

Life Management of Cycling Plant Components utilising RemLife™ Software

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ABSTRACT

Due to changes in the mix of power generation that includes both wind and solar, base-load power, for example coal and combined cycle plants, are faced with challenging market conditions that increasingly necessitates operating the units in a cyclic mode. These types of operations can place increased damage rates on the plant. In order to categorise and understand the damage, the common practice is to undertake a Remaining life assessment. These assessments can be both time consuming and expensive, particularly; if multiple components are to be assessed. This paper describes a computer package developed that enables the user to quickly and efficiently assess the remaining life of high temperature components. The program is based around state of the art creep-fatigue methodologies and is designed to rapidly simulate different cycle types and assess the relative merit of each type of operation. This paper will outline the basic program methodology and illustrate a case study undertaken on a tertiary stage superheater header, that is proposed to change from base load to two shifting operation.

1. INTRODUCTION

The increasing demand for cyclic service (variable power output and more frequent shut-downs) has increased the damage rates on plants originally designed for base load operation. This has led to a greater demand for reliable design and assessment methods that take creep-fatigue into account for future more flexible operating plants. Plant engineers and managers are faced with three highly significant pressures namely:

- The need to operate plant more flexibly, possibly with faster start-ups
- The need to cycle plant that has not been designed for this type of operation
- The need to safely operate ageing plant with lower maintenance budgets

In order to be able to predict the damage cost of cyclic operation in all its possible combinations a model is required that will determine with reasonable accuracy the overall impact of any given cycle on the damage to the various unit components. In order to

understand the effects of different cycling strategies, rapid scenario testing is of considerable importance. As part of long term initiative within the Australian power industry, the RemLife program was developed to allow power stations to rapidly simulate the effects of unit cycling on both the damage sustained by the equipment and the economic benefits or not of the chosen cycling regime. Since the release of version 1 in 2006 the program has undergone 17 minor and major releases, with version 4.0 to replace V3.10 in May 2018. The program contains a number of modules that are highly integrated. The core modules include a creep fatigue crack initiation module which is seamlessly integrated to a creep-fatigue crack growth module. The tube module handles oxide kinetics for boiler and super heater tube life calculations. Scar Life can be used to assess the effects of scaring on tubes, headers and other components, both at creep and non-creep temperatures. The results from an analysis can be integrated with inspection results and maintenance scheduling to generate risk based inspection outcomes, (Figure 1).

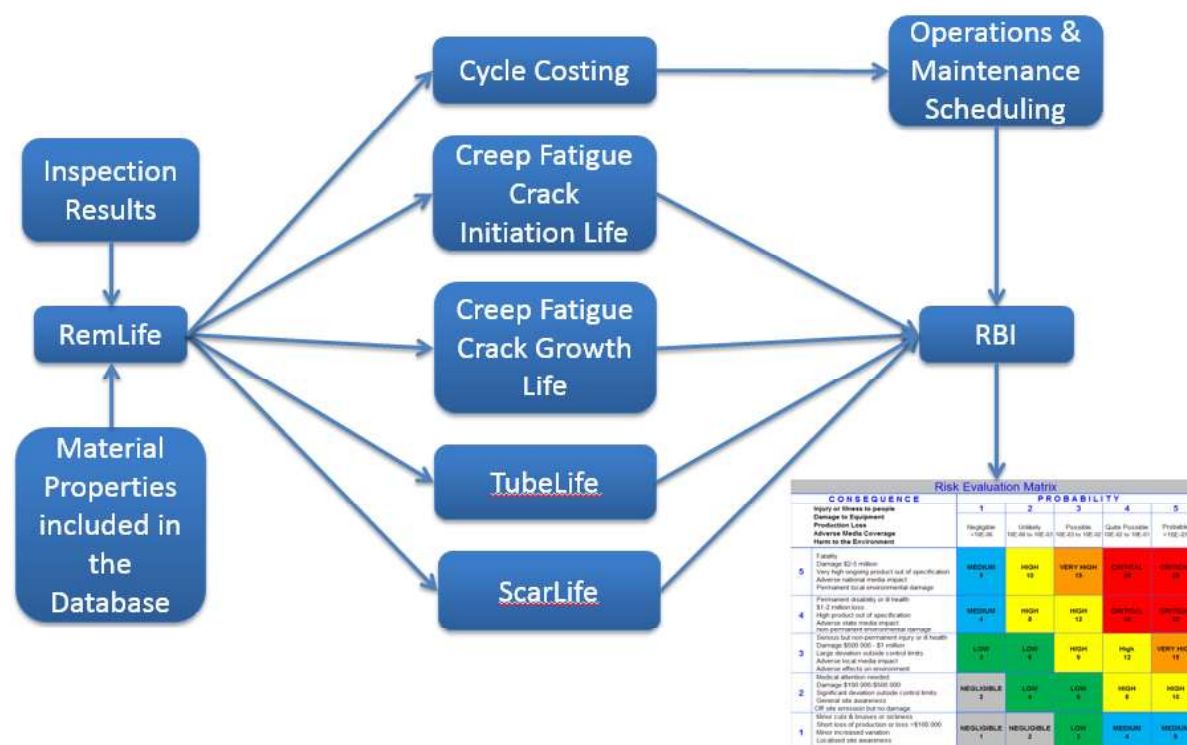


Figure 1 RemLife Program Flowchart General View

1.1 Design Codes

The core program is based on 28 generic shapes that can be modified to cover most unit components (Table 1). The code uses inverse design calculations based on the following standards, ASME VIII, Div1 and Div2, ASME III NB-NC, ASME B31.1, EN12593, EN13445, AS1228, BS1113, AS1210, AS4041. [1-7]

Thermal stress and primary stress concentration factors (SCF) are based on code solutions where available. For some components, detailed finite element analysis was used to generate SCF maps. For higher fidelity analysis, finite element results can be fed directly in using a user defined component.

Table 1 RemLife Components

General Shapes • General Cylindrical shape • Bend • Dished Ends • Unstayed Flat Ends • Reducer Headers • Header General • Header Regular Drilled • Header All Other Drilling • Header Combined Stresses Branches Cylindrical • Branch or Nozzle General • Branches Specific • Interacting Branches • Bifurcation (Lateral) • Y Piece • Hill Side Branch	Branches Spherical • Spherical Single Opening • Spherical Adjacent Branches Valves • Turbine Stop Valves • Boiler Stop Valves • Throttle Valve • Economiser Check Valve • General Valves Turbine Components • Steam Chest • Turbine Rotor • HP Outer Turbine Casing • IP Outer Turbine Casing • HP IP Inner Casing User Defined Component • User defined
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1.2 Thermal Stress

The methodology to generate thermal stress is based on a modified version of EN12952–2 it uses the concept of a metastable temperature gradient that develops during a start-up. The concept is shown in Figure 2, where after a certain time the temperature difference between the inside and outside wall becomes constant. RemLife extends the concept by fully deriving the “shape form” across the whole of the section[8].

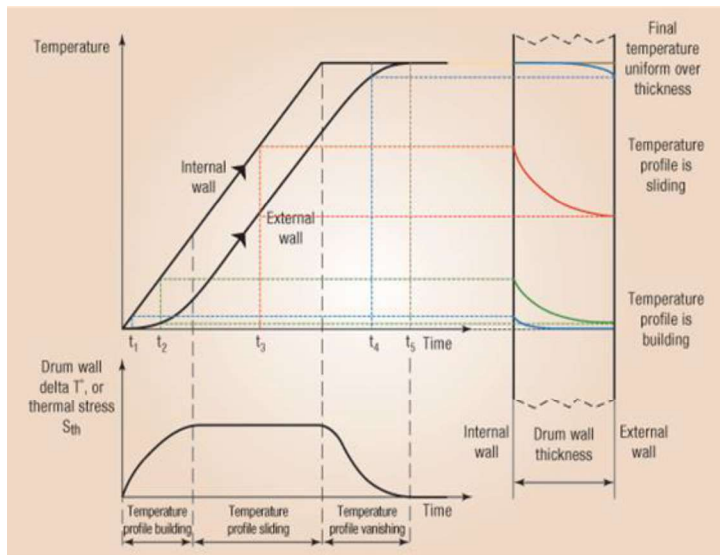


Figure 2 Temperature heat up profiles

In its simplest form, the metastable temperature can be characterised by a thermal shape function as, ψ [2]

$$\psi = \frac{1}{8} \frac{(u^2 - 1)(3u^2 - 1) - 4u^4 \ln u}{(u^2 - 1)(u - 1)^2}$$

The Maximum thermal stress at any time point (not including the SCF) is defined as;

$$\sigma = \frac{\alpha E}{1 - \gamma} \cdot \frac{VS^2}{a} \cdot \psi$$

V = rate of temperature change, degrees °C per min = $\Delta T / \Delta t$
 S = wall thickness, m
 α = thermal expansion coefficient
 E = Young's modulus, Pa
 γ = Poisson ratio
 ρ = density, kg/m³
 C = specific heat, J/kg.K
 λ = thermal conductivity, W/m.K
 r_o = outside radius, m
 r_i = inside radius, m
 $\alpha = \frac{\lambda}{C\rho}$ Thermal diffusivity
 $u = r_o / r_i$

For the point of maximum stress the metastable gradient V_m can be found from the following equation.

$$V_m = -\sigma[-1 + \rho] \cdot \frac{\alpha}{\alpha E S^2 \gamma}$$

The above methodology is conservative as it assumes that any temperature pulse remains for sufficient time to establish a constant gradient. This limits the maximum allowable ramp rates. A further refinement can be realized by using synthetic temperature pulses, which can be used to establish allowable ramp rates that are time dependent.

1.3 Fracture Mechanics

The fracture mechanics module contains 18 crack geometries (Table 2) based primarily on BS7910[9] which can be used in conjunction with the 28 generic components (Table 1).

Table 2 RemLife Fracture 2 Crack Geometries based on BS7910 and API 579[10]

- Through thickness flaw in plate
- Edge flaw in plate
- Surface flaw in plate
- Extended surface flaw in plate
- Embedded flaw in plate
- Corner flaw in plate
- Corner flaw in hole (double and single flaw)
- Internal surface in cylinder oriented circumferentially
- Internal fully circumferential flaw cylinder
- Internal surface flaw in cylinder oriented axially
- Extended internal surface flaw in cylinder oriented axially
- External surface in cylinder oriented circumferentially
- External fully circumferential flaw cylinder
- External surface flaw in cylinders oriented axially
- Extended external surface flaw in cylinders oriented axially
- Through thickness flaw in cylinder oriented axially
- Through thickness flaw oriented circumferentially
- Corner nozzle cracks

1.4 Material Properties

A large number of material properties are required to undertake a full creep-fatigue analysis, the program currently contains a database of 23 materials, including; Carbon Steels, Low Alloy Steels, Chrome Molly Vanadium, High Cr Steels, Stainless Steels, and Nickel based Alloys. The following standard and damage related properties are included;

Standard Material Properties

- Design Allowable
 - Design Allowable stress for required operating hours
- Elastic and Physical constants
 - Young's Modulus, Poisson's Ratio,
 - Thermal expansion, Diffusivity, Conductivity
 - Density
- Mechanical Properties
 - Monotonic tensile data (Room temperature and at operating temp)
 - Yield stress/0.2% proof stress (Room temperature and at operating temp)
 - Cyclic stress strain curves

Damage Related Properties

- Creep rupture data (virgin and aged if available)
- Creep ductility data
- Continuous cycling (fatigue) data
- Stress relaxation data
- Creep strain versus time curves (Forward Creep)
- Fatigue Endurance data.

2. METHODOLOGY

2.1 Procedure

The three dominant factors of component lifetime in high-temperature plants are material creep, low cycle fatigue, and thermal aging. Plant systems operating at high temperatures are subjected to load cycles, this depending upon the severity of the cycle, results in accumulating damage from cyclic (fatigue) and more steadily progressing (creep) mechanisms of deformation and fracture[11].

The prediction of material resistance to combined creep and fatigue is therefore critically important for both new design and life management of aging plants. Many sophisticated approaches are available to facilitate these types of assessment. They all form part of the wider scope of Fitness for service (FSS) guidelines. Cyclic damage where both creep and fatigue is active is a complex mechanism, and different components experience the damage at different points in the thermal cycle.

The most common methods of creep fatigue assessment are those based on code or guidance documents. These almost unilaterally follow a linear damage summation; although there are significant differences in the various implementation methods between the codes. Two primary methods are;

- Time fraction
- Strain fraction (ductility exhaustion)

These design codes and assessment procedures include; ASME III-NH [5], RCC-MRx[12] , R5[13], DDS[14], ASME VIII [6] and API579 [10]. In ASME III-NH, RCC-MR and DDS, calculations of creep damage are carried out using a time-fraction approach. The RCC-MRx and DDS procedure are similar; however, ASME III is considerably different in a number of features, one primary one is in the use of isochronous curves to estimate strain ranges. The R5 procedure is based on a ductility-exhaustion methodology and is currently the only code following this technique. A recently implemented ASME VIII code case uses another technique after Prager[15] based on Omega projection. These procedures generally use the results of creep tests to determine the creep damage-accumulation models, which are subsequently applied

to predict damage in creep-fatigue cycling and in particular strain-controlled dwells that arise during steady operation within a thermal cycle. For time-fraction approaches, the rupture strength of the material is used to calculate creep damage, while in the ductility-exhaustion approach; the creep ductility is used to calculate creep damage.

A number of other methods are also available that relate directly to the creep-fatigue test; these include – frequency-modified strain-range partitioning, strain-range partitioning, and energy expenditure. These latter methods are not currently included in high temperature design codes or assessment procedures.

The basic assessment steps are as follows, (Figure 3):

- Determine load history
- Calculate the stresses
- Determine the gross steady state creep damage
- Carry out shakedown tests, (excessive plastic deformation and incremental collapse)
- Determine the cyclic curves and from these the starting stress at state (dwell or hold stress)
- Check for creep fatigue significance, if not significant then the assessment would be complete.
- If creep fatigue significant then calculate localized creep damage
- Calculate the Fatigue Damage
- Combine the Creep and Fatigue Damage using the chosen methodology
- Assess whether crack initiation has occurred

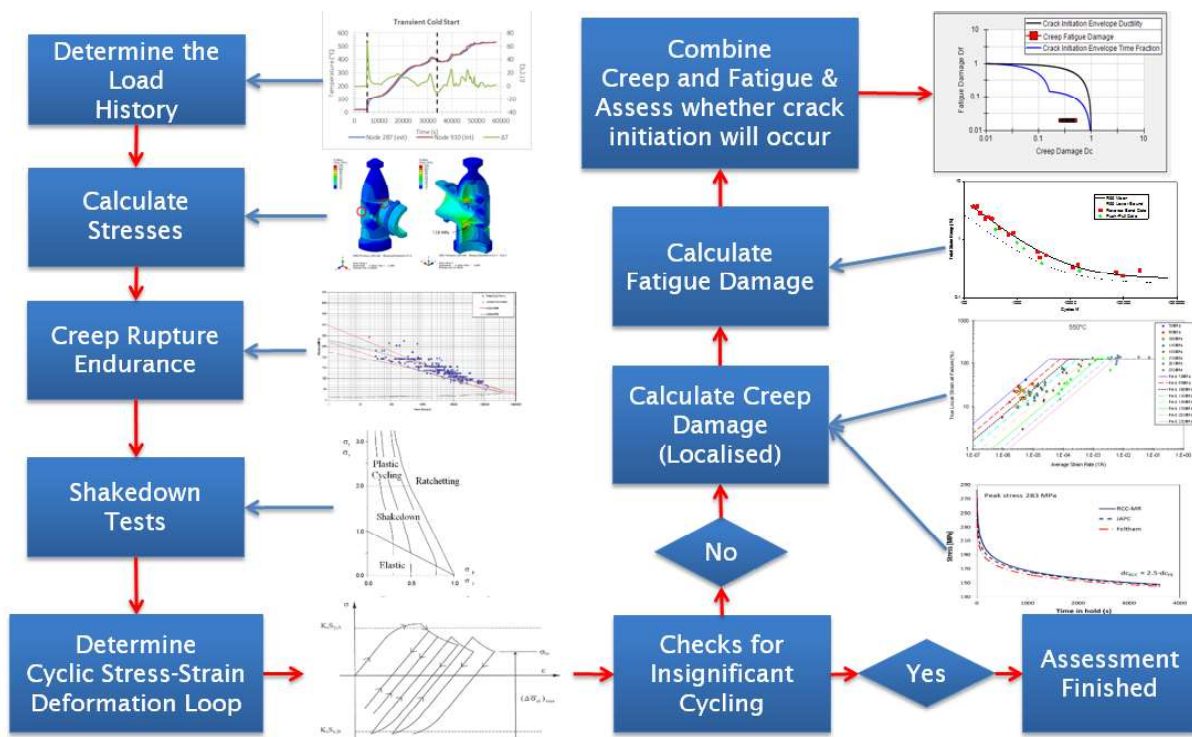


Figure 3 General flow-diagram for creep fatigue assessment

2.2 Creep Fatigue Interaction

Whichever assessment route is chosen, determining the extent, if any, of creep-fatigue interaction is one of the primary aims. This interaction occurs as a consequence of both primary and secondary stresses. These stresses may occur as a result of pressure loading, system loads as well as transient stresses in start-ups and shutdowns. The development of creep-fatigue damage depends upon temperature, strain range, strain rate and the hold or dwell time of the component at steady state operating conditions.

If the hold time (time at steady state) is negligible crack initiation and growth will be dominated by fatigue even in components operating at high temperature. For increasing hold time the creep damage becomes more important to a point where crack initiation and growth becomes fully creep dominated. At intermediate hold times, for example, under two shifting, the fatigue damage may interact with the creep damage.

When a hold time is applied at peak strains either in tension, in compression or under a combination of both, the stress will relax with time due to the conversion of the elastic strain into the inelastic strain when the total strain is kept constant, this causes increased creep damage and occurs at local features with high stress concentrations.

While many types of complex cycling are possible, two main cycles describe the most relevant features:

- In the first case, Figure 4a, the cycle results from compressive yield which can occur on start-up together with a primary stress to give a cycle that is within strict shakedown but still forms a hysteresis loop reset as the cycle is influenced by the creep strain on the stress-strain cycle, hence the dwell stress forms at the peak of the loop.
- The second cycle Figure 4b, occurs when the yield is exceeded on both ends of the cycle, this primary occurs when both the start-up stress and the shutdown stress are high. When this happens the dwell occurs at intermediate level.

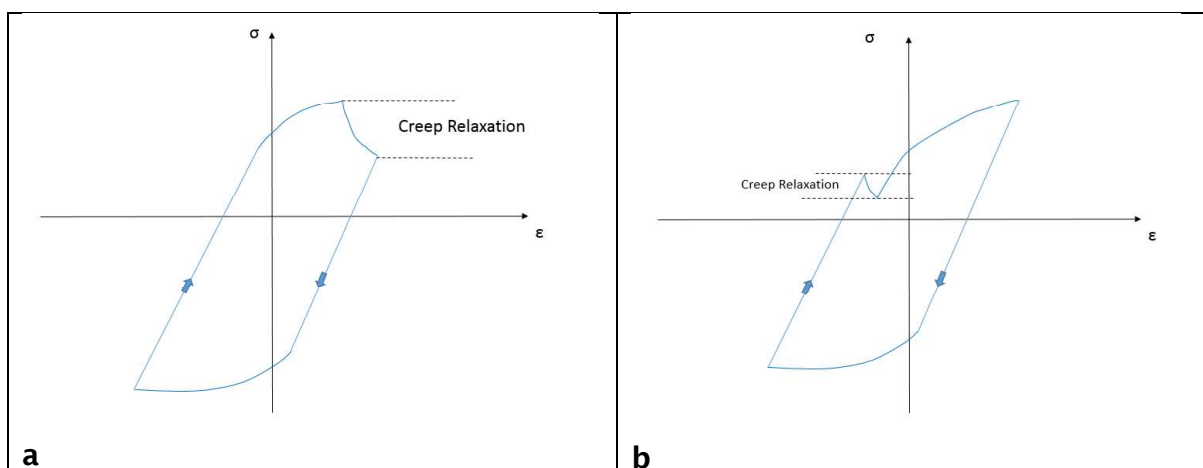


Figure 4 Creep fatigue loops

2.3 Creep–Fatigue Analysis

The methodology adopted for RemLife is based on the linear summation concepts incorporated into the R5 procedure. The actual calculations are involved; however, the basic procedure is that any arbitrary cycle can be separated into an elastic–plastic component and a creep relaxation component. The elastic–plastic component is responsible for low cycle fatigue and the stress relaxation causes creep damage by a process of ductility exhaustion.

Both components fatigue and creep contribute to the overall damage which is calculated using a linear damage rule. The fatigue damage per cycle, D_f is defined as the inverse of the continuous cycles to failure at some specified criterion.

$$D_f = \frac{1}{N_f(\varepsilon_t)}$$

where ε_t is the total strain range, and N_f is the fatigue endurance linked to a specific embryo crack size.

The creep damage per cycle, D_c , is calculated by means of the ductility exhaustion approach using.

$$d_c = \int_0^{t_h} \frac{\dot{\varepsilon}_c}{\varepsilon_f(\dot{\varepsilon}_c, T)} dt$$

The total damage for each type of cycle

$$\sum_{n=0}^{N_{CF}} (d_c + d_f)_n = D_c + D_f \leq D$$

A number of other creep damage approaches used by codes and standards are also incorporated into RemLife, these are shown in table 3, they include Time fraction, Stress modified ductility exhaustion and energy modified ductility exhaustion [16–23]. All methods have a degree of conservatism, and which method for any particular problem gives the lowest degree of conservatism can change. By incorporating these methods into RemLife it is possible to rapidly carry out sensitivity studies to determine the most accurate prediction. Depending upon the model chosen different interaction rules are used, this is illustrated in Figure 5. For example the R5 code uses linear interaction locus at (0.5, 0.5) for the creep and fatigue damage and hence total combined damage to failure is always 1, regardless of the material type. RCC–MRx uses a bi–linear interaction locus set at (0.3, 0.3). This means that the combined fatigue and creep damage that a component experiences during its service life should not exceed the (0.3, 0.3) line, while the ASME–NH code uses (0.15, 0.15) for ferritic, and (0.3, 0.3) for austenitic steels. For comparison a typical OEM diagram is included which

because of the hardness based approach and hence empirical data fit behaviour has an intersection point at $\sim (0.4, 0.05)$.

Table 3 Creep damage Integration Models

Creep Model	Damage Integration	Type	Applicability
$d_c = \int_0^{t_r} \frac{dt}{t_r(\sigma, T)}$		Time Fraction (TF)	ASME-NH, RCC-Mrx
$d_c = \int_0^{t_r} \frac{\dot{\epsilon}_c}{\epsilon_f(\dot{\epsilon}_c, T)} dt$		Ductility Exhaustion (DE)	R5 Current ductility approach Modified ductility approaches MDE
$d_c = \int_0^{t_r} \frac{\dot{\epsilon}_c}{\epsilon_f(\dot{\epsilon}_c, \sigma, T)} dt$		Stress Modified Ductility Exhaustion	R5 SMDE approach
$d_c = \int_0^{t_r} \frac{\dot{w}}{w_f(\dot{w}, T)} dt$		Energy Modified Ductility Exhaustion	SEDE, MSE and MSEDE approaches

Note: t_r is time rupture, T is temperature, σ is stress, $\dot{\epsilon}_c$ is the instantaneous strain rate, ϵ_f is the ductility to failure, w_f is the strain energy to failure and $\dot{w}$ is the instantaneous energy rate

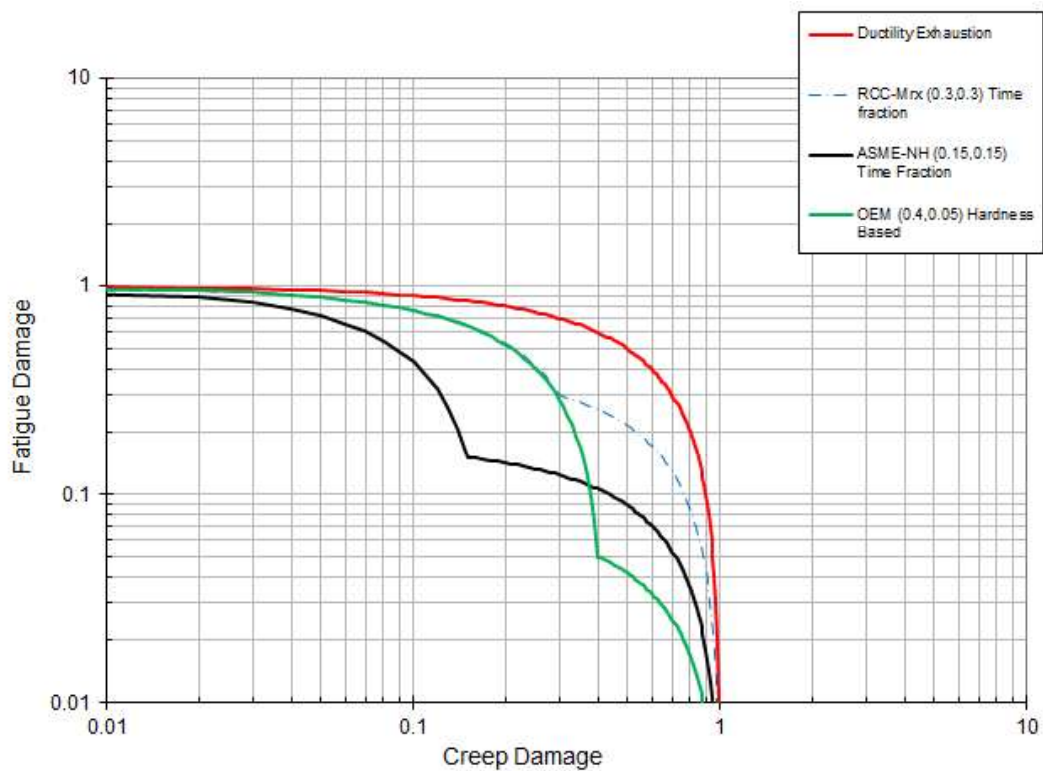


Figure 5 Creep Fatigue Interaction Diagram (Log-Log Scale)

3. CASE STUDY – COMPONENT EXAMPLE

To demonstrate an example analysis on a regular drilled header has been used. The header is constructed from 2.25 Cr 1 Mo materials (P22) with an operating pressure and temperature of 12 MPa (1.74 ksi) and 540 °C (1004 °F) respectively. The unit has seen a total of 200,000 hours of service life, and has a planned future life of 20 years at an assumed availability of 0.95. The unit currently operates as a base load station, with a total of 207 starts, (100 cold, 67 warm and 40 hot), Table 4, this represents approximately 8 starts per year. For future operation the station owner is considering a two shift type operation, because of the short interval these starts are considered to be hot starts, with a total additional starts of 300 per year.

Two specific questions were asked:

- Can the unit handle 300 hot start per years for 20 years
- Can we ramp the unit on hot starts to 4 °C/min (7.2 °F/min)

3.1 Geometry and Operating Conditions

The component has the following dimensions:

- Header Type = Regular Drilled
- Thickness = 60 mm (2.36 inch)
- Header IR = 170 mm (6.69 inch)
- Header OR = 230 mm (9.06 inch)
- Angle Between stubs = 30°
- Stub ID = 50 mm (1.97 inch)
- Stub Thickness = 10 mm (0.39 inch)
- Pitch = 250 mm (9.84 inch)
- Weld Leg = 6 mm (0.24 inch)

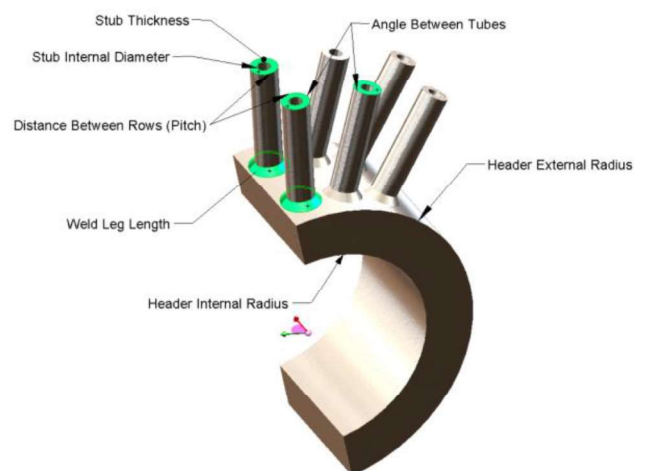


Table 4 Operating History

Parameter	Average Per Year	Hours/Starts
Total Service Hours	--	200,000
No. of Cold Starts	4	100
No. of Warm Starts	2	67
No. of Hot Starts	2	40
Total Starts	8	207

3.2 Transient Temperature Data

To characterise ramp rates from the unit, typical start-up data is obtained for the various types of starts. These are analysed using a Finite Difference thermal stress routine to generate the metastable ramp rate used in the component stress analysis module. An example of a typical cold start temperature data, instantaneous rate of changes and the calculated metastable gradient is shown in Figure 6.

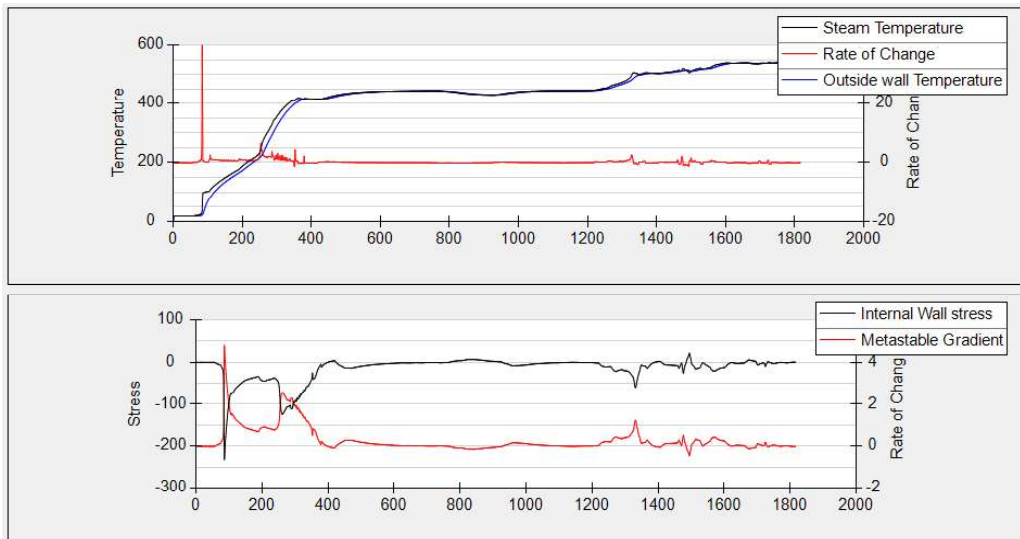


Figure 6 Temperature data for a cold start

Based on processed station data, maximum rate of temperature change for the starts (Cold, Warm and Hot) are listed in Table 3, with Cold starts giving the maximum rate of change of 4 °C/min (7.2 °F/min).

Table 5 Maximum Rates of Temperature Change during Transients

Start	Rate of Change
Cold	4.0 °C/min (7.2 °F/min)
Warm	2.0 °C/min (3.6 °F/min)
Hot	1.5 °C/min (2.7 °F/min)
Shutdown	-1.5 °C/min (-2.7 °F/min)

4. CASE STUDY – RESULTS

Four cases were analysed, Case 1 assumes that the unit will continue as a base load station with a current operating strategy of 8 starts per year and hence represents a typical based load operating pattern. Case 2 analysed a two shift strategy and assumes 300 hot starts per year. Case 3 again analysis the same two shift strategy, but with the ramp rate increased to 4 °C/min (7.2 °F/min). Case 4 undertakes a sensitivity analysis based on ramp rates and different creep-fatigue calculation methods.

4.1 Case 1

The initial base case was analysed, including the design or operating stress (also referred to as the rupture reference stress), the maximum primary stress caused by stress concentration effects and the thermal stresses due to start-ups and shutdowns (Table 4).

Table 6 Current Operating and Transient stress

Property	Calculated Values
Primary SCF	3.17
Secondary SCF	1.55
Ligament Eff	0.81
Operating Stress	49 MPa (7.1 ksi)
Maximum Primary	127 MPa (18.4 ksi)
Cold Start Stress	–94 MPa (–13.6 ksi)
Warm Start Stress	–47 MPa (–6.8 ksi)
Hot Start Stress	–35MPa (–5 ksi)
Shut down Stress	35 MPa (5 ksi)

Both hot and warm start thermal stresses were generally low with cold starts giving a compressive stress of 94 MPa (13.6 ksi). Peak pressure stresses due to the primary stress concentration factor were 126 MPa (18.3 ksi). This generates a stress range of 220 MPa (31.9 ksi) for cold starts. The reconstructed cyclic curve (Figure 7) shows a small amount of plastic strain is developed on the inside ligament corners of the header. Shutdown stresses were found to be lower than the maximum primary stress and hence the cyclic loop reconstruction follows Figure 4a.

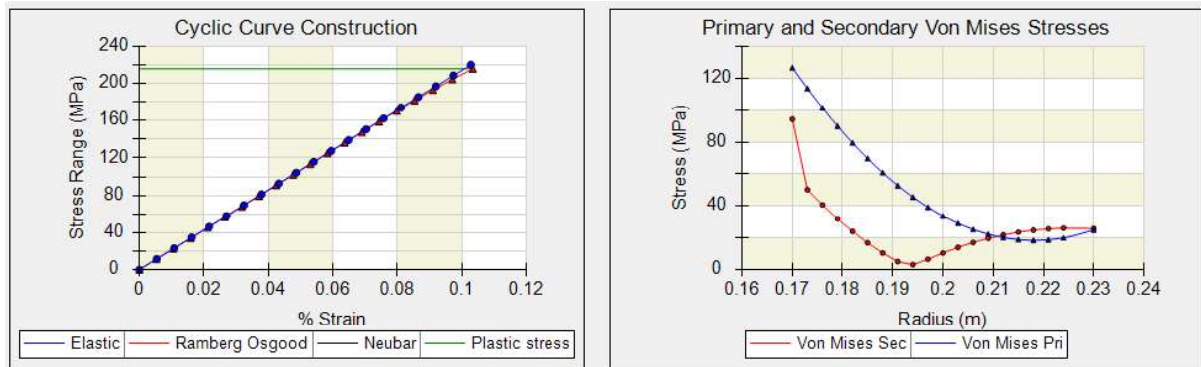


Figure 7 Cyclic Curve and Primary and secondary Von Mises stress

The calculated damage and endurance life are shown in Table 7. Both hot starts and warm starts were cyclic insignificant and creep damage is accumulated at the base rupture endurance level for these types of starts.

Table 7 Creep and Fatigue Damage Base Case

Type	Calculated Values
Creep Damage Cold (per cycle)	0.0022
Creep Damage Warm (per cycle)	NA
Creep Damage Hot (per cycle)	NA
Fatigue Damage	NA
Total Current Damage	43%
Creep Endurance life	59 years
Remaining Endurance life	38 years
Cycles to Consume Life	479
Remaining Cycles	272
Remaining Years to crack initiation	34 years

The total creep endurance life was 59 years and as a result the header has 38 years of remaining creep rupture life left. However, as damage is occurring due to cold starts, the analysis predicts crack initiation after 34 years or 272 more cycles of operation. The fatigue damage was minimal with localised creep damage dominating. The damage envelope for this case is displayed in Figure 8, which illustrates that under current operating strategy, the component has sufficient life for the required future service life. The results show that currently 43% of the localised life has been used.

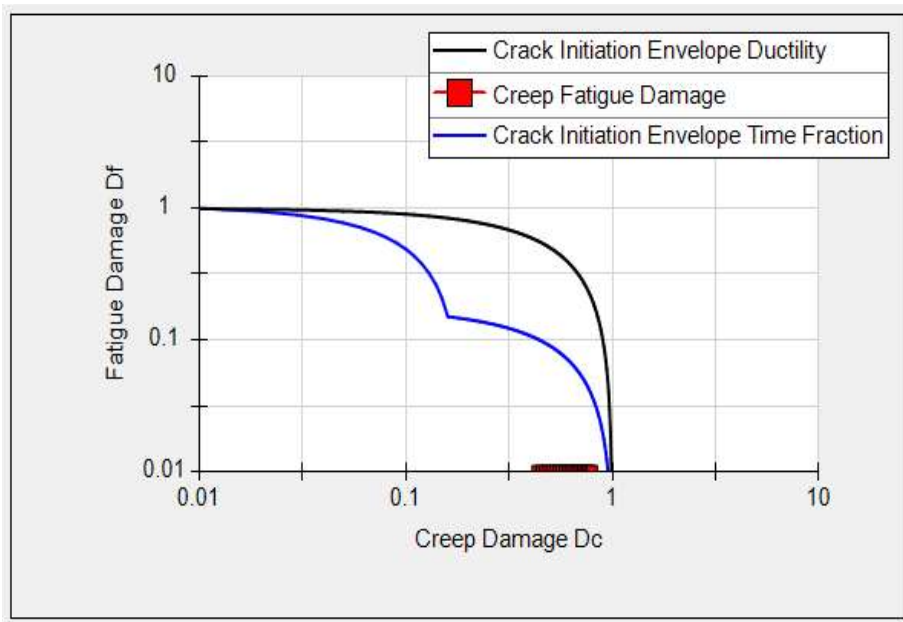


Figure 8 Creep Fatigue Damage Envelope

4.2 Case 2

The second analyse was simulated by changing to a two shift operating strategy with ~300 hot starts per year. Based on the previous case, the hot start was found to be cyclic in-significant. Over twenty years base on two shifting over 6000 hot starts will be accumulated. The results show (Table 8) that the component has 8874 remaining cycles or 29 years. Hence based on hot starts of 1.5 °C/min (2.7 °F/min) the component can operate in two shift mode with little impact.

Table 8 Creep and Fatigue Damage Base Case

Type	Calculated Values
Cycles to Consume Life	9081
Remaining Cycles	8874
Remaining Years	29 years

4.3 Case 3

Case 3 is the same as case 2 and hence 300 hot starts per year is used however; the ramp rate was increased to 4 °C/min (7.2 °F/min). Using these ramp rates only 612 cycles remain, and using this two shift strategy would mean that crack initiation is likely after only a further 2 years of operation. This is considered to be unacceptable.

Table 9 Creep and Fatigue Damage Base Case

Type	Calculated Values
Cycles to Consume Life	819
Remaining Cycles	612
Remaining Years	2 years

4.4 Case 4 Sensitivity Study

To understand the component response, a sensitivity analysis is carried out based on currently projected operation of a relatively small number of starts per year ~10, and then one with ~300 starts per year.

This is automated within the program, which rapidly sweeps across a range of ramp rates and in this case a second response variable, the percentage change in starts.

The resultant 3-D projection maps are shown in Figure 9, the left hand image displays the 10 starts per year and the right hand image 300 starts per year (the plane represents the required life). At 10 starts with percentage changes of $\pm 100\%$ show a viable operating windows that would allow changes in the ramp rate from the current $1.5\text{ }^{\circ}\text{C}$ ($2.7\text{ }^{\circ}\text{F}/\text{min}$) to levels approach the required $4\text{ }^{\circ}\text{C}/\text{min}$ ($7.2\text{ }^{\circ}\text{F}/\text{min}$). For 300 starts per years the viable envelope is constrained below $4\text{ }^{\circ}\text{C}/\text{min}$ ($7.2\text{ }^{\circ}\text{F}/\text{min}$).

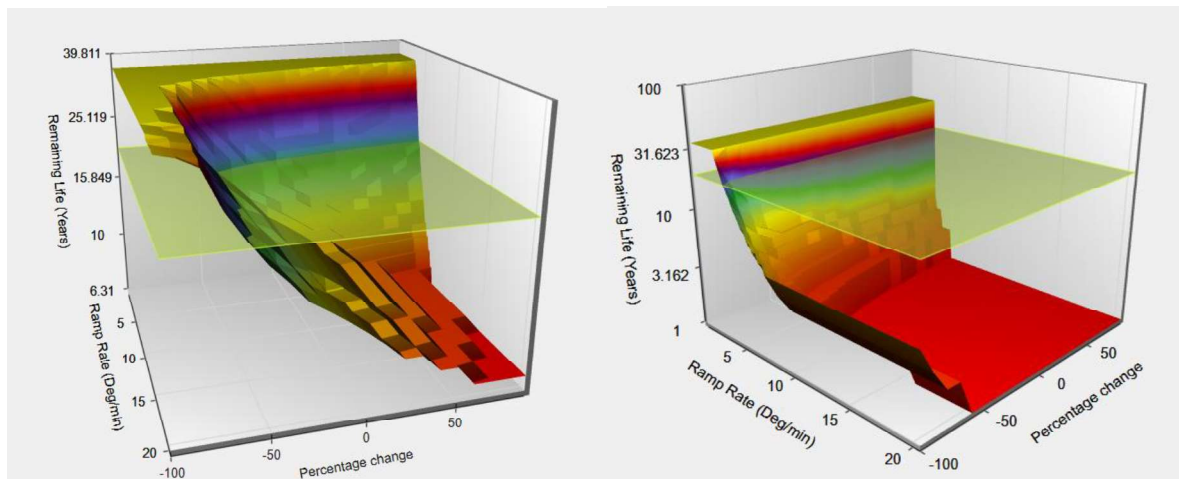


Figure 9 Contour showing the effects of percentage change on number of starts (left 10 starts, right 300 starts basis)

2-D plots are illustrated in Figure 10 and 11, for the 10 and 300 start operation. A sensitivity study is performed using time fraction, ductility exhaustion and energy based methods. For the 10 start operation a viable ramp rate of between 4 and $6.5\text{ }^{\circ}\text{C}/\text{min}$ (7.2 – $11.7\text{ }^{\circ}\text{F}/\text{min}$) can be used, without risk of cracks initiating within the required service life.

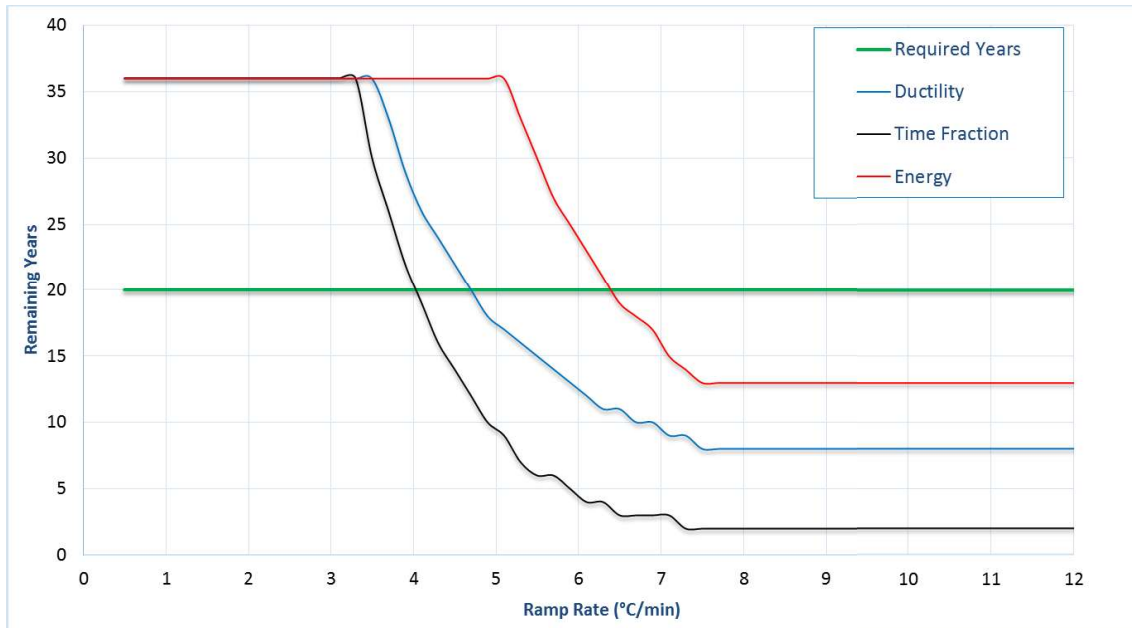


Figure 10 Projected life (years) as a function of ramp rate in °C/min ~10 starts/years

At 300 starts per year the acceptable ramp rate decreases with a range of 3 to 3.8 °C/ min (5.4– 6.8 °F/min).

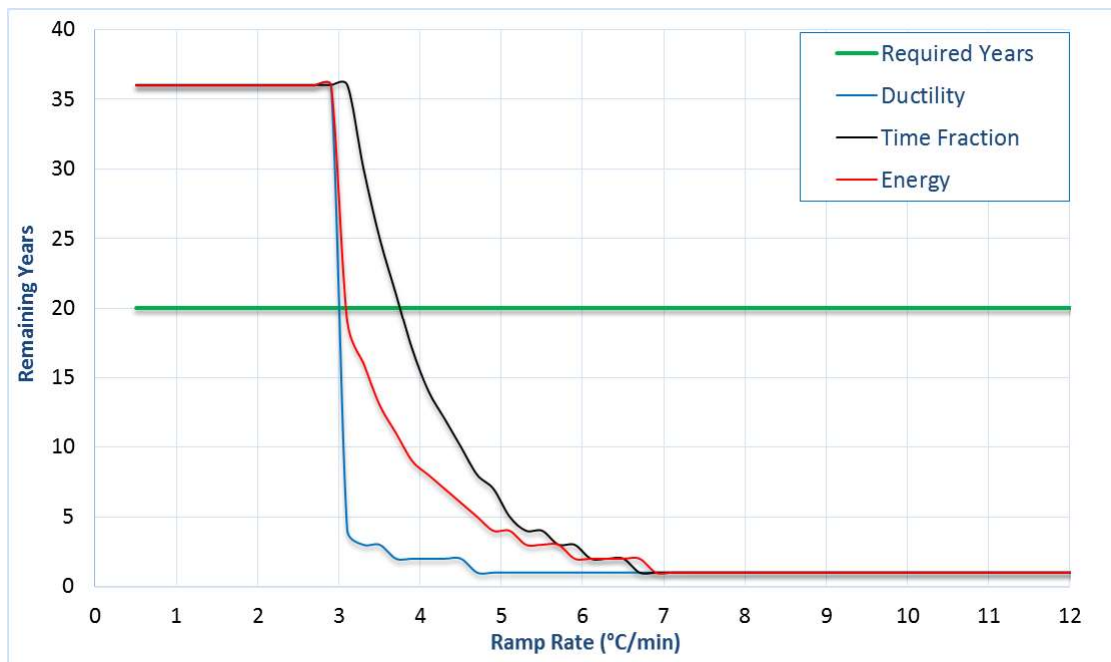


Figure 11 Projected life (years) as a function of ramp rate in °C/min ~300 starts/year

5. DISCUSSION AND CONCLUSIONS

For the assessed header, ramp rates less than 3 °C/min (5.4 °F/min) show minimal effect on the life of the component as the component operates in base rupture and cycling damage would be insignificant. For ramp rate above 3 °C/min (5.4 °F/min), the life of the component decreases rapidly as a result of creep-fatigue ductility exhaustion, (Creep dominated). At 4 °C/min (7.2 °F/min) the sensitivity study showed that the life has reduced to well below the required 20 years.

Based on this assessment, the header can feasibly be ramped at rates up to ~3.0 °C/min (5.4 °F/min) for the required two shifting operation, twice the current 1.5 °C/min (2.7 °F/min). Any faster than this would result in unacceptable damage accumulation. It is also clear that the current cold start ramp rates are approaching the “cliff edge” (Figure 10 and Figure 11), to even further extend life a reduction of 1 °C/min (1.8 °F/min) in the cold starts would have a significant beneficial impact.

Although this cycling regime is successful for this component it would be necessary to analyse all components in the high temperature system before approving such an operating strategy.

RemLife allows rapid scoping and sensitivity of components to assess the effects of current and future operations. While not covered in this paper, but once cracks have initiated RemLife has the ability to rapidly assess the likely crack growth rates of initiated defects and the associated remaining life to critical crack size and final failure.

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