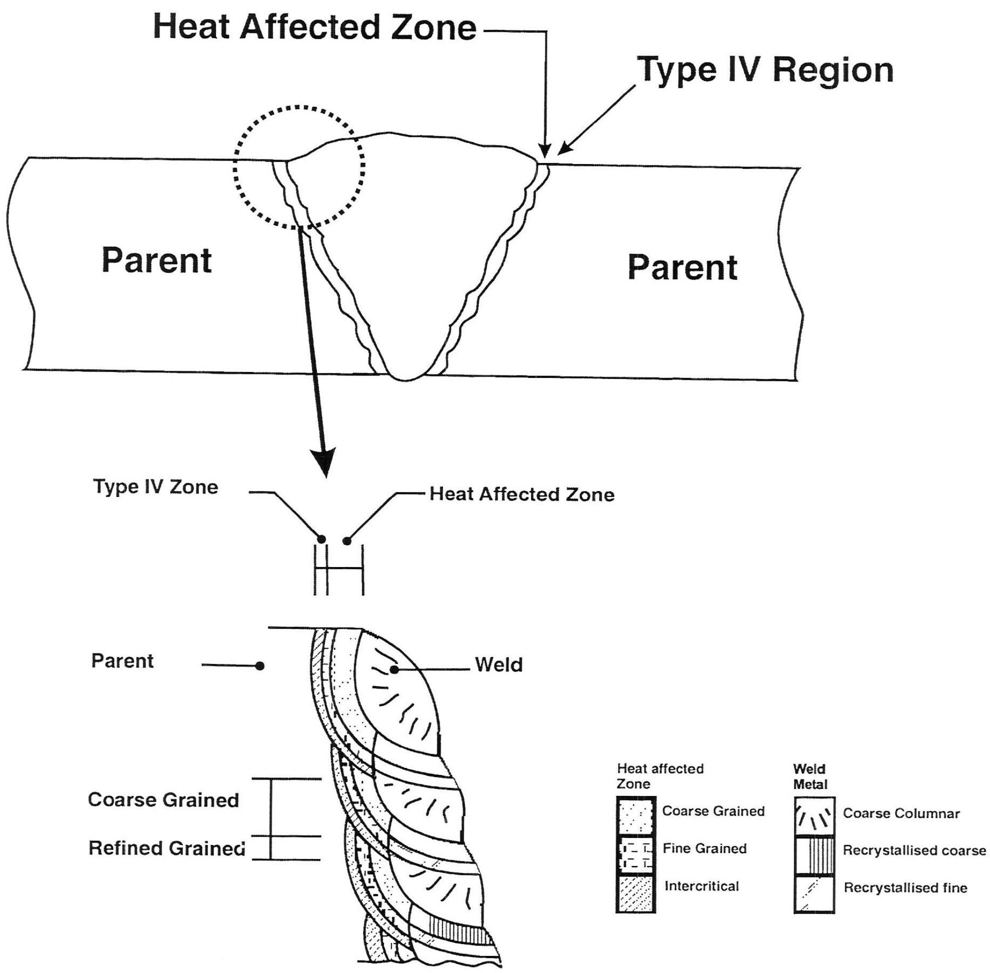
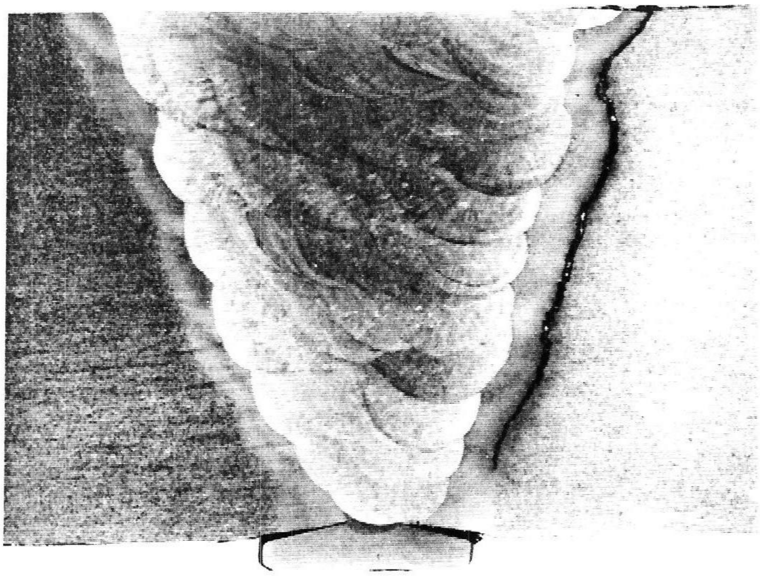


**Figure 6: Example Type IV crack a a CMV weldment:-**



**Definition of Types 1, 2, 3, and 4 cracks – it's simply based on their location:-**

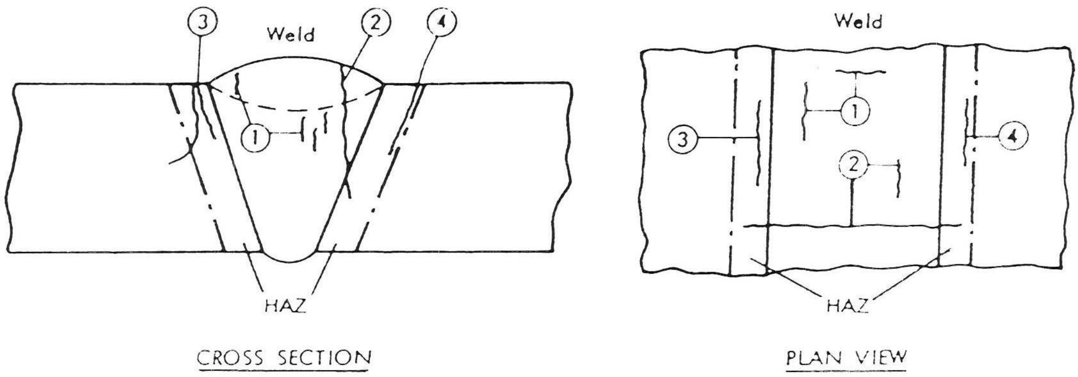
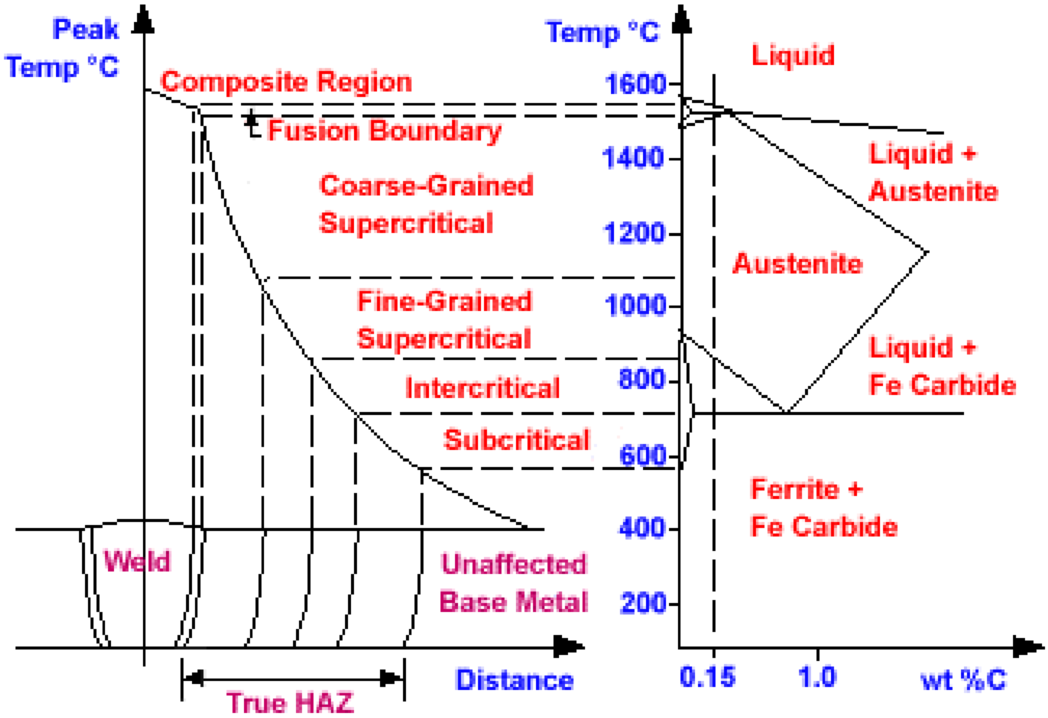



**Figure 7: Why the HAZ Zones Arise - Peak Welding Heat & the Phase Diagram**



Qu.: To which materials does R5V7 apply?

The procedure was developed with the parent material 0.5%Cr 0.5%Mo 0.25%V in mind (commonly shortened to "CMV"), and assuming a weld consumable of 2.25%Cr 1%Mo. However, it is equally applicable to minor variants on this theme, i.e., low alloy ferritics – providing that you have the materials data. Note that the procedure assumes the availability of materials data for the various zones.

Qu.: How do the weldment zones differ in material properties?

Assuming the standard configuration of CMV parent and a 2.25%Cr 1%Mo weld consumable, the broad-brush picture is roughly as follows,

- Refined HAZ creep properties are generally taken to be the same as those of parent material (and hence not subject to specific assessment);
- 2.25Cr1Mo weld material creeps faster than the other weldment zones or the CMV parent;
- Coarse HAZ creeps more slowly than weld or parent or refined HAZ;
- The Type IV zone creeps faster than parent, and faster than other HAZ zones, but not as fast as weld material;
- 2.25Cr1Mo weld material has lower creep strength than CMV parent material;
- (In fact, 2.25Cr1Mo *parent* material has lower creep strength than CMV parent material);
- Coarse HAZ has better rupture strength than parent. R66 advice at the time of writing is that the lower bound rupture strength of coarse HAZ equals the mean rupture strength of parent.
- The rupture strength of Type IV zone material is intermediate between that of weld and parent (see Fig.2).

Note the tendency for faster creeping material to have lower creep rupture strength, as one might intuitively expect. But this means that, when redistribution occurs, the stress acting on the weaker regions tends to reduce. Consequently the effect of redistribution is beneficial for the lifetime of the weldment as a whole.

Note that welds onto 2.25%Cr1%Mo parent will have different properties (see R66, IMAN#4 and the R66 User Queries lists - some of which, up to 2010, are listed in the Appendix).

| |
|---|
| Materials data for ferritic weldment zones has tended to change relatively frequently, so it is particularly important to check the R66 and R5 User Queries lists when carrying out a rupture assessment on ferritic weldments, and also use local OPEX. |

Qu.: What are the "weld stress redistribution factors", k?

Material zones which creep faster than neighbouring zones will tend to shed stress onto these neighbouring zones – providing that this is possible whilst respecting equilibrium. In the case of a circumferential butt weld in a pressurised cylinder, such offloading is possible for the hoop stresses but not for the axial stresses. This is because the mean axial stress is fixed by the applied axial load, for every weldment zone. In contrast, the hoop stress can redistribute sideways – away from the softer zones.

The k-factor is the fraction of the reference stress which remains acting on the material zone in question after redistribution has occurred. Thus, for fast creeping zones $k < 1$ (e.g. ~0.7 for weld, and perhaps ~0.9 for Type IV zone).

But slow creeping zones pick up more stress and hence $k > 1$ (e.g. ~1.4 for coarse HAZ, and perhaps ~1.2 for mixed HAZ, depending upon the degree of mixity). But these apply only for hoop dominated loading. In these cases the stress used to estimate the rupture life is factored by k.

All zones have $k = 1$ for axially dominated loading.

Parent and refined HAZ have k = 1 even for hoop dominated loading.

Qu.: What are the best, up-to-date values for k?

In addition to various places in R5 and its references (summarised below) I strongly advise paying close attention to the R5/R66 User Queries lists to identify current best advice. Also, use local OEF – colleagues who have carried out assessments recently will most often be the best source of advice. This applies particularly to creep data for CMV weldment zones, which has changed frequently in the past.

Note a particular issue of consistency: the k factors are derived using the deformation and rupture data for the weldment zones. Consequently, whenever this creep data is updated, the k factors should be re-evaluated for consistency. However, these two activities tend not to be coordinated. At the present time (November 2014) the k factors are lagging ~5 years behind the creep data as regards updates. I give advice below on how to proceed in this (protracted) interim position...but always seek local advice to confirm this, since things change...

Note that the k values given in R5V7 Table A1.1 are approximate only. The k factors are stress and temperature dependent. R5V7 Figs.A7.2-A7.4, and R5V7 References [A7.3,A7.4] and the User Queries lists should be consulted when performing assessments. Watch the User Queries lists for updates. Use OPEX.

The Appendix to these notes lists relevant User Queries and reports which may be helpful – but I don't guarantee that I haven't missed something important – and the list will probably become out of date sometime after October 2010.

Qu.: Have the k factors been updated to be consistent with the latest CMV and CMV Type IV rupture data?

As of November 2014, no.

The current k factors will certainly be out of step with the "new" CMV and CMV Type IV rupture data in Refs.[7,8]. My paraphrasing of the interim advice of R5 User Queries 133 & 153 is,

**Interim Advice Pending Revision of Type IV k-Factors**

- Use the new CMV parent rupture data
- Carry out assessments to both the old and the new Type IV rupture data;
- For the old Type IV rupture data use the existing $k_{IV}$ factors, i.e., those of Ref.[10] as plotted in R5V7 Fig.A7.4;
- For the new Type IV rupture data use $k_{IV} = 1$.

It follows that Type IV assessments using the "new" rupture fit ("AJB3") at temperatures below ~525°C will be more onerous than those using the "old" fit (giving shorter rupture times) since the new rupture data is more onerous and the $k_{IV}$ is larger (1 rather than slightly less than 1).

**Table 1 Redistribution Factors for CMV Pipework Welds**

| Material Zone | Redistribution factor k to use for hoop stress dominant case. |
|---|---|
| ½Cr½Mo¼V Parent | 1.0 |
| 2¼Cr1Mo Weld | 0.7 (CMV parent on both sides#) |
| ½Cr½Mo¼V Type IV | <u>Old rupture data (minimum commitment model)</u>: Stress and temperature dependent, given by Dean & Kiff, Ref.[10], and plotted in R5V7 Fig.A.7.4. Generally slightly less than 1.<br><u>New rupture data (AJB3, Ref.[7])</u>:<br>k factors not yet evaluated, but interim advice is to use 1. |
| ½Cr½Mo¼V Coarse HAZ | 1.4 |
| ½Cr½Mo¼V Mixed HAZ ($\alpha$ = 1.5) | 1.207* |
| ½Cr½Mo¼V Mixed HAZ ($\alpha$ = 9.0) | 1.346* |
| 2¼Cr1Mo Parent | 1.0 |
| 2¼Cr1Mo Type IV | 1.0@ |
| 2¼Cr1Mo Mixed HAZ ($\alpha$ = 1.5) | 1.0 and 1.207# |
| 2¼Cr1Mo Mixed HAZ ($\alpha$ = 9.0) | 1.0 and 1.346# |

# *See IMAN#4 for case when one or both sides is 2.25Cr1Mo parent.*

* *These values result from Equ.(10) below for the corresponding values of $\alpha$.*

@ *For 2¼Cr1Mo type IV, if necessary a k value less than 1.0 can be calculated using the same methodology as for ½Cr½Mo¼V type IV (reference 10) and the appropriate deformation in R66, Section 5.3.7.*

Qu.: PWHT versus non-PWHT

The above advice applies for welds which have been PWHT'd (post-weld heat treated). The rupture strength of weld material which has not been PWHT'd is better than that of PWHT'd material. However, it is not clear to me whether the weld k of 0.7 remains valid for non-PWHT'd weld, since I would expect it to creep slower than PWHT'd weld material. Seek advice if assessing non-PWHT'd welds.

In addition, a non-PWHT'd weld requires consideration of the residual stresses, as discussed below.

Qu.: How are hoop and axial dominated cases distinguished?

Whether the axial or hoop stress is dominant should be decided on the basis of the direction of the maximum principal stress from an elastic, uncracked body analysis (see R5V7 Section A3.6 and R5V4/5 Section A4.3.2). Which stress component is dominant should be decided *before* application of the k factor. However, there is potential ambiguity if the stresses vary through the section of interest. There may also be ambiguity regarding what is meant by the 'axial' and 'hoop' directions for an arbitrary geometry (e.g., at a pipe branch for which the axial direction for the branch pipe may approximate to the hoop direction of the main pipe at the 'flank' positions).

For a pipe butt weld, hoop/axial dominance is simply taken to mean whichever of the primary hoop membrane or primary axial membrane stresses are the larger.

For other geometries consult IMAN#4.

In particular, for pipe branches the definition in common usage is based upon the term $\gamma$ which occurs in the inverse code method for finding a branch reference stress. This $\gamma$ term accounts for the contribution of system loading to the reference stress. The larger the system stress, the smaller is $\gamma$, and the larger is the reference stress. Hoop dominance is assumed to prevail for $\gamma > 0.9$, and axial dominance for $\gamma < 0.9$. For further details see IMAN#4 or session 25.

Qu.: Why are axial and hoop stresses treated differently?

It is important to realise that the different treatment of axial and hoop stresses is really due to the assumption that the weld is circumferential (including branch welds). So, 'axial' really means transverse to the weld, and 'hoop' really means longitudinal along the weld.

If we were assessing an axial seam weld in a pipe, then the roles would reverse. In this case no redistribution would be possible for the hoop stresses, and k would be unity for hoop dominance. On the other hand, redistribution of the axial stresses would be possible, and the k values quoted above for hoop dominance of a circumferential weld might apply for axial dominance of an axial weld (though they would really need re-evaluation). However, as far as I am aware, BE has no axially seam welded pipe operating in the creep regime. Such situations do occur abroad, though.

Qu.: What is "mixed HAZ". What is the mixing parameter, α?

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

| Specifically, α is the ratio of the amount of coarse HAZ to refined HAZ along the section of interest. |
|---|

The value of α depends upon,

- the weld prep angle,
- the welding process, and,
- the PWHT (since this can cause a change in microstructure).

- see R5V7 Appendix A1. α takes a small value (1.5) for narrow angle welds, and a large value (9) for wide angle welds.

Having decided on the appropriate α, a mixed value of the weld stress redistribution factor is defined by,

$$k_{mixed} = \frac{\alpha + 1}{\alpha + k_C / k_R} k_C \qquad (10)$$

where the subscripts refer to coarse and refined HAZ. Hence, for wide angle welds the mixed k is only slightly smaller than that for coarse HAZ, whereas for a narrow angle weld it is substantially smaller.

This provides some alleviation in assessments, avoiding having to assess coarse and refined HAZ zones separately, and instead only assessing weld, mixed HAZ, Type IV zone and parent.

Qu.: How is the rupture life found for mixed CMV HAZ?

It is assumed that the CMV parent is welded using 2.25%Cr1%Mo weld consumable.

Recall that the lower bound rupture life of coarse CMV HAZ is equated with the mean rupture life of parent CMV. So the lower bound rupture life of mixed HAZ will lie between the lower bound and mean ruptures lives of parent CMV. A factor is thus applied to the stress at which to enter the parent CMV rupture equation, known as the m-factor. R5 User Queries 113 and 153 give the following prescription, Best Estimate Mixed HAZ Rupture Life

$$\text{Put} \quad m_M = \frac{\left(\frac{\alpha}{\xi}\right)+1}{\alpha+1} \quad \text{and} \quad \sigma = k_{mixed} \cdot m_M \cdot \sigma^R_{ref,0} \tag{11}$$

and enter the parent mean CMV rupture equation at the stress $\sigma$. This $m_M$ factor is less than one, and converts the parent mean data to be the mean for mixed HAZ. In (11) the term $\xi$ is,

- 1.2 for old parent rupture data (i.e., R66 Rev.007);
- 1.307 for new parent rupture data (i.e., R66 Rev.009, "AJB2");

Here $\sigma^R_{ref,0}$ is the rupture reference stress for the homogeneous body. Although not stated in UQ113, this should be the creep *rupture* reference stress, i.e., also applying the factor based on $\chi$ factor as defined in R5, Volume 2, Section 6.2.4. IMAN#4 specifies those geometries for which this is required.

Lower Bound Mixed HAZ Rupture Life

$$\text{Put} \quad m_{LB} = \frac{\left(\frac{\alpha}{\xi}\right)+1}{\alpha+1} \quad \text{and} \quad \sigma = \xi \cdot k_{mixed} \cdot m_{LB} \cdot \sigma^R_{ref,0} \tag{12}$$

and enter the parent mean CMV rupture equation at the stress $\sigma$. This $m_{LB}$ factor is less than one, and converts the parent lower bound data to be the lower bound for mixed HAZ. In (12) the term $\xi$ is,

- 1.25 for old parent rupture data (i.e., R66 Rev.007);
- 1.307 for new parent rupture data (i.e., R66 Rev.009, "AJB2").

I note that some 2014 assessment reports, e.g., E/REP/BBJB/0196/DNB/13, appear not to have used this prescription.

Qu.: Are the various combinations of assumption summarised somewhere?

For CMV and 2.25Cr1Mo there is a summary of the various key elements in a Table attached to R5 User Query 116. This may be helpful – but note that it is now over 8 years old and so may no longer be consistent with the latest materials data advice. ***Anyone want to volunteer to produce an up-to-date version?***

Qu.: Which weldment zone is weakest?

We have already noted, above, the tendency for zones with higher creep strength to have slower creep strain rates and hence larger k-factors (though there's no guarantee that this will always be the case in other materials). Consequently there is a degree of auto-correction in that the zones which pick up additional stressing due to redistribution also tend to have greater creep strength, and zones with lower strength tend to have reduced stresses. Because of this it is not obvious which zone will rupture first.

Most often it is the Type IV zone which is predicted to fail first. This aligns with expectation since Type IV cracking is often held to be the life determining mechanism of this class of welds.

However, if coarse HAZ is assessed (as opposed to mixed HAZ) then coarse HAZ will often be predicted to fail before the Type IV zone.

But to-date it has been common practice not to assess coarse HAZ, preferring to assess only weld, mixed HAZ, Type IV zone and parent. The use of mixed HAZ k values usually results in the Type IV zone being limiting – but there are exceptions.

Recent experience (e.g., with hot reheat drain pots at HYA/HAR) raises the question as to whether coarse HAZ should be assessed as well.

Qu.: How is the use of mixed HAZ in assessments being challenged?

The use of mixed HAZ properties, thus avoiding assessing coarse HAZ separately, is being challenged by observations of coarse grained HAZ cracking in the hot reheat drain pots at HYA/HRA/HPB. The concern is that these instances of aligned cavitation and/or micro-cracking in the coarse HAZ are not predicted by the current stress-rupture based R5V7 procedure.

However there are elements within the existing R5 procedure that could re-establish its conservatism:-

[1] R5 User Query 132 has observed that existing data for coarse HAZ implies that it is creep brittle according to the R5 definition, see R5 V2/3 Section A1.7. This same Section advises that, for creep brittle materials, it should be assumed that the whole structural section fails if the usage factor reaches unity at one point. This could be interpreted as undermining the mixed HAZ approach to the assessment, since the coarse HAZ component is brittle.

It may be that re-introducing a separate assessment of 'pure' coarse HAZ may be closer to the truth in these cases. The difficulty is that the current procedure is generally regarded as quite conservative – and adopting a more conservative approach to improve agreement for this class of feature may make the procedure overly conservative for the large bulk of welds. We do not want to be obliged to recommend wholesale pipework replacements unless there is a genuine need.

[2] Alternatively, there is already a requirement to carry out a ductility exhaustion based rupture assessment (R5V7 Section A4.3) which is generally ignored but which may be the best means of addressing these drain pot issues. (This is discussed further below).

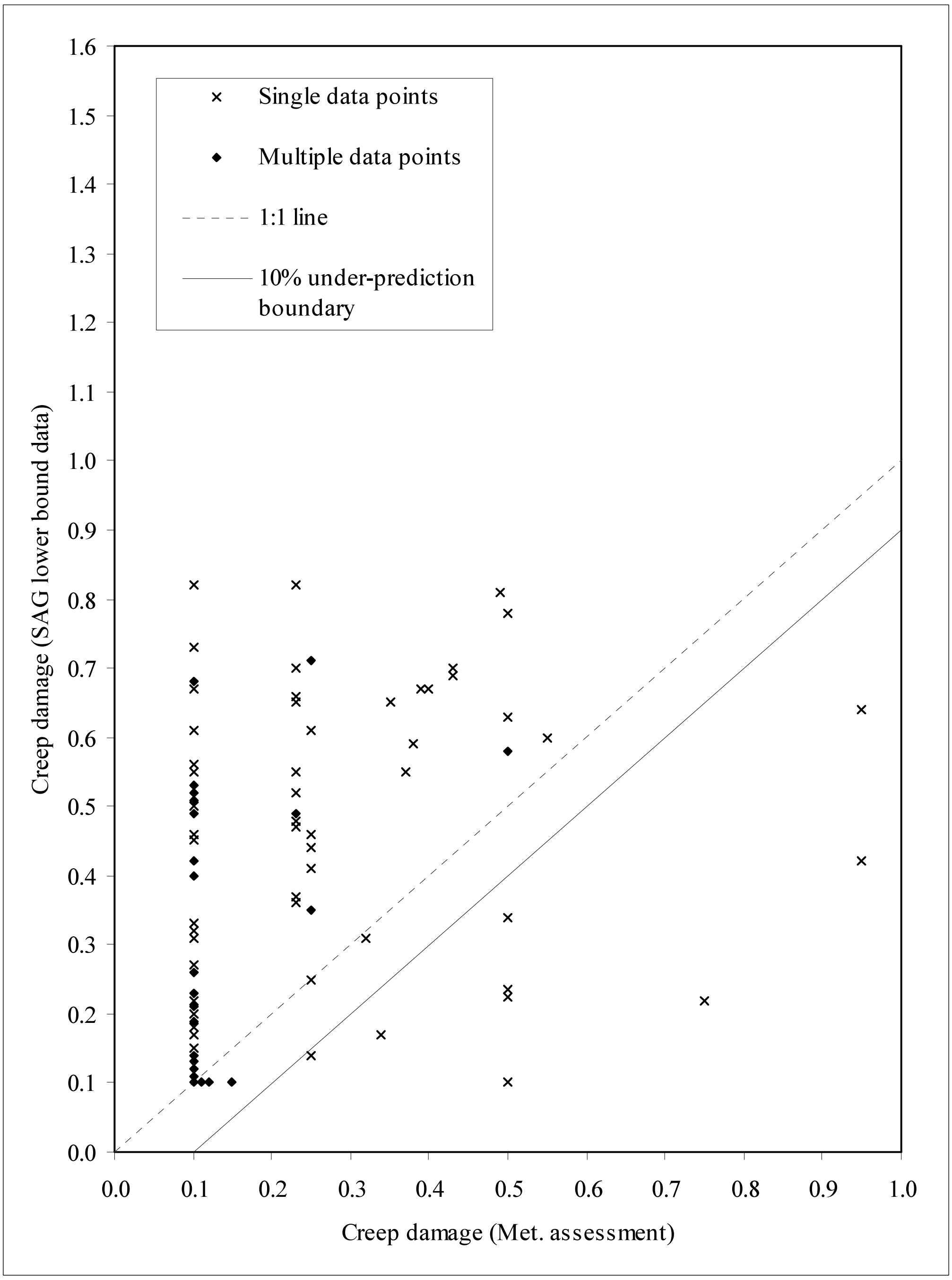
Qu.: Are the k factors used to calculate creep strain also?

No.

R5V7 also includes a procedure for assessing creep crack growth in low alloy ferritic weldments. For this purpose strain rates are needed in the various weldment zones. However, the k factors are ***not*** used to factor the stresses in calculating these creep strain rates (see the notes in italics in Sections A4.3.2 and A6.1). Instead, for hoop dominance (the case for which the k's would differ from unity) strain compatibility is assumed, i.e., all weld zones are assumed to have the same creep strain as parent.

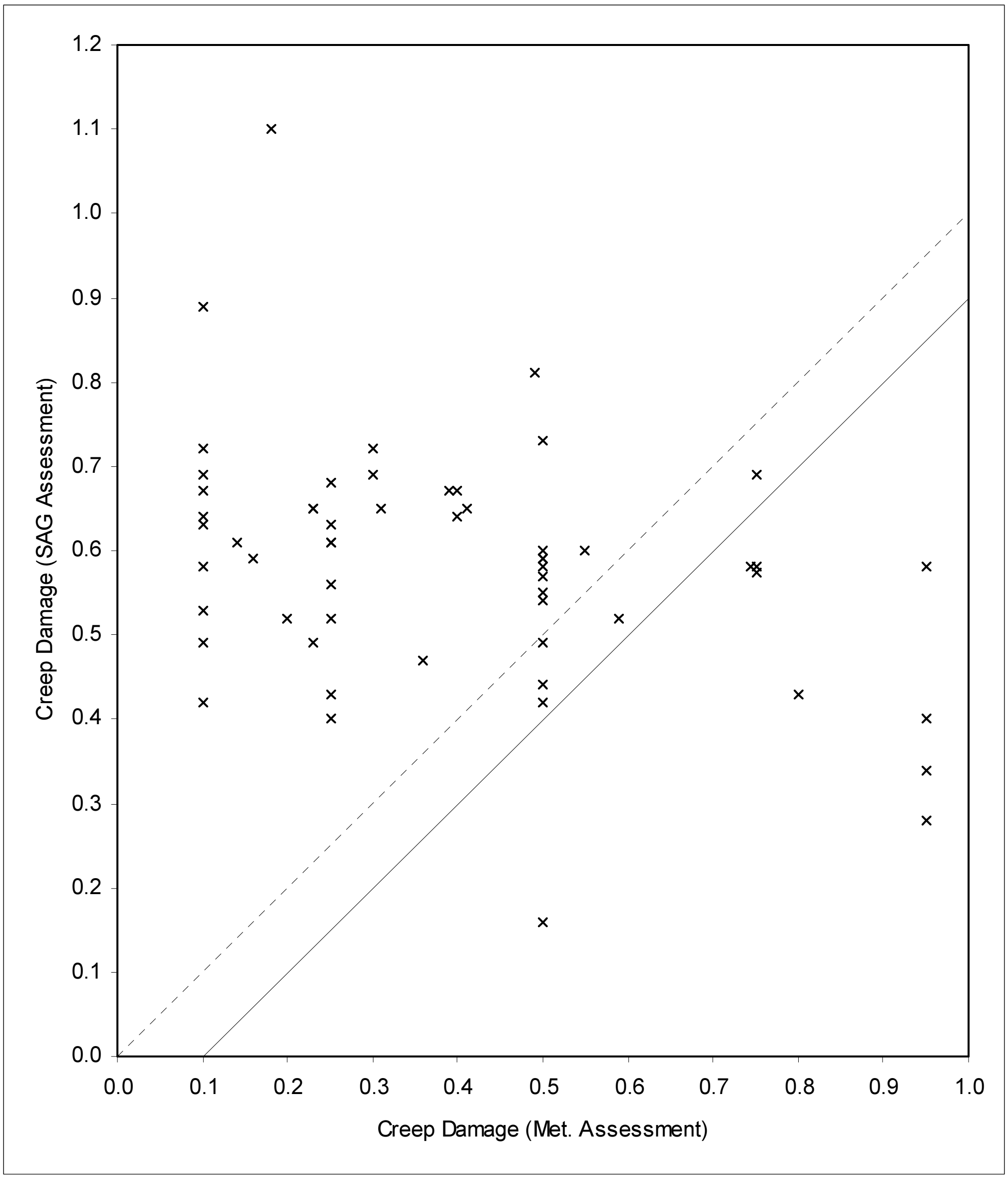
But the individual weldment zone k's *are* used to calculate the elastic strains.

**Figure 8 – Comparison between measured and predicted damage in welds from the general CMV population across all AGRs (Ref. 3)**




133 points above the continuous line, 9 below

**Figure 9 – Comparison between measured and predicted damage in Hartlepool /Heysham 1 hot reheat drain pot branch welds (Ref.4)**




48 points above the continuous line, 9 below

Qu.: Are the k factors used to calculate creep damage due to secondary stresses?

Yes.

The k-factors are included when calculating the secondary stress contribution to rupture via a ductility exhaustion approach (see R5V7 Section A4.3 – to be discussed in Session 27).

The k-factors are also included when calculating C* and hence creep crack growth rates (see R5V7 Section A6.1). Note that C* is proportional to the reference stress times the reference creep strain rate. The stress is factored by k, but the k factor is not used when calculating the strain rate. Consequently C* is proportional to k (whereas it would otherwise have been proportional to $k^{n+1}$).

Qu.: Isn't this all a bit complicated?

It is rather. But unfortunately the difference between the weldment zones is crucial. The HAZ is invariably the weak link in ferritic weldments under creeping conditions. So an assessment which recognises the distinction between HAZ and parent/weld is unavoidable.

Qu.: What is the R5 procedure for assessing rupture life?

The basic procedure has been discussed in previous sessions. Here we present a recap and incorporate the additional issues introduced in this session, i.e., the ferritic weldment zone HAZ-mixity $\alpha$ term, the redistribution k-factor, the mixed HAZ m-factors, and Robinson's rule. The procedure is,

[1] Evaluate the 'ordinary' reference stress (from a collapse solution), $\sigma_{ref}$;

[2] Enhance this by a factor to account for local stress concentration, to find the "rupture reference stress", $\sigma_{ref}^R$ (R5V2/3 Sect.6.5 and R5 V7 Sect.A3.5). Note that an exception to this applies when the inverse code method has been used to find the reference stress. This is deemed to constitute a rupture reference stress without further correction. Butt welds which are hoop dominated and for which the reference stress is found using the Tresca formula are also an exception for which $\sigma_{ref}^R = \sigma_{ref}$. IMAN#4 includes specific advice on evaluating $\chi$ and when this factor is required;

[3] For the HAZ assessment of a low alloy ferritic weldment, decide if this will be based upon 'mixed HAZ', and if so decide upon the relevant mixity parameter, $\alpha$. The associated mixed HAZ redistribution factor, $k_{mixed}$, is then determined, as is the m-factor which determines how the mixed HAZ lower bound rupture time is found from the parent mean rupture equation;

[4] For a CMV weld, or similar low alloy ferritic weldment, determine whether the stressing is hoop or axial dominated, and hence if the weldment zone in question has a k-factor different from unity. If so, use stress $k\sigma_{ref}^R$ as the basis of the rupture assessment. But for mixed HAZ use Equs.(11) or (12) involving the m-factor;

[5] For the Type IV zone, use the "minimum commitment" rupture model together with the Type IV k-factor from R5V7 (2003), i.e., Ref.[10], ***as well as*** the rupture fit from Ref.[7] with k = 1. The overall result is the worse of the two.

[6] Enter the appropriate rupture curve at the stress derived above, and at the operating temperature or MECT as required, to derive a rupture time for this condition;

[7] Alternatively, if stress or temperature conditions have varied in the past, or are projected to differ in future, use Robinson's rule to assess the total fractional life usage.

[8] For the assessment of the HAZ of low alloy ferritic welds to R5V7 it may also be necessary to carry out a ductility exhaustion assessment, as stipulated in R5V7 Section A4.1 (i,ii).

Note that this procedure accounts for primary stresses only, since it is based on the 'ordinary' reference stress, $\sigma_{ref}$, appropriately factored. The influence of secondary loads is discussed in the next session. However, the last point, [8], is partly a recognition that residual stress might influence the rupture life. This is discussed next.

Qu.: When is a ductility exhaustion rupture assessment required?

The assessment of the HAZ of low alloy ferritic welds to R5V7 requires a ductility exhaustion assessment, as defined in R5V7 Section A4.3, if the PWHT was not sufficient to result in a high degree of HAZ refinement. R5V7 Section A4.1(i,ii) states that the ductility exhaustion assessment is required when the mixity parameter, α, is greater than 1.5. However, R5 User Query 125 implies that a ductility exhaustion assessment may be omitted for rather larger α, at least 2, and perhaps 4 or 5 according to judgment. It is therefore rather ill defined when a ductility exhaustion assessment is needed.

In practice I suspect that ductility exhaustion assessment to R5V7 Section A4.3 is generally ignored – even when it is strictly required. But this is bad practice.

As noted in R5 user Query 125, this non-conformance may be pertinent in the case of hot reheat drain pots for which the usual stress-rupture assessment has proved non-conservative in some cases (see above). The ductility exhaustion approach might re-establish the conservatism of the procedure – though this is unproved at present (as far as I know).

Qu.: What about the effects of multi-axial stressing?

R5 is rather weak on the effects of multi-axial stressing. In response to the austenitic reheat cracking problems in the 1990s, R5 now contains advice on the effects of multi-axiality on creep *ductility*. For triaxial states the reduction of ductility can be very marked. Consequently one might expect that creep rupture would also depend upon stress state. Indeed it does, in general, but R5 contains little advice on the matter. R5 does *recognise* the issue. V2/3 Sect.6.5 states that the procedure is applicable to "*situations where creep rupture is controlled by the equivalent stress or where the stress state is biaxial*". However, it does not give any advice on how to account for triaxial effects on creep rupture when using the stress-based time-fraction approach.

My advice would be to take account of triaxiality if this seems significant, since failure to do so will generally be non-conservative. However, this supposes that you have available an experimentally based recommendation for triaxial conditions. Examples are Huddleston (Ref.1) and Baker (Ref.2). These provide a rupture reference stress which is stress state dependent by appropriately factoring the Mises stress:-

Huddleston (1993): $$\sigma_{ref}^{R} = \bar{\sigma} \exp b\left\{\frac{3\sigma_H}{\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}} - 1\right\}$$

Baker (2005): $$\sigma_{ref}^{R} = \bar{\sigma}\left(\frac{\bar{\sigma}}{\sigma_1}\right)^{\left(\frac{m+1}{-m-n}\right)} \exp\left\{\frac{1}{m+n}\left(\frac{3}{2}\frac{\sigma_H}{\bar{\sigma}} - \frac{1}{2}\right)\right\}$$

For austenitic steels, the Huddleston $b$ is 0.24, but is zero for 2.25Cr1Mo (i.e. no triaxial effect).

For 316H, the parameters in Baker's expression are $m = 2.5$, $n = 8.2$.

The characteristic of multi-axial rupture formulations is that they depend upon all three principal stresses, or, equivalently, upon the hydrostatic and maximum principal stresses as well as the Mises stress.

When the above expressions are deployed on plant components I presume the Mises stress can be replaced by the reference stress – but I don't know this for sure. Do check if you intend to use them.

Qu.: What about rupture under compressive stress?

R5V2/3 Section A.5.2.2.1 advises the use of a suitable multi-axial rupture formulation if compression is dominant, e.g. Huddleston for austenitics.

Qu.: Do the results of an R5V7 rupture assessment compare well with metallurgical examination based estimates of damage?

Not brilliantly, no. Comparisons have been reported by Nick Tyas, Refs.[3,4] and are reproduced above as Figures 8 and 9. The situation is worst for the HYA/HRA HRH drain pots for which the assessment route fails to distinguish between those with high damage and those with low damage (mostly a coarse HAZ problem).

**References**

[1] R.L.Huddleston, "Assessment of an improved multiaxial strength theory based on creep-rupture data for type 316 stainless steel", ASME J.Pres.Ves.Tech. 115, 177-184 (1993). See also R5V2/3 Appendix A5, Section A.5.2.2.1.

[2] A.Baker, "Multiaxial creep rupture of Type 316H steel", E/REP/BDBB/0066/GEN/05, October 2005.

[3] E/REP/MATS/0030/AGR/01 Revision 000, A Comparison Between Measured and Predicted Damage in CrMoV Weldments Based Upon Revised Materials Property Data, N. H. Tyas, December 2002.

[4] N.Tyas, "A Comparison Between Measured and Predicted Damage in Hot Reheat Drain Pot Welds and Consideration of the Implications for General CMV Component Strategies", E/REP/BBHB/0019/AGR/09, October 2009.

[5] Baker, E/REP/BDBB/0041/AGR/04, 2.25Cr1Mo parent and weld rupture and deformation models. Recommended in R66 Rev.009.

[6] Baker & Douglas, E/REP/BBGB/0038/AGR/08, Extrapolation of the Creep Rupture Model Equations for ½CMV Weldment Zones to Long Rupture Lifetimes.

[7] S.Spindler & Baker, E/REP/BBGB/0015/AGR/07 (issued April 2009) CMV Type IV creep rupture, "AJB3" model, which can be found in R55 Rev.009 as an option instead of the "Minimum Commitment" model, which also appears in R66 Rev.009 - see text of these notes for details.

[8] S.Spindler & Baker, E/REP/BBGB/0021/AGR/07 (issued Dec. 2009) CMV parent creep deformation & rupture advice, which is recommended in R66 Rev.009.

[9] Baker & Dean, E/EAN/BBGB/0021/AGR/09, Advice on assessing CMV welds between new and service aged materials.

[10] D W Dean and S J Kiff, Creep Deformation Data and Weld Redistribution Factors for ½Cr½Mo¼V Type IV Zones, EPD/GEN/REP/0443/99, Issue 2, 2000

**Appendix: Quick Review of R5/R66 User Queries Relating to CMV & 2.25Cr1Mo Creep Rupture Assessments (Compiled by RAWB, 18/10/10)**

Do not use this list as an alternative to searching the User Queries databases yourself! I do not guarantee that I have not missed something important – and new User Queries are being added all the time. However, this list may be helpful; as a start.

**R5 User Queries**

Be warned that the older UQs may be superseded by more recent UQs. I leave you to work this out. I have highlighted in yellow the UQs which I think are possibly most important.

| UQ | Subject | Response Date |
|---|---|---|
| 4 | "2.25Cr1Mo HAZ rupture & k factors | 2003 |
| 17 | Axial & hoop dominance | 2005 |
| 31 | k factors for CMV Type IV zone | - |
| 44 | k factors for CMV Type IV zone | 2001 |
| 97 | Axial & hoop dominance for growing cracks | 2004 |
| 113 | CMV HAZ creep rupture properties & bounds (includes definition of the $m_{LB}$ and $m_M$ factors for HAZ) | 2002 |
| 116 | Summary of creep rupture life methodology for CMV and 2.25Cr1Mo parent and their weldment zones | 2006 |
| 125 | Is a ductility exhaustion assessment required for α only a little greater than 1.5? | 2008 |
| 129 | Following UQ125, what is the appropriate 'mixed HAZ' creep ductility? | None |
| 131 | Assessment of new welds in old pipes | None but see EAN0021 |
| 132 | Is coarse HAZ creep brittle? Is the R5V7 'mixed HAZ' approach valid? | None |
| 133 | New CMV Type IV rupture advice and the issue of the compatible k factors to use. | Mar'2010 |
| 140 | Assessment of new welds in old pipes | None but see EAN0021 |
| 144 | Methodology for rupture reference stress for CMV-to-2.25Cr1Mo branches | None |
| 145 | CMV Mixed HAZ m-factors for R66 Revision 008 CMV Rupture Data. *This one has been updated to the new data by 153.* | None - but follows from 153 |
| 150 | Stress to use for R5 Volume 7 rupture life | None |
| 153 | Use of 0.5CMV creep rupture and creep deformation data for minimum thickness calculations: *This is the interim advice on the use of the new CMV parent & Type IV data.* | 8/10/10 |