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Assessment of Negligible Creep Curves for High-Temperature Nuclear Materials

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1. Introduction

Mod. 9Cr-1Mo (hereafter Grade 91) steel is one of the materials envisaged for the Reactor Pressure Vessel (RPV) of Very High Temperature Reactors (VHTR), because it is better than other ferrite steels. Also, type 316L(N) steel, a low-carbon, nitrogen-enhanced version of 316 molybdenum-bearing austenitic stainless steel, which is the material of reactor vessel for Sodium-cooled Fast Reactors (SFR) has excellent strength comparing with other austenite stainless steels. For the RPV materials, to avoid the implementation of a surveillance program covering the monitoring of the creep damage throughout the whole life of the reactor, it is recommended to operate within the negligible creep regime [1]. Thus, the negligible creep curves for the two materials should be investigated to judge disregard creep as design criterion during normal service operation if the temperature, stress and time limits of negligible creep are respected. No negligible creep curve is proposed in the present edition of the RCC-MRx for Grade 91 and creep is only said to be negligible for temperatures less than 375°C, whatever the hold time is [2].

In this study, a detail description of the negligible creep curves is preliminarily presented, and then, the negligible creep curves for the Grade 91 and 316L(N) steels are proposed using reference stress (σ_{ref}) from the tensile and creep rupture data given in RCC-MRx code. Finally, the proposed negligible creep curves are assessed by comparing with RCC-MRx curves.

2. Description of negligible creep curves

For simplified design of components operating at high temperatures it is recommended to design in the No Creep (NC) or Negligible Creep (NEC) temperature regimes of the material. Negligible creep curves are set based on generating time and temperature of damageable creep strains of each material, and provide diagrams which present the relationship between temperature and accumulated operation time. Creep design area is settled for each material. In case the accumulated operation time at the temperature is short, non-creep design is adopted. The judgment is carried out by the following equation [3];

$$\sum_{i=1}^{n} \frac{t_i}{t_{id}} \leq 1 \qquad (1)$$

where t_i is duration time at a high temperature, and t_{id} is maximum duration without significant creep at the temperature.

To avoid expensive implementation of surveillance programs and/or frequent inspections of (monitoring creep damage) required for components operating in the significant creep regime it is recommended to design for service below the NC temperature or the time dependent Negligible Creep temperature (T_{NEC}). For nuclear components, it is possible to disregard creep as design criterion during normal service operation if the temperature, stress and time limits of negligible creep are respected. However, it is not easy to define these limits reliably in the temperature range where creep behavior (time to strain and/or rupture) is traditionally not tested.

Fig. 1 shows a negligible curve describing the relationship of time and temperature limits below which accumulated creep strain and damage is insignificant at a specified reference or design stress. A blue line indicates a negligible curve (T_{NEC}). At the below temperature of the negligible curve, time independent design is done, and at the above temperature, time dependent design is done. At much longer time, creep is developed and finally failed, as indicated with a black line. Also, a red line is NC regime, at the below temperature, time independent design is considered. The NC temperature limits are given for various materials in Table 1. Time independent rules for design can be applied if the design temperature of a component is restricted below the negligible creep temperature (T_{NEC}).

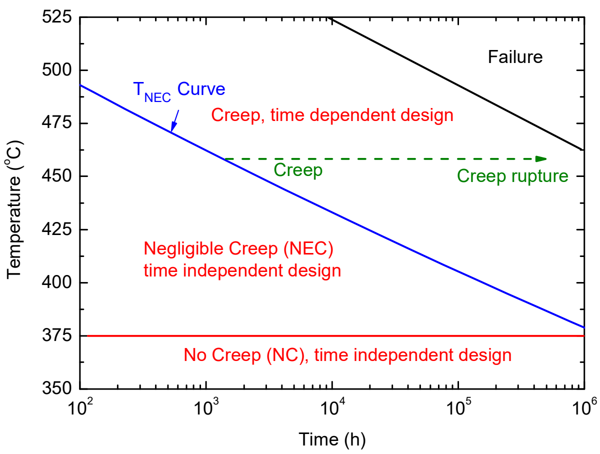

Fig. 1. A detail description for negligible creep curve showing the relationship temperature and time

Negligible creep criteria can be given in ASME [4] and RCC-MRx [5] codes. For Class 1 component, applicable rules in the ASME code are given in subsection NB. These rules are applicable if metal temperatures do not exceed the temperature limits of Section II part D Table 2A. The maximum temperature limits for various metals are summarized in Table 1. As listed in Table 1, type 316L(N) austenitic stainless steel of 425°C is higher than Grade 91 martensite stainless steel of 370°C. This temperature limit depends on creep strength of metals.

Table 1 Temperature limits for various metals in ASME code

Material	Maximum temperature limit, T_{max} (°C)
Carbon steel and low alloy steel	370
Martensitic stainless steel	370
Austenitic stainless steel	425
Nickel-chromium-iron steel	425
Nickel copper	425

3. Proposition of negligible creep curves

A negligible curve for Type 316L(N) steel are found in in the nuclear design code RCC-MRx. However, for the ferritic/martensitic steel of Gr. 91, there is currently no T_{NEC} curve available RCC-MRx.. Negligible creep curves for the Grade 91 and 316L(N) steels are proposed using reference stress (σ_{ref}) from the tensile and creep rupture data given in RCC-MRx code. The reference stress has been set at 2/3 R_{p02} for Grade 91 and 1.5 R_{p02} for type 316L(N). Hence, R_{p02} is defined as yield stress (MPa) at specified temperature. This study applied a semi-graphical method for determining the T_{NEC} curve. This method uses tabulated values of creep rupture strength at specified rupture times and temperatures as well as the corresponding yield stress for the definition of the T_{NEC} curve.

For Grade 91 steel, the yield strength $R_{p0.2}$ and the creep rupture strengths $R_{u/t/T}$ (creep rupture strength (MPa) to time t at temperature T) of durations of 1,000, 3,000, 10,000, 30,000, 100,000 and 300,000h are divided by the same correction factor SCF (stress correction factor) of 1.5. The reference stress has been defined as $R_{p0.2}$ / 1.5 and the safety on creep rupture is induced by keeping the rupture time the same but lowering the stress by $R_{u/t/T}$ /1.5. The modified rupture and yield curves are plotted against temperature to localize the intersection points. The determination of intersection points is shown in Fig. 2. From the intersection points of Fig. 2, the T_{NEC} curve of Grade 91 steel can be obtained, as shown in Fig. 3. A blue line indicates its negligible curve.

For type 316L(N) steel, similarly, the same manner used for Grade 91 steel is applied. The reference stress is applied for 1.5 R_{p02} and the creep rupture strengths $R_{u/t/T}$ are divided by the same SCF of 1.5. From the intersection points of Fig. 4, the T_{NEC} curve of type 316L(N) steel can be obtained finally, as shown in Fig. 5. The three negligible curves are presented herein for different reference stresses of 1.5 S_m, 1.5 $R_{P02(min)}$ and 1.5 $R_{P02(moy)}$ tabulated in RCC-MRx code. Hence, $R_{p02(min)}$ is minimum yield strength at 0.2% offset, $R_{p02(moy)}$ is average yield strength at 0.2% offset, and S_m is maximum allowable stress.

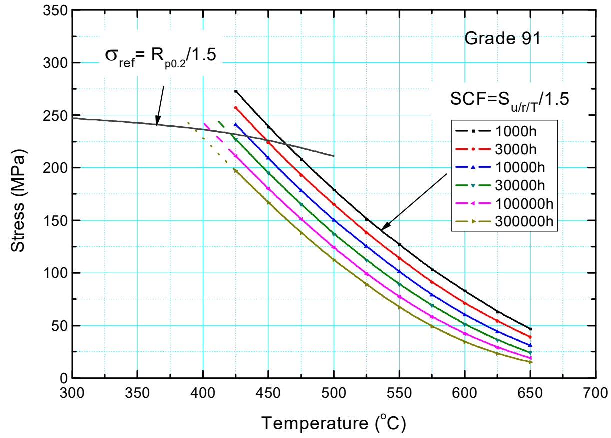

Fig. 2. Creep rupture properties and yield strengths corrected by reference and creep strength correction factors for Grade 91 steel.

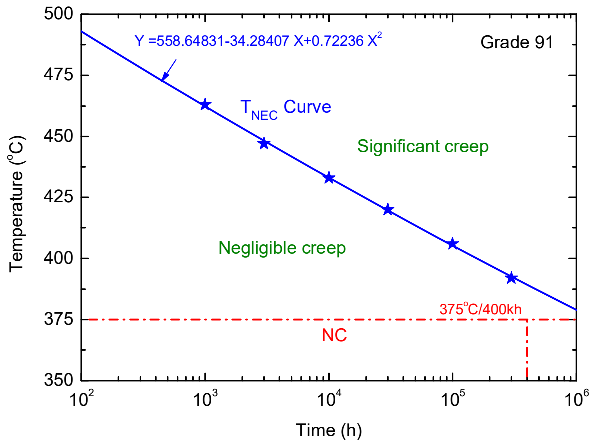

Fig. 3. T_{NEC} curve obtained for Grade 91 steel

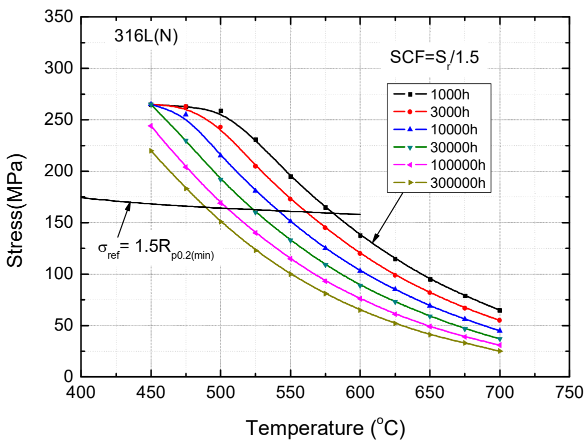

Fig. 4. Creep rupture properties and yield strengths corrected by reference and creep strength correction factors for type 316L(N)steel

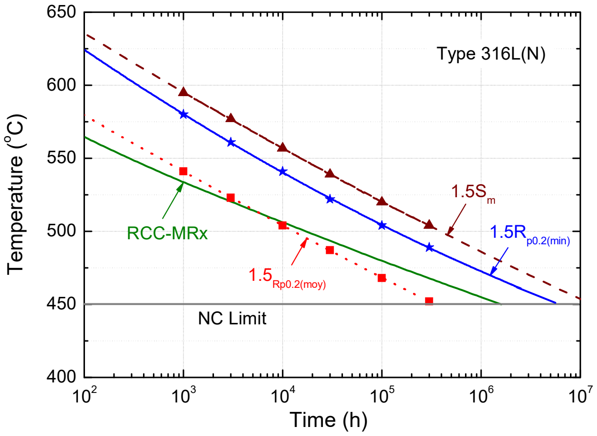

Fig. 5. T_{NEC} curves obtained for type 316L(N) steel

As shown well in Fig. 5, it is found that a negligible curve (red line) defined by reference stress of $R_{p02(moy)}$ exhibits good match with RCC-MRx. It is thus assumed that RCC-MRx curve is conservative. In addition, it is clear that the negligible curve depends on the reference stress significantly. In the safety viewpoints, it is reasonable to determine conservative negligible curve of a lower value in reference stress.

4. Conclusions

Preliminarily, a negligible creep curve was described in detail, and then, the negligible creep curves for Grade 91 and 316L(N) stainless steels were proposed by defining reference stress (σ_{ref}) values using tabulated tensile and creep rupture data presented in RCC-MRx code. It appeared that the negligible curves depend on the reference stress significantly. For type 316L(N), it was found that a negligible curve defined by reference stress of $R_{p02(moy)}$ exhibited good match with RCC-MRx code.

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