MECT Algorithm

MECT algorithms are usually defined via creep rupture. That is, the MECT is the temperature which, if constant over life, would produce the same time fraction creep damage as the actual, varying, temperature history. This is the most appropriate approach for ferritic materials where creep rupture is the threat. However, for austenitic materials in BE plant, creep rupture is not generally the mechanism of greatest concern. For austenitics, the quantity of most interest is usually the creep strain (or strain rate). Consequently it is desirable to base the MECT for austenitics on deformation rather than rupture. Hence, it is more appropriate to define the MECT as that temperature which, if constant, would give rise to the same creep strain as the true operating history.

Both the rupture and the deformation based definitions of MECT are complicated by the fact that these mechanisms also depend upon stress. Thus, if stress varies over life, then the exact MECT does not depend only upon the temperature history but also upon the stress history. For the usual (rupture based) MECT, this complication is often regarded as a refinement too far, and some sensible level of constant stress is assumed to evaluate the MECT. For a deformation based MECT in the primary creep regime there is a more virulent problem. The instantaneous strain rate depends both upon the current stress and also upon the accumulated creep strain to-date, typically via an equation of the form $\dot{\varepsilon}_c = K\varepsilon_c^x\sigma^y$ (or alternatively $\dot{\varepsilon}_c = C_1 t^{C_2}\sigma^{n_1}$ in time hardened form). All the coefficients K, x, y, C_1, C_2 and n_1 are generally temperature dependent.

This makes it rather challenging to formulate an effective algorithm for calculating an MECT. The explicit strain (or time) dependence means that the MECT is dependent on the temporal order of the temperature data.

The apparent complexity of the temperature dependence of $\dot{\varepsilon}_c = K\varepsilon_c^x\sigma^y$ or $\varepsilon_c = C_1 t^{C_2}\sigma^{n_1}$ belies the fact that, on physical grounds, the temperature dependence of the creep rate is expected to be simply exponential, due to creep being a thermally activated mechanism (see below). Consequently, it is expected that the creep strain rate will change by a factor of the form $\exp\{\alpha(T_2 - T_1)\}$ when the temperature is changed from T_1 to T_2, other things being equal. To be useful, the value of α should be insensitive to stress and accumulated strain (or time).

A past application provides an example. The stresses in this example lay between 100 MPa and 200 MPa, and the metal temperatures were generally in the range 470°C to 530°C. The value of α has been calculated from the ratio of the best estimate RCC-MR strain rates for 316ss (Ref.[7]) at these two temperatures, considering the two bounding stresses and also the times 1,000 hours, 10,000 hours and 100,000 hours. This results in the following values for α compared at the same times (i.e. time hardening),

Time Hardening

Table gives α	1,000 hours	10,000 hours	100,000 hours
100 MPa	0.032 (0.034)*	0.033 (0.036)	0.035 (0.037)
200 MPa	0.033 (0.035)	0.035 (0.037)	0.038 (0.048)

*Based on ratio of strains (based on ratio of strain rates)

This nicely confirms the hypothesis, i.e. that α should be roughly constant, and provides the basis of a simple MECT algorithm (below). (The point at the largest time and stress is not so good, but this is because it exceeds the end of the primary creep period at 530°C). A check on the physical reasonableness of the above value of α is as follows: Creep rate is expected to vary according to an Arrhenius factor, $\exp\{-E/kT\}$, where T is the absolute temperature, k is Boltzmann's constant, and E is the activation energy of the process. Hence the activation energy can be written as $E = \alpha k T_1 T_2$, which evaluates to,

$$E = 0.035 \text{ x } 1.38\text{x}10^{-23} \text{ x } (470+273)*(530+273) / 1.9\text{x}10^{-19} = 1.5 \text{ eV}$$

(the last term converts Joules to eV). This is sensible since typical dislocation movement or vacancy creation/diffusion activation energies are of the order of an eV.

The above α values are for time hardening. Below are the corresponding strain hardening values. These are based upon the same times at 530°C, but at 470°C the strain rates are evaluated at the same strain as derived at 530°C. Hence, the times implicit in the 470°C cases are very long indeed (hundreds of times longer than at 530°C).

<u>Strain Hardening</u> (Based on ratio of strain rates)

Table gives α	1,000 hours (530°C)	10,000 hours (530°C)	100,000 hours (530°C)
100 MPa	0.091	0.096	0.101
200 MPa	0.096	0.101	0.117

Hence, the values for α are again reasonably insensitive to the period or stress considered, but they differ substantially from the time hardened values (by about a factor of 3). Herein we shall employ values α = 0.035 for time hardening and α = 0.1 for strain hardening.

MECT Algorithm

The strain rate at any temperature T_i can be written,

$$\dot{\varepsilon}_c(T_i) = \dot{\varepsilon}_c(T_{eff})\exp\{\alpha(T_i - T_{eff})\}$$

where $\dot{\varepsilon}_c(T_{eff})$ is the strain rate at some arbitrary reference temperature, T_{eff}, and at the same stress and total strain (or time). Suppose strain accumulates over a time period t, which consists of a sequence of intervals Δt_i during which the temperature is T_i. The total strain accumulated is,

$$\varepsilon_c = \sum_i \dot{\varepsilon}_c(T_i)\Delta t_i = \sum_i \dot{\varepsilon}_c(T_{eff})\exp\{\alpha(T_i - T_{eff})\}\Delta t_i = \dot{\varepsilon}_c(T_{eff})\exp\{-\alpha T_{eff}\}\sum_i \exp\{\alpha(T_i)\}\Delta t_i$$

But, if T_{eff} is the MECT, then this is required to equal $\dot{\varepsilon}_c(T_{eff})\cdot t$, hence,

$$\exp\{\alpha T_{eff}\} = \frac{1}{t}\sum_i \Delta t_i \exp\{\alpha T_i\}$$

i.e.,

$$T_{eff} = \frac{1}{\alpha}\ln\left[\frac{1}{t}\sum_i \Delta t_i \exp\{\alpha T_i\}\right]$$

where, $t = \sum_i \Delta t_t$. In the case of N equal time intervals this becomes,

$$T_{eff} = \frac{1}{\alpha}\ln\left[\frac{1}{N}\sum_i \exp\{\alpha T_i\}\right]$$

This algorithm implicitly ignores the effects of any variations in stress. More importantly, it also ignores the effect of temporal order on the accumulated creep strain. This latter effect will not be significant as long as the temperature variations are random over the period analysed. However, if the temperature varies systematically, being generally hotter or cooler at the start than at the end of the period, say, then order dependence may be significant. In this case the full formulation of the current creep strain rate should be used and integrated over the true history.

It is easily proved that the above MECT is greater than or equal to the simple arithmetic average of the temperature data, the equality holding if and only if all the temperature data are equal.