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Investigation of the Stress Intensity Limits of ASME Section III Div.5 for Structure Design Criteria of SFR Fuel Assembly

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1. Introduction

Sodium-cooled Fast Reactor (SFR) is one of the 4[th] generation reactors that uses liquid sodium coolant. The SFR fuel assembly is considerably different from the light water reactor (LWR) fuel assembly in its shape, dimension, material, and the environment except the overall length (~ 4.5 m). These affect the mechanical design of the fuel assembly components. And thus, appropriate structural design criteria should also be chosen to incorporate the specific design conditions of the SFR fuel assemblies. Among them, the temperature is one of the most crucial conditions to be concerned because the sodium coolant temperature is normally more than 500℃ which is much higher than that of the LWR (< 350℃). This implies that a thermal creep should be significantly considered in the SFR fuel assembly mechanical design.

In addition to the high temperature condition, an irradiation swelling is also an important behavior that the SFR fuel assembly material should accommodate. To incorporate the temperature and irradiation impacts, the material of the fuel assembly components is presently determined to be made of HT-9, the ferriticmartensitic steel.

In this paper, the ASME Sec. III Div. 5 (referred to as ‘Div. 5’ hereinafter) [1], which was developed for a ‘high temperature reactor’, is considered as one of the structural design criteria for the mechanical design of SFR fuel assemblies. However, the stress intensity limits of the HT-9 material are not provided in the Div. 5. Therefore, it is attempted here to build the stress intensity limits of HT-9 steel at the temperatures of concern by using the formulae provided for the mechanical properties of HT-9.

2. Structure Design Criteria of ASEM Div.5

Different from Div. 1 Subsection NB, which is applied for the LWR fuel assembly mechanical design, Div. 5 considers time-independent and time-dependent stress intensity limits, i.e. S_m and S_t, respectively. In comparison with S_m, S_t is associated with the creep behavior of the material.

For strength design, temperature and pressure data as a function of fuel assembly duct`s height are used to calculate the stress intensities such as P_m and P_b. The section geometry parameters, K and K_t need to be determined as well. The calculation is carried out for both normal and transient conditions. The duration time of the transient and duty cycles of each off-normal event are also necessary.

After P_m, P_b, K, K_t for each off-normal event as well as normal operation condition are evaluated, they are compared with S_m and S_t such as

$$P_m \leq S_{mt}$$
$$P_m + P_b \leq KS_m \quad (1)$$
$$P_m + P_b / K_t \leq S_t$$

and, $S_{mt} = \mathrm{Min}[S_m, S_t]$.

SFR nuclear fuel assembly`s outlet temperature and initial core is 521~564℃, and the equilibrium cycle core is 531~575℃. So, the temperature range to which the fuel assembly mechanical components are subject to is considered as 450~650℃.

3. Analysis of HT-9`s S_m and S_t

3.1 On S_m

S_m is the lowest stress intensity value at a given temperature among the time-independent strength quantities that are listed in Section II, Part D, Subpart 1 as criteria for determining S_m; in this Subpart, the S_m values are extended to evaluated temperatures by using the same criteria. S_m is defined as follows.

$$S_m = \mathrm{Min}\,[1/3\times\sigma_{u.min}\,@\mathrm{RT},\ 1/3\times\sigma_u\,@\mathrm{T},\ 2/3\times\ \sigma_{ys.min}\,@\mathrm{RT},\ 2/3\times\sigma_{ys}@\mathrm{RT}] \quad (2)$$

where σ_u and σ_{ys} are the ultimate and yield strengths, respectively. RT means room temperature.

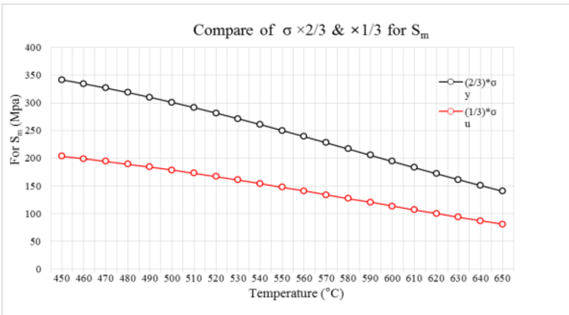

Fig. 1. S_m data as a function of temperature obtained from the formulae.

However, S_m values of HT-9 are not provided in the ASME code. Those are obtained by using the relevant formulae for the yield and ultimate strengths. The calculated S_m values were compared with the experimental results and validated. Finally obtained S_m values are given in Fig. 1.

In conclusion, S_m of HT-9 is determined from the ultimate strength (i.e., $1/3\times\sigma_u$) for the concerned temperature condition of the present SFR.

3.2 On S_t

S_t is a temperature and time-dependent stress intensity limit; the data considered in establishing these values are obtained from long-term, constant load, uniaxial tests. For each specific time, t, the S_t values shall be the lesser of

(a) 100% of the average stress required to obtain a total (elastic, plastic, primary, and secondary creep) strain of 1%;
(b) 80% of the minimum stress to cause initiation of tertiary creep; and
(c) 67% of the minimum stress to cause ruptures

These are referred to as the candidates 1, 2 and 3 in order. The primary, secondary and tertiary creep equations are given in the form of $f(\sigma^n, T, \text{constant})$.

Fig. 2 shows a schematic behavior of creep curve [2]. As for the tertiary creep, 0.2% offset from the secondary creep is adopted to find the onset of tertiary creep.

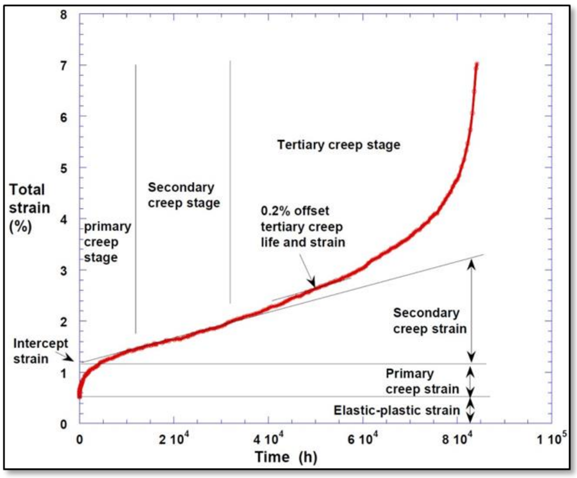

Fig. 2. Schematic of creep curve [2].

In addition, the elastic and plastic strains are ignored for Candidate 1. For Candidate 3, a factor of 0.866 is multiplied to change the hoop stress obtained from the formulae to the equivalent stress.

The result for the temperature and time ranges is given in Fig. 3. The detail values of S_t are not inserted. Rather, the area governed by each candidate is illustrated to show the overall view.

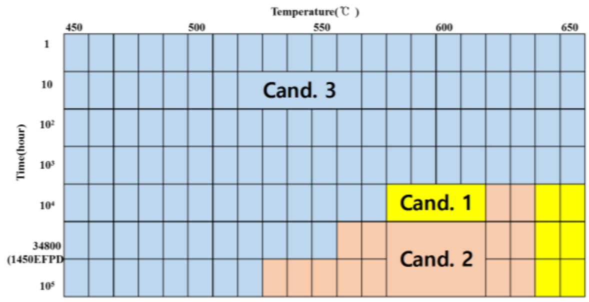

Fig. 3. Table of S_t candidate`s distribution.

As we can see the Fig. 3, candidate 3 rules the table in 1000 hours and less of all temperature range and all time range with 520℃ and less. And, on 530℃~630℃ with 10000 hours or more, candidate 2 rules the great part of that scope. And, candidate 1 is governing on 640℃ or more with 10000 hours or more, and especially on 580℃~610℃ and 10000 hours range.

On the most interested scope, 34800 hours(EFPD), candidate 3 rules under 560℃, and candidate 2 rules on 560℃~640℃. On 640℃ or more, candidate 1 rules the table.

3.3 On S_{mt}

According to the ASME code, S_{mt} is determined as the lesser value of S_m and S_t. Therefore, S_{mt} depends on the temperature and duration time. For instance, Div. 1 Subsection NH includes the S_{mt} data of 9Cr-1Mo-V such as given in Fig. 4 [3]. It is apparent that the S_{mt} is S_m when the temperature is lower and time is shorter. As the temperature increases and the time longer, S_t becomes S_{mt}.

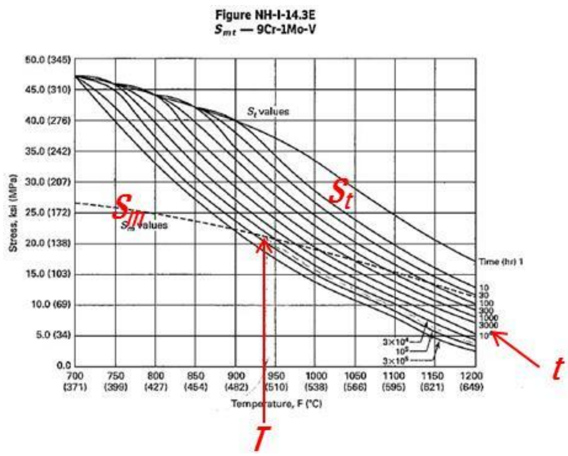

Fig. 4. S_{mt} Curve of 9Cr-1Mo-V [3].

Since S_m and S_t were obtained in the previous sections, we can draw S_{mt} for HT-9, which is shown in Fig. 5. It is found that S_m becomes S_{mt} when the temperature is lower than around 470℃ regardless of the duration time. However, S_t can be S_{mt} as the temperature exceeds 470℃ and the time is longer. It is noted that the S_t values at lower temperature (say, < 400℃), the necessary time for material creep should be incorporated, which cannot be incorporated in Fig. 5 presently. This is why each curve of S_t cannot converge to a single point which is shown in Fig. 4.

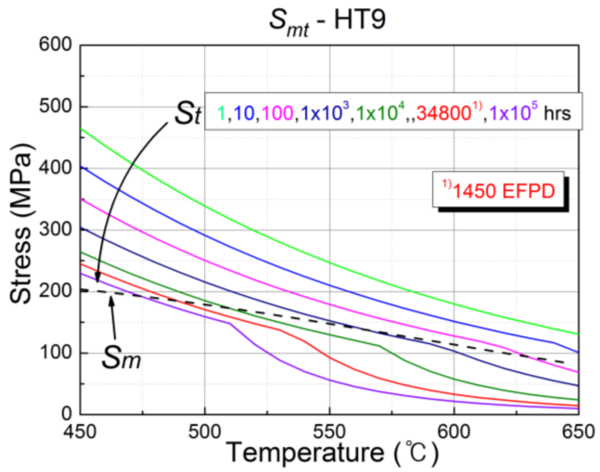

Fig. 5. Curve of S_{mt} (using factor 0.866).

3. Conclusions

In this paper, the stress intensity limits, S_m and S_t of HT-9 were built for the structural criteria of an SFR fuel assembly. S_m is obtained from the ultimate strength. As for S_t, it is more complicated because of its dependency of time duration in addition to temperature.

Following the definition of S_{mt}, the method in the ASME Sec. III Div. 1, Subsec. NH was consulted. We found that the S_m is adopted as S_{mt} under the temperature about 470℃ which is relatively low temperature range and over 470℃ with relatively short time duration as 1000 hours. And the S_t is adopted as S_{mt} at over 470℃ and long time duration over 34800 hours, and over 520℃ and 10^4 hours too. And at over 570℃ and 1000 hours, and at over 630℃ and 100 hours, S_t is also adopted for S_{mt}.

To use the present result as design criteria, a stringent examination needs to be carried out, because those are calculated from the formulae of HT-9 without an experimental validation. Therefore, an experimental work on the mechanical properties of HT-9 will be necessary.

ACKNOWLEDGMENT

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REFERENCES

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