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Preliminary application of the draft code case for alloy 617 for a high temperature component

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Abstract

The ASME draft Code Case for Alloy 617 was developed in the late 1980s for the design of very-high-temperature gas cooled reactors. The draft Code Case was patterned after the ASME Code Section III Subsection NH and was intended to cover Ni-Cr-Co-Mo Alloy 617 to 982°C (1800°F). But the draft Code Case is still in an incomplete status, lacking necessary material properties and design data. In this study, a preliminary evaluation on the creep-fatigue damage for a high temperature hot duct pipe structure has been carried out according to the draft Code Case. The evaluation procedures and results according to the draft Code Case for Alloy 617 material were compared with those of the ASME Subsection NH and RCC-MR for Alloy 800H material. It was shown that many data including material properties, fatigue and creep data should be supplemented for the draft Code Case. However, when the evaluation results on the creep-fatigue damage according to the draft Code Case, ASME-NH and RCC-MR were compared based on the preliminary evaluation, it was shown that the Alloy 617 results from the draft Code Case tended to be more resistant to the creep damage while less resistant to the fatigue damage than those from the ASME-NH and RCC-MR.

Keywords: Creep-fatigue; High temperature design code; Alloy 617; Alloy 800H; Very high temperature reactor; Hot gas duct

1. Introduction

The draft Code Case for Alloy 617 [1] was prepared for the design of alloy 617 nuclear components at up to 982°C (1800°F). The draft Code Case is a modification from ASME Section III Subsection NH [2] by a special task force of the ASME subgroup on an elevated temperature design. The primary intended application of the code case is a very high temperature reactor (VHTR).

KAERI (Korea Atomic Energy Research Institute) has been developing the NHDD (Nuclear Hydrogen Development and Demonstration) plant which has a capacity of 200MW (thermal) and core outlet temperature of 950°C [3]. A core outlet temperature as high as 950°C is needed for efficient production of hydrogen. Materials of potential interest include nickel Alloy 800H, Alloy 617 and Hastelloy X [4].

The draft Code Case which was intended to be a stand-alone provides design rules only for alloy 617. However, the code development work was suspended at the end of the 1980s due to a lack of support and interest.

Many data should be supplemented for the draft Code Case so that a design by analysis (DBA) using the draft Code Case could be done reliably. The DBA rules for the lower temperatures, which correspond to ASME code Subsection NB in the case of Subsection NH, are not provided and the isochronous curves for the temperature range of 427°C to 649°C are not provided.

Nevertheless, it would be useful to carry out a preliminary application of the draft Code Case to a high temperature structure, in order to define what technical items should be developed further, what technical issues on the draft Code Case are, what actions should be taken to make the draft Code Case complete, and

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finally to compare the design evaluation procedure and results according to the ASME-NH and RCC-MR [5] codes.

In the high temperature design, the load controlled stress limits, strain limits and creep-fatigue damage limits should be satisfied. In an actual design evaluation, however, creep-fatigue damage limits are usually more critical than the other two limits [6-10].

In this study, a preliminary evaluation of the creep-fatigue damage for a hot duct pipe structure which connects the reactor system to the power conversion system was carried out according to the draft Code Case for Alloy 617. In addition, a design evaluation according to the ASME-NH and RCC-MR code for the same structure made of alloy 800H was carried out, and the analysis results were compared. Since the draft Code Case deals with only Alloy 617 material, and the ASME-NH and RCC-MR code do not deal with Alloy 617, a direct comparison of the design codes is not possible. In this study it is intended to go through the evaluation according to the draft Code Case, and to define needs for the material data and structural design methodology.

2. Status of the ASME draft code case for alloy 617

2.1 Background

The draft Code Case for Alloy 617 was intended to cover the design rules for a very high temperature reactor (VHTR) structure up to 982°C (1800°F) for the material of Alloy 617. The initial request to the ASME B&PV code committee for design rules for VHTR components originated from US DOE (Department of Energy) and one of its contractors. An ad hoc task force of the ASME Code was established in 1983, completed the draft Code Case in 1989 and submitted it to the subgroup on an elevated temperature design, which approved the draft Code Case later. No further work has been done on the draft Code Case due to a lack of further interest from the US DOE and its contractor [11].

2.2 Status of the draft Code Case

The draft Code Case for Alloy 617was formed after the Code Case N-47 (currently ASME-NH) and was limited to Alloy 617 components for design temperatures up to 982°C (1800°F) for a maximum service life of 100,000 hours or less. The chemical composition of Alloy 617 is shown in Table 1, and its material properties in Table 2.

Table 1. Chemical composition of Alloy 617.

	Ni	Cr	Co	Mo	Fe	C	Al	Ti	Cu	Si	Mn	B	P	S
ASTM min	44.5	20	10	8	-	0.05	0.8	-	-	-	-	-	-	-
ASTM max	44.5	24	15	10	3	0.15	1.5	0.6	0.5	1	1	0.006	-	0.015
Standard composition	Bal.	220	12	9	1	0.06	1.0	0.4	0.07	0.15	0.1	0.002	<0.005	<0.002

Table 2. Yield strength and thermal expansion coefficients.

		Alloy 617	Alloy 800H
YS$^{(*)}$	RT	241	172
	600°C	159	108
	815°C	154	90
	982°C	77	-
$\alpha_m^{(**)}$	482°C	14.0	16.7
	593°C	14.6	17.1
	815°C	16.2	18.0

$^{(*)}$: Yield strength (MPa), $^{(**)}$: Mean thermal expansion coefficients (m/m-°C×10^{-6})

As shown in the tables, it is a high Nickel base alloy and has a better yield property than Alloy 800H as shown in Table 2 while having relatively low thermal expansion coefficients, which means that Alloy 617 has better material properties at high temperature than Alloy 800H.

Alloy 617 is also known as having unique material characteristics under the distinction between the time-independent and time-dependent behavior, the high dependence of the flow stress on strain rate and softening with time, temperature and strain [11], but those aspects of Alloy 617 are not taken into account in the draft Code Case.

The draft Code Case states that inelastic design analyses for temperatures above 649°C (1200°F) should be based on unified constitutive equations, but no specific constitutive model or validation procedure is provided in the Code Case. Activities to improve the design rules for a very high temperature application are underway in France, the USA and Korea, and others as a part of the Generation IV international collaboration program.

2.3 Actions to be taken for a further development of the draft Code Case

The draft Code Case is based on a limited database and service experience. Further development of the draft Code Case is needed for the following fields so that it could be reliably applied. The design rules for

Alloy 617 components should be added to the low-temperature rules of ASME code Section III (as sub-section NB). Simplified ratcheting evaluation procedures need to be developed for material temperatures above 649°C. The material data such as weldment stress rupture factors, additional isochronous stress-strain curves for the temperature range of 427°C to 649°C, thermal expansion coefficients, the effects of aging on the toughness of materials and weldment fatigue data, etc. must be added [4].

The linear damage summation rule is used in the draft Code Case like ASME-NH for a creep-fatigue evaluation, which is known as one of the biggest shortcomings of the draft Code Case. A new rule for the creep-fatigue damage for Alloy 617 must be developed.

No rules are given for piping, pumps and valves and the Alloy 617 bolting is excluded.

Since the draft Code Case states that for temperatures above 649°C all inelastic calculations should be based on unified constitutive equations, appropriate constitutive equations for a high temperature range application must be developed. In addition, the draft Code Case rules are applicable when the fluid does not influence a component's behavior greater than air. So rules to consider the environmental effects of a coolant such as He gas on the structure must be developed.

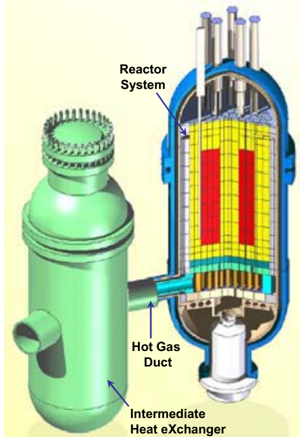
Fracture mechanics analysis is required to justify the safety of component materials after a significant toughness reduction and fracture assessment methodologies must be developed.

The weld strength reduction factors are not included in the draft Code Case, and should be added so that the weldment design could be possible.

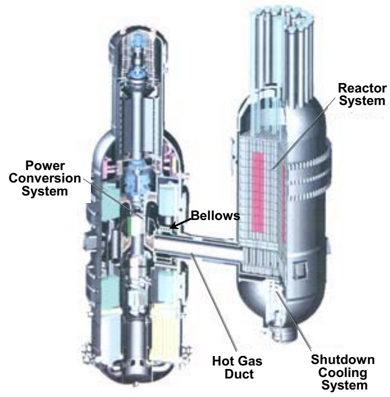
3. Very high temperature reactor, NHDD plant

KAERI has established a plan to demonstrate the mass-production of hydrogen by using a very high temperature reactor (VHTR) by the early 2020s and to obtain an operating license for a nuclear hydrogen development and demonstration (NHDD) reactor, followed by commercial plants using the best available international and domestic technologies in the early 2010s [3] (Chang et al., 2007).

Fig. 1 shows the reactor system, the power conversion system and the hot gas duct structure for the NHDD plant of KAERI and the GT-MHR of US General Atomics. The hot gas duct, which is the structure to be evaluated in this study, is a coaxial type double wall pipe connecting the reactor system to the power conversion system.



(a) NHDD Plant

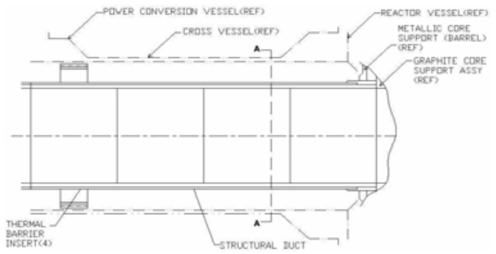


(b) GT-MHR

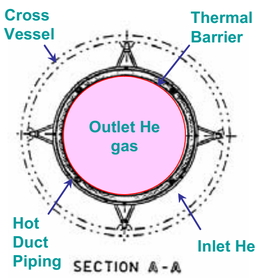
Fig. 1. Very high temperature gas cooled reactors.

The temperature of hot He gas inside the hot duct pipe shown in Fig. 2 is about 950°C, while that of the cold He gas at the outer annular space is about 400°C. The hot duct pipe structure subjected to a high temperature is the target structure of design evaluation in the present study. Since no detailed thermo-hydraulic analysis has been carried out yet, the wall temperature of the hot duct piping was assumed to maintain 550°C at a steady state, which is a conservative temperature for the piping wall.

The dimensions and materials of the NHDD hot gas duct and internal structures are now under case study stage and are not fixed yet. However, a preliminary sizing of the hot gas duct structure has been



(a) Hot gas duct structure



(b) Section view

Fig. 2. Hot gas duct piping structure.

done; the outer pressure vessel has a diameter of 1~1.5m with the thickness of 80mm and the hot duct pipe has a diameter of 0.6m with the thickness of 5mm. Inside the hot duct pipe, there is a liner (5mm), multi-foiled metal insulation (30mm), a partition plate (5mm) and a fibrous insulation (60mm). The length of the hot gas duct ranges from 5 to 10m, and most of the thermal expansion would be clamped with the bolted joint of the flange at the IHX vessel and the reactor core.

4. Evaluation of a creep-fatigue damage on the hot duct piping

The evaluation procedure of the creep-fatigue damage to the draft Code Case is similar to that of the ASME-NH and RCC-MR, and the damage is calculated by the formula over the design life as shown below:

$$\sum_{j=1}^{P}\left(\frac{n}{N_d}\right)_j+\sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \le D \tag{1}$$

where D = total creep-fatigue damage

p = number of different cycle types

$(n)_j$ = number of applied repetitions for cycle type j

$(N_d)_j$ = number of design allowable cycles for cycle type j

q = number of time intervals for the creep damage calculation

$(\Delta t)_k$ = hold time applied for one creep-fatigue load cycle type k

$(T_d)_k$ = allowable time determined from the stress-to-rupture curves during the time interval, k.

It should be noted that the intersection point in the damage envelope for the Alloy 617 is (0.1, 0.1) in the Code Case, while the point for Alloy 800H is (0.1, 0.1) in ASME-NH and (0.3, 0.3) in RCC-MR as shown in Fig. 3. It should be also noted that the design fatigue curves for Alloy 617 are provided only for three temperatures of 704°C (1300°F), 871°C (1600°F) and 982°C (1800°F), while stress-to-rupture data are provided only for the range of 593°C (1100°F) to 982°C (1800°F) in the draft Code Case.

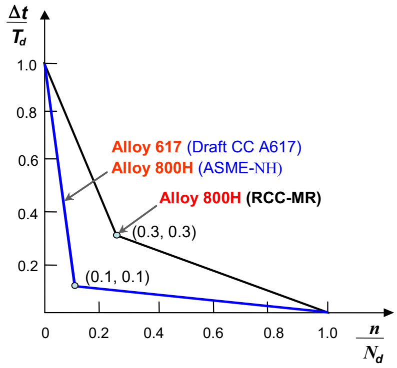
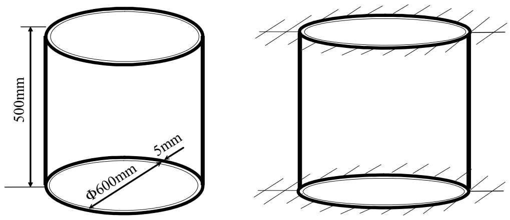


Fig. 3. Creep-fatigue damage envelope.

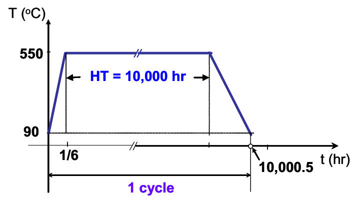


(a) Simplified analysis model (b) Boundary conditions

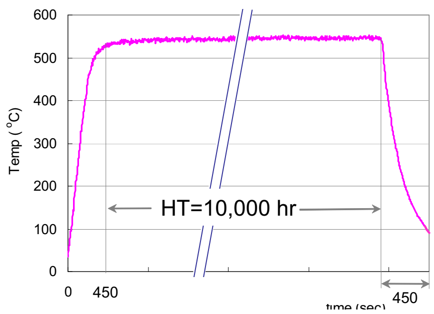
Fig. 4. Simplified modelling of the hot gas duct piping.

4.1 Numerical modelling of the hot duct piping

The temperature of the coolant gas flowing through the annular space of the cross vessel in Fig. 2 is 400°C, while the temperature of hot duct piping is higher than that. The wall temperature of the hot duct piping was assumed to be 550°C and the piping was selected as a target model. The hot duct pipe model was simplified as a cylindrical shell with a height of 500mm, diameter of 600mm and thickness of 5mm as shown in Fig. 4(a), and the both ends were fixed by



(a) Thermal load



(b) Temperature profile for Alloy 800H

Fig. 5. Thermal load conditions and temperature profile.

boundary conditions as shown in Fig. 4(b).

One load cycle of the creep-fatigue is to heat the model from 90°C up to 550°C and hold the temperature for 10,000 hours and cool down to 90°C as shown in Fig. 5(a). Only thermal loads were taken into account in this analysis. In the finite element analysis, as-received temperature data for Alloy 800H as shown in Fig. 5(b) from the structural creep-fatigue test shown in Fig. 5(b) [10] were used. In the structural test, a hold time of two hours at about 550°C was applied, but the hold time was extended to 10,000 hours in this analysis as shown in Fig. 5(b).

4.2 Creep-fatigue damage according to the draft Code Case for alloy 617

A preliminary evaluation on the creep-fatigue damage according to the draft Code Case was carried out for the hot duct piping for Alloy 617 material. Since the material data of Alloy 617 was not sufficiently provided in the draft Code Case, the required material data and design parameters were selected or assumed in a conservative way.

Finite element analysis of the hot duct piping was carried out by using the 2D ABAQUS [12] axisymmetric model. The analysis results of the equivalent strain range, $\Delta\varepsilon_{eqiv,i}$ the modified maximum equivalent strain range, $\Delta\varepsilon_{\mathrm{mod}}$ and the total strain range ε_t are as follows:

Table 3. Evaluation results of creep-fatigue damage according to the three design codes.

Material	Alloy 800H		Alloy 617
Design code	ASME-NH	RCC-MR	Draft CC Alloy 617
Total strain range	$\varepsilon_t = K_v\varepsilon_{\mathrm{mod}} + K\Delta\varepsilon_c = 0.01813$	$\Delta\bar{\varepsilon} = \Delta\bar{\varepsilon}_{\mathrm{el+pl}} + \Delta\bar{\varepsilon}_{cr} = 0.00507$	$\varepsilon_t = K_v\varepsilon_{\mathrm{mod}} + K\Delta\varepsilon_c = 0.011934$
Fatigue damage	$D_f = \frac{\sum n}{42.4}$	$D_f = \frac{\sum n}{970.4}$	$D_f = \frac{\sum n}{18.8}$
Creep damage	$\frac{S_r}{K'} = \frac{143}{0.67} = 213.43 \Rightarrow t_r = 396.9$ (hr)	$\frac{S_r}{K'} = \frac{246.8}{0.9} = 274.2 \Rightarrow t_r = 270.5$ (hr)	$\frac{S_r}{K'} = \frac{158.6}{0.67} = 236.7$ (MPa) $\Rightarrow t_r = 82732$ (hr)
C-F Damage	$\frac{n}{42.4} + \frac{\Delta t}{396.9} \le D$	$\frac{n}{970.4} + \frac{\Delta t}{270.5} \le D$	$\frac{n}{18.8} + \frac{\Delta t}{82732} \le D$

$$\Delta\varepsilon_{eqiv,i} = 0.875(\%) \tag{2}$$

$$\Delta\varepsilon_{\mathrm{mod}} = 1.030(\%) \tag{3}$$

$$\varepsilon_t = 1.193\ (\%) \tag{4}$$

In determining the total strain range, the isochronous curve of Alloy 617 at 649°C (1200°F) was used, which was the curve at the lowest temperature in the draft Code Case. Using the higher temperature isochronous curve generally results in a higher strain range, which will eventually cause larger fatigue and creep damage. The allowable fatigue cycle was calculated to be $N_d = 18.8$ cycles as shown in Table 3. It should also be noted that the fatigue cycle was calculated based on the fatigue curve for 704°C.

The sustained stress for the calculation of the creep damage is $\overline{\sigma_K} / K' = \overline{\sigma_K} / 0.67$ where K' (=0.67) is a safety factor. The creep rupture time, T_d was calculated to be 82,732 hours as shown in Table 3. In the draft Code Case, the stress-to-rupture values are provided for temperature range of 593°C to 982°C up to 100,000 hours, and the creep damage was calculated with the stress-to-rupture value for 593°C.

Then the creep-fatigue damage equation for Alloy 617 material according to the draft Code Case was calculated as

$$\frac{n}{18.8} + \frac{\Delta t}{82732} \le D. \tag{5}$$

4.3 Creep-fatigue damage according to the ASME-NH

An evaluation of the creep-fatigue damage according to the ASME-NH was carried out for the Alloy 800H hot duct piping. Since the material data of Alloy 800H was well provided in the code, the damage could be calculated in a straightforward way. The evaluation according to ASME-NH was carried out in the same way as the draft Code Case.

The analysis results of the equivalent strain range, $\Delta\varepsilon_{eqiv,i}$ the modified maximum equivalent strain range, $\Delta\varepsilon_{\text{mod}}$ and the total strain range ε_t are as follows:

$$\Delta\varepsilon_{eqiv,i} = 1.109(\%) \tag{6}$$

$$\Delta\varepsilon_{\text{mod}} = 1.572(\%) \tag{7}$$

$$\varepsilon_t = 1.813\,(\%). \tag{8}$$

The isochronous curve of Alloy 800H at 566°C was used, and the allowable fatigue cycle was calculated to be $N_d = 42.4$ cycles for the above mentioned total strain range. The sustained stress for the calculation of the creep damage was $\overline{\sigma_K} / K' = \overline{\sigma_K} / 0.67$ where K' (=0.67) was the safety factor. The creep rupture time, $T_{d,}$ was calculated to be 396.9 hours as shown in Table 3.

Thus the creep-fatigue damage for Alloy 800H according to the ASME-NH calculation was calculated as

$$\frac{n}{42.4} + \frac{\Delta t}{396.9} \le D. \tag{9}$$

4.4 Creep-fatigue damage according to the RCC-MR

The evaluation procedures of the creep-fatigue damage by the ASME-NH (Alloy 800H) are very similar to those by the draft Code Case (Alloy 617), but those of RCC-MR are quite different from the other two codes. In this study, evaluation of creep-fatigue damage of the Alloy 800H hot duct pipe was also carried out according to RCC-MR for a comparison purpose of the previous results.

In RCC-MR, the elastic-plastic strain was determined by the summation of four strain terms: the elastic strain range, increase in the plastic strain due to a primary stress range, increase in the plastic strain according to Neuber's rule and the increase in the plastic strain due to a triaxiality.

Then the elastic-plastic strain ($\Delta\overline{\varepsilon}_{el+pl}$) was determined by the summation of the above four strain terms as $\Delta\overline{\varepsilon}_{el+pl} = 0.457(\%)$.

The creep damage was determined by using the creep law provided in RCC-MR A3 [13] instead of using the isochronous curves, unlike ASME-NH or the draft Code Case. The strain rate for Alloy 800H was given in RCC-MR A3 as

$$\dot{\varepsilon}_c = 4.6\times10^7 \exp\left(-\frac{44191}{T}\right)\sigma^{0.034} \tag{10}$$

Then the creep strain range ($\Delta\overline{\varepsilon}_c$) and the total strain range ($\Delta\overline{\varepsilon}$) were calculated as follows.

$$\Delta\overline{\varepsilon}_c = \int_0^{t_H} \dot{\varepsilon}_c \mathrm{d}t = 0.050(\%) \tag{11}$$

$$\Delta\overline{\varepsilon} = \Delta\overline{\varepsilon}_{\text{el+pl}} + \Delta\overline{\varepsilon}_c = 0.507(\%) \tag{12}$$

The allowable fatigue cycle for the total strain range was calculated to be $N_d = 970.4$ cycles. The safety factor (K') in the sustained stress for the calculation of the creep damage was 0.9 as shown in the equation of $\overline{\sigma_K} / K' = \overline{\sigma_K} / 0.9$, while K' was 0.67 for both the ASME-NH and the draft Code Case. The creep rupture time, $T_{d,}$ was calculated to be 270.5 hours as shown in Table 3.

Thus the creep-fatigue damage equation for Alloy 800H according to the RCC-MR is calculated as

$$\frac{n}{970.4} + \frac{\Delta t}{270.5} \le D. \tag{13}$$

5. Discussion

In this study, a preliminary application of the ASME draft Code Case was carried out and the evaluation results were compared with those by the design codes of ASME-NH and RCC-MR. The comparison between the different codes would be meaningful for the cases with the same materials and loads. However, since the rules on Alloy 800H are not provided in the draft Code Case while the rules for Alloy 617 are not provided in ASME-NH and RCC-MR, it is intended to apply the draft Code Case to the VHTR component to examine the evaluation procedures and the behavior of the creep-fatigue damage with reference to those of the existing ASME-NH and RCC-MR codes.

First, for the Alloy 617 and Alloy 800H, comparisons were made in terms of the evaluation procedure and results under creep-fatigue loads. One of the most significant differences between Alloy 617 and Alloy 800H is that the calculated creep damage of Alloy 617 was far lower than those of the other two cases for the Alloy 800H, indicating a two orders ($\times10^2$) difference in creep rupture time (t_r) differences as shown in Table 3. Considering that the isochronous curve of 649°C was used for Alloy 617 instead of using an actual temperature of 550C°, the stress-to-rupture for the Alloy 617 could be increased and the creep damage results would decrease accordingly.

As for the fatigue damage, the fatigue lifetime of the Alloy 617 was calculated to be smaller than that by the ASME-NH and RCC-MR for the Alloy 800H as shown in Table 3. However, considering a high temperature fatigue curve of 704°C was used, the fatigue damage of the Alloy 617 would be decreased with an increase of the fatigue life cycles so that the damage by the draft Code Case could become smaller than that of ASME-NH.

Second, the creep-fatigue damage by ASME-NH and RCC-MR was compared. Table 3 shows that the fatigue life cycles per ASME-NH (42.4 cycles) are much lower than that of RCC-MR (970.4 cycles), because the total strain for ASME-NH is 1.81%, while that for RCC-MR is 0.507% as shown in Table 3. As for the creep damage, the stress-to-rupture time for ASME-NH (396.9 hrs) was slightly higher than that of RCC-MR (270.5 hrs). This difference in the stress-to-rupture time is essentially cased by the procedural differences in the isochronous curves (ASME-NH) and creep laws (RCC-MR) used in calculating the creep damage directly.

The above results can be reduced to the following relations for the present problem:

(1) total strain range: ASME-NH > draft Code Case for A617 > RCC-MR

(2) fatigue damage: draft Code Case for A617 > ASME-NH > RCC-MR

(3) creep damage: RCC-MR > ASME-NH >> draft Code Case A617

The conservative aspect of the above design rules can be quantified based the structural test results with those of the design code evaluations.

6. Conclusions

In this study, a preliminary application of the draft Code Case for Alloy 617 was carried out, and the evaluation results were compared with those by the design codes of ASME-NH and RCC-MR for the hot duct pipe structure of the NHDD plant. Since the material data for Alloy 617 is provided only in the draft Code Case but not in the other two codes, Alloy 800H material, which is one of the two candidates for the hot gas duct piping, was used for the design evaluation by the ASME-NH and RCC-MR. The three design codes were compared and the required actions that must be taken to complete the draft Code Case were identified.

The preliminary evaluation results on the creep-fatigue damage for the hot duct pipe structure according to the three design codes can be summarized as follows:

- total strain ranges: ASME-NH > draft Code Case A617 > RCC-MR
- fatigue damage: draft Code Case for A617 > ASME-NH > RCC-MR
- creep damage: RCC-MR > ASME-NH >> draft Code Case for A617

The evaluation results according to draft Code Case showed that creep rupture time for the Alloy 617 is far higher (by two orders ($\times 10^2$)) than the other two cases when compared with the results by ASME-NH and RCC-MR, while the allowable fatigue cycle was lower in the draft Code Case than the other two cases. The above results show the overall trends of the damage aspects, but it should be noted that the results for the draft Code Case are based on a conservative evaluation with the isochronous curve (649°C) and a fatigue curve (704°C). Therefore, a large number of data and structural design methodologies must be supplemented so that reliable results can be obtained. In addition, a structural test should be used in order to validate the design procedures and to quantify the conservative aspect of the design rules.

Acknowledgments

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References

[1] Draft Alloy 617 Code Case, Case N-47-28, Task Force Very High Temperature Design, ASME, (1988).

[2] ASME Boiler and Pressure Vessel Code, Section III, Rules for Construction of Nuclear Power Plant Components, Div. 1, Subsection NH, Class 1 Components in Elevated Temperature Service, ASME; (2007).

[3] J. H. Chang, Y. W. Kim, K. Y. Lee, Y. W. Lee, W. J. Lee, J. M. Noh, M. W. Kim, H. S. Lim, Y. J. Shin, K. K. Bae and K. D. Jung, A study of a nuclear hydrogen production demonstration plant, *Nuclear Engineering and Technology*, 39 (2) (2007) 111-122.

[4] J. M. Corum and J. J. Blass, Rules for design of alloy 617 nuclear components to very high temperatures, Attachment 2, Draft Code Case for Alloy 617,

(1988).
[5] RCC-MR, 2002a, Section I Subsection B, Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, 2002 Edition, AFCEN.
[6] H. Y. Lee, J. B. Kim and J. H. Lee, Progressive inelastic deformation characteristics of cylindrical structure with plate-to-shell junction under moving temperature front, *Korean Society of Mechanical Engineering (KSME) International Journal,* 17 (3) (2003) 403-411.
[7] H. Y. Lee, J. B. Kim and J. H. Lee,Thermal ratcheting deformation for 316L stainless steel cylindrical structure under moving temperature distribution, *International Journal of Pressure Vessel and Piping*, 80 (2003) 41-48.
[8] H. Y. Lee, J. H. Lee and B. H. Kim, Creep-fatigue crack behaviour of a structure with crack like defects at the welds, *Journal of Mechanical Science and Technology*, 20 (12) (2006) 2136-2146.
[9] H. Y. Lee, J. B. Kim, S. H. Kim and J. H. Lee, Assessment of Creep-Fatigue Crack Initiation for Welded Cylindrical Structure of Austenitic Stainless Steels, *International Journal of Pressure Vessel and Piping*, 83 (2006) 826-834.
[10] H. Y. Lee, S. H. Lee, J. B. Kim and J. H. Lee, Creep-fatigue damage for a structure with dissimilar metal welds of Mod 9Cr-1Mo and 316L stainless steel, *International Journal of Fatigue,* 29 (2007) 1868-1879.
[11] NUREG/CR-6816, Review and assessment of Codes and Procedures for HTGR Components, ANL-02/36, (2003).
[12] ABAQUS Users manual, Version 6.6, H.K.S, USA; (2006).
[13] RCC-MR, Section I Subsection Z Technical Appendix A3, Design and Construction Rules for Mechanical Components of FBR Nuclear Islands, 2002 Edition, AFCEN, (2002).