



Inelastic Analysis of Intermediate Heat Exchanger for HTGR

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ABSTRACT

An intermediate heat exchanger (IHX) of high-temperature-gas-cooled reactor (HTGR) for hydrogen production is a component that exchanges heat between primary helium gas (950°C) and secondary helium gas (300°C). This component is composed of center pipe, manifold tube plate (perforated structure) and helical heat transfer tubes, all made of nickel-based alloy Hastelloy XR. In this study, a detailed inelastic analysis considering 500,000-hour operation (100 cycles of 5,000-hour hold time) was carried out to clarify the characteristics of inelastic behavior and creep-fatigue damage. Considering the features of these inelastic behaviors, an applicability of a simplified creep-fatigue evaluation method based on both elastic analysis results and elastic-follow-up coefficient is examined, which has been utilized in the Fast Reactor design guideline. Creep damage by the simplified creep-fatigue evaluation method is found to give a conservative prediction within a factor of 2, when compared with the prediction by the detailed inelastic FE analysis.

INTRODUCTION

In steel-making and chemical industries in Japan, innovative technologies such as a hydrogen-reduction steel making and a carbon-free hydrogen production process is under examination (Sato et.al. (2016), Kusuda et. el. (2021), Suyama et.al. (2022)). High temperature gas-cooled reactors (HTGR) can provide a stable and large amount of hydrogen by supplying a heat source above 800°C. Structural integrity of an intermediate heat exchanger (IHX) and a recuperative heat exchanger (RHX) is an important issue in the structural design of HTGR. In the past development of HTTR (High Temperature Test Reactor) (Sato et.al. (2016)) and the following R&D program, structural model tests have been carried out such as perforated-plate structure of the intermediate heat exchanger (Igari et.al. (2001a, 2001b)); and the plate-fin structure of the recuperative heat exchanger (Mizokami et.al. (2013)). The purpose of these tests is to confirm a failure limit and a creep-fatigue life prediction accuracy when using inelastic analysis.

In an initial stage of structural design for parametric study considering influences of configuration and operational conditions, practical application of a simplified creep-fatigue life evaluation method on the basis of elastic analysis is necessary. In this evaluation method, specific features of inelastic behavior which are based on a detailed inelastic analysis of HTGR components must be reflected. To clarify the specific features of HTGR components, it is useful to compare HTGR with Fast Reactor (FR) nuclear power plants. In FR components using liquid sodium (~550°C) as a coolant, an operating pressure is low at an atmospheric pressure; and an inelastic behavior due to high secondary stress (thermal stress) during a thermal transient is a key in creep-fatigue evaluation. In HTGR components using helium gas (~950°C) as a coolant, on the other hand, an operating pressure is high at about 5 MPa; and creep damage due to primary stress becomes a key. Although secondary stress (thermal stress) due to thermal transient is low reflecting a heat transfer coefficient of coolant, inelastic behavior due this thermal stress is also a key in creep-fatigue evaluation.

In this study, a detailed inelastic analysis assuming 500,000-hour operation consisting of 100 cycles of normal start and stop (holding time of 5000 hours) is carried out for an IHX in a demonstration HTGR. Features of the inelastic behavior under the combination of primary and thermal stress are clarified, such

as an elastic-follow up coefficient and a level of post-relaxation stress due to creep during a holding time. A simplified creep-fatigue life evaluation method on the basis of elastic analysis is proposed in which the above-mentioned features of creep during holding time is reflected. Applicability of this method is confirmed by comparing the predicted creep damage with that by detailed inelastic analysis. Application example of this method is shown in which influence of maximum temperature on creep-fatigue life is studied.

OVERVIEW OF IHX IN HTGR

The IHX for the demonstration reactor consists of a helical-coil tube and a center pipe just like as the HTTR in Fig.1 (Goto et.al. (2012)). The IHX exchanges heat between primary helium gas (950°C, about 5 MPa) flowing outside tubes and secondary helium gas (~950°C, about 5 MPa near a manifold of center pipe) flowing inside tubes. In Fig.2, a design allowable stress of Hastelloy XR (Nuclear Safety Bureau, Japan (1990)), a candidate material for tubes and center pipe, is compared with those of two kinds of materials (JSME (2020)); one is a modified 9Cr-1Mo steel, representative material in power plant application; and the other is a 316FR, candidate material in fast reactor application. As shown in the figure, a design allowable stress of Hastelloy XR is about 1 MPa (940°C for 500,000 hours), which is very low compared with those of modified 9Cr-1Mo steel (about 60 MPa: 600°C, 100,000 hours) and 316FR steel (about 100 MPa: 550°C, 500,000 hours). In IHX of HTGR, structural design against primary stress due to a pressure difference 0.3MPa at 940°C is important for locations subject to maximum temperature, such as a perforated manifold of center pipe and tubes nearby. In the steady-state operation, both tubes and center pipe with different averaged temperature, try to extend freely downward from the top connected location at the vessel. Since tubes and center pipe are connected to each other at bottom end with the maximum temperature, a thermal bending stress is generated in the tubes near the bottom connection with manifold. In the manifold of center pipe, on the other hand, a thermal stress is generated due to the temperature distribution in both the thickness and axial direction; and a peak stress in the manifold is generated due to a stress concentration around holes. Prevention of both a progressive deformation and creep-fatigue damage is also a key in structural design against a combination of a primary stress and cyclic thermal stresses.

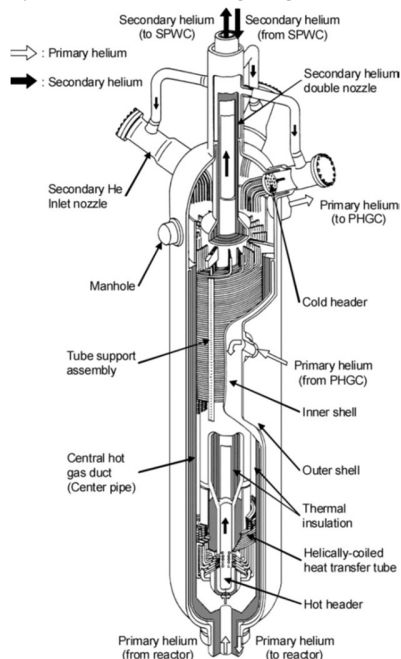


Figure 1. Structure of the HTTR's IHX.
 (Goto et.al., 2012)

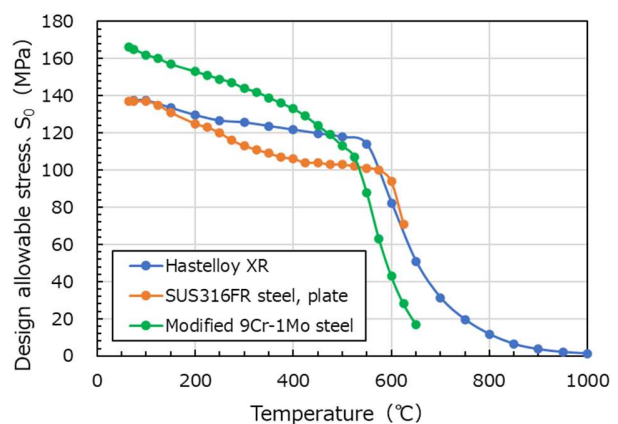


Figure 2. Design allowable stress of Hastelloy XR.

ANALYSIS AND RESULTS

Analysis conditions

In this study, two kinds of analysis were performed for a structure consisting of three-layer tubes and center pipe; one is an elastic analysis as a baseline of a simplified creep-fatigue life evaluation method; and the other is a detailed inelastic analysis to clarify features of inelastic behavior. Material property data for the analysis were referred from the design guideline for HTTR (Nuclear Safety Bureau, Japan (1990)). An elastic-perfectly plastic property and secondary creep were considered in the inelastic analysis using a code ABAQUS.

Loading of dead weight, internal pressure and temperature distribution was considered in the analysis. A 500,000-hour operation consisting of 100 cycles of normal start and stop (holding time 5000 hours) is considered; a temperature distribution in the steady state of 5000 hour was obtained from a static heat transfer analysis; quasi-static variation was assumed between a uniform room temperature and the temperature distribution at steady state.

Strength evaluation results based on elastic analysis

Comparison of stresses and allowable values is shown in Fig.3 for both tubes and manifold. Primary stress was less than the allowable stress $K_t S_t$ for both tubes and manifold; “primary + secondary stress” was less than the design yield stress S_y ; and both the primary stress evaluation and the progressive deformation evaluation were acceptable. Fig.3 shows that a margin of primary stress evaluation is small and that of progressive deformation evaluation is large. Creep-fatigue damage evaluation on the basis of linear damage rule “ $D_f + D_c = 1$ ” was carried out, where fatigue and creep damage are respectively obtained from the design fatigue curve and design creep rupture curve of Hastelloy XR in Fig.4 and Fig.5. Obtained results, where fatigue damage is negligible and creep damage is dominant, was not acceptable. As shown in Sections 3 and Fig.6, an inelastic behavior during a normal start-up/shutdown operation is an elastic shakedown behavior with a relaxation of thermal stress during the steady state of 5,000hours. In the present design standard on the basis of elastic analysis, on the other hand, relaxation of thermal stress is not considered when the primary stress is high. This is the reason of overestimation of the creep damage.

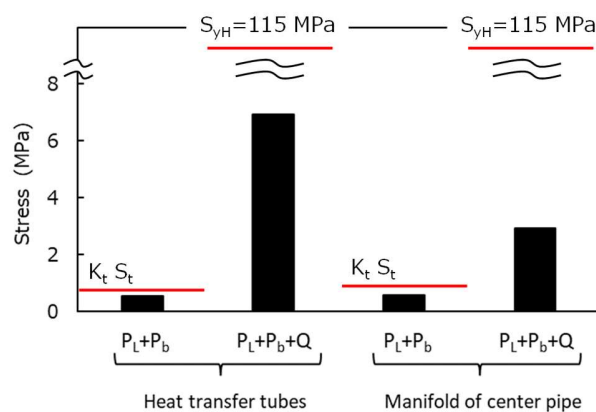


Figure 3. Comparison of stresses and allowable values for the heat transfer tubes and the manifold of center pipe.

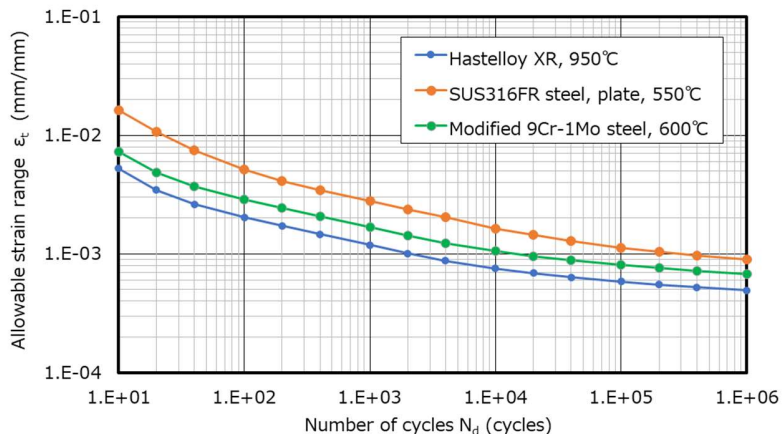


Figure 4. Design fatigue curve of Hastelloy XR.

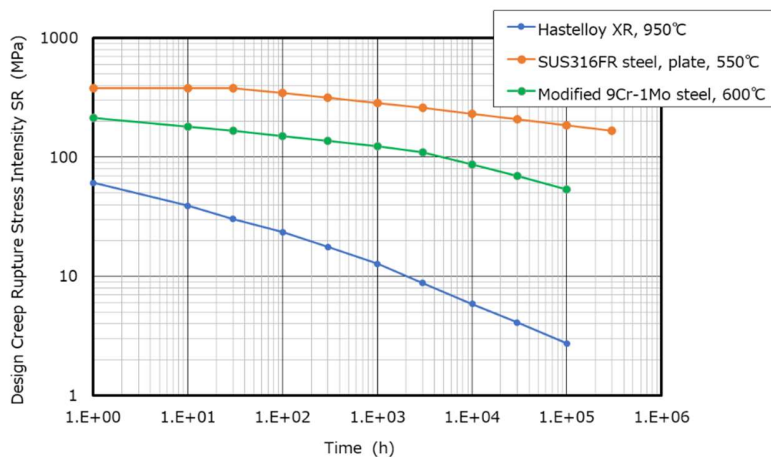


Figure 5. Design creep rupture curve of Hastelloy XR.

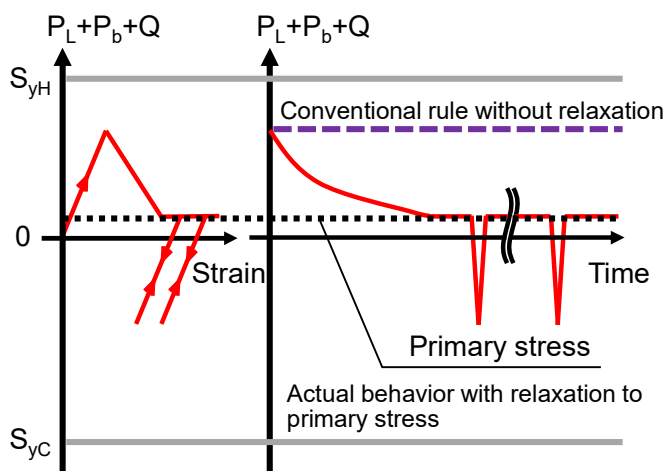


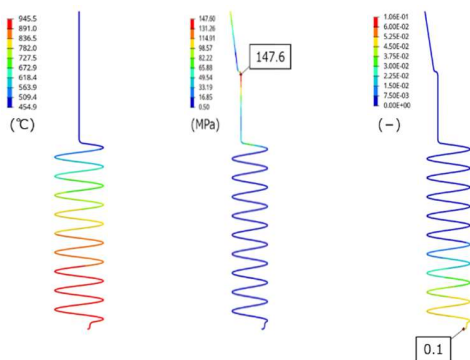
Figure 6. The inelastic behavior during normal operation (elastic shakedown).

Detailed inelastic analysis results

Fig. 7 shows detailed inelastic analysis results for the most inner-layer tube whose stress is the highest among the 3 layers, such as temperature distribution, von Mises' equivalent stress at the start of operation and the creep damage after 500,000 hours. Although the high stress about 148 MPa is observed in upper part near the tube-weight support, a temperature of this part is low about 500°C where the creep damage is not a problem. Creep damage is large up to 0.1 at the vicinity of the connection with the manifold whose temperature is high about 950°C.

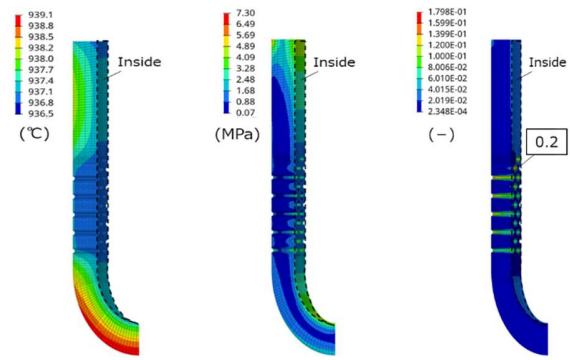
Temperature distribution around the manifold, von Mises' equivalent stress at the start of operation and creep damage after 500,000 hours are shown for manifold in Fig.8. Stress on the inner diameter side is high at the start of the operation and that in on the outer diameter side becomes high due to stress redistribution caused by creep. Creep damage after 500,000 hours was about 0.2 at a circular hole on the inner diameter side.

Table 1 shows the time histories of von Mises' equivalent stress and creep damage at locations with high creep damage (Fig.7 (c) and Fig.8 (c)) for both tube and manifold. Von Mises' equivalent stress was relaxed by creep and saturated after several thousand hours in the first cycle. Creep damage tended to increase gradually during the subsequent 100 cycles (500,000 h). In the manifold, von Mises' equivalent stress reduced to 0 MPa and then increased again. This is because the difference among stress components decreased and became equal in the process of stress relaxation, and then these differences increased again.



(a) Temperature (b) von Mises effective stress at 0 h. (c) Creep damage after 500,000h.

Figure 7. Thermal stress analysis results of detailed inelastic analysis for the heat transfer tubes.



(a) Temperature (b) von Mises effective stress at 0 h. (c) Creep damage after 500,000h.

Figure 8. Thermal stress analysis results of detailed inelastic analysis for the center pipe.

SIMPLIFIED CREEP-FATIGUE LIFE EVALUATION METHOD REFLECTING INELASTIC BEHAVIOR

Elastic-follow-up coefficient and post relaxation stress

Based on the inelastic analysis results showing elastic shakedown behavior as shown in Sec.3, a simplified creep-fatigue life evaluation method is examined. There are two items to be clarified from inelastic analysis results; one is an elastic-follow-up coefficient q during the stress relaxation process; and the other is a stress after the relaxation, i.e., a post relaxation stress.

Table 1 Time histories of von Mises effective stress and creep damage for high creep damage area shown in Fig.7(c) & Fig. 8 (c).

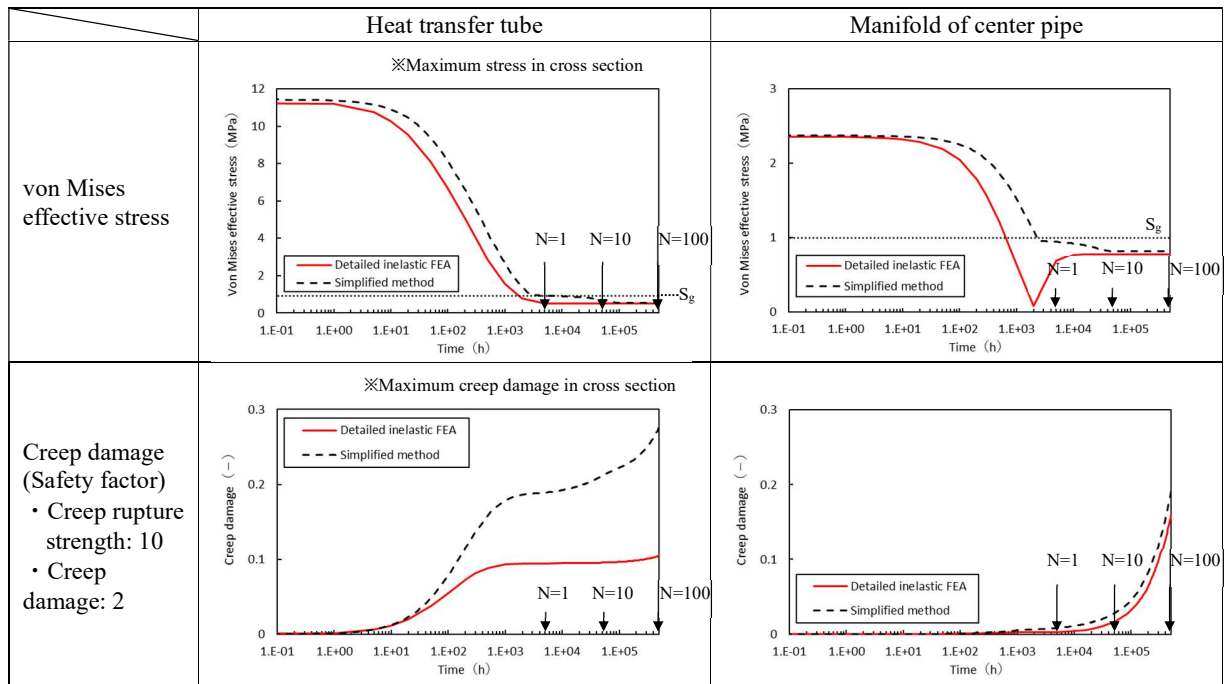


Fig. 9 shows the relaxation behavior during the steady state in the first cycle. An elastic-follow-up coefficient q is found below $q=3$, a recommended value in the Fast Reactor Standard. In a simplified creep-fatigue life evaluation method for IHX, the elastic-follow-up coefficient $q=3$ can be an adequate choice for conservatively predict creep damage during relaxation.

Second problem in the simplified creep-fatigue life evaluation method for IHX is a determination of a post relaxation stress. In fast reactors with low primary stress, post relaxation stress is set as the stress level S_g , which is obtained from the creep damage (recommended value: 0.3) depending on temperature and time duration at high temperature. Since the primary stress of the IHX for HTGR is high, different approach is necessary based on the detailed inelastic analysis results.

With respect to a ligament in manifold, Fig. 10 shows a comparison between post-relaxation stress distribution by detailed inelastic analysis and primary stress intensity distribution by elastic analysis. The post-relaxation stress after 500,000 hours almost corresponded to the primary stress intensity “PL+Pb+F” including the peak component F. Results of comparison between post-relaxation stress by detailed inelastic analysis after 500,000 h and primary stress intensity “PL+Pb+F” are summarized in Fig.11 for both manifold and tubes ($F=0$ for tube). Primary stress intensity “PL+Pb+F” is found to be an adequate measure for the post relaxation stress in the simplified creep-fatigue life evaluation method for IHX.

Comparison of creep-fatigue damage with those by detailed inelastic analysis

A simplified creep-fatigue life evaluation method suitable for IHX in HTGR is based on the following assumptions: uniaxial strain-strain hysteresis loop with a strain range “(PL+Pb+Q+F)/E” is assumed; stress relaxation from maximum stress “(PL+Pb+Q+F)” obeys a creep law of the material and the elastic-follow-up coefficient $q=3$; stress relaxation stops at the post relaxation stress “(PL+Pb+F)”.

Creep-fatigue life prediction of structures on the basis of uniaxial stress-strain hysteresis modelling from elastic analysis results has been discussed in several works (JSME (2020)). An elastic follow-up in relaxation process is usually considered, depending on structure and thermal/primary stress levels. In a case

where a peak elastic stress intensity “(PL+Pb+Q+F)” exceeds a yield stress of the material, an increase of a strain range due to plastic strain is considered. The case of IHX in HTGR is a special case where plastic strain is not included, and only an elastic-follow up in relaxation process is considered. Figure 12 shows the comparison of creep damage from the simplified creep-fatigue life evaluation method and detailed inelastic analysis. The simplified creep-fatigue life evaluation method could estimate creep damage conservatively, and the estimation accuracy is about factor of 2.

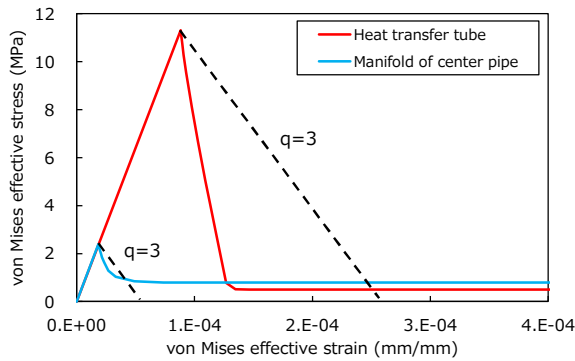


Figure 9. Relaxation behavior in the 1st cycle and the elastic follow-up behavior.

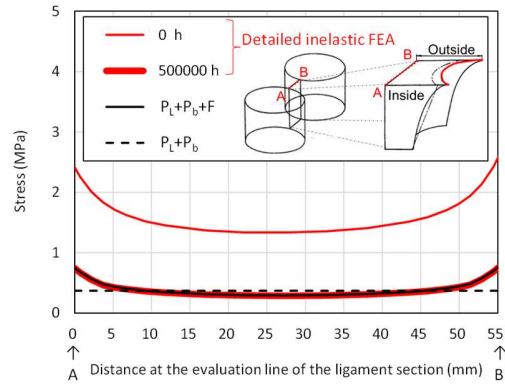


Figure 10. The relationship between initial and post-relaxation stress in the manifold of center pipe.

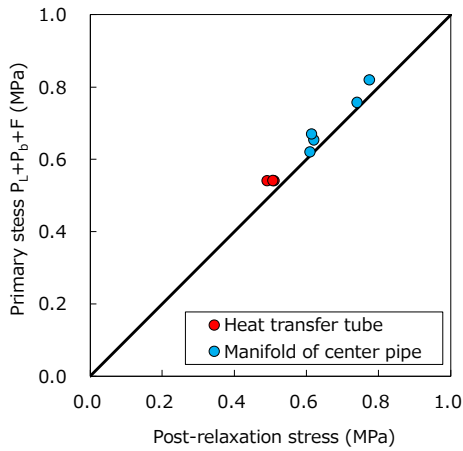


Figure 11. The relationship between the post-relaxation stress and the primary stress.

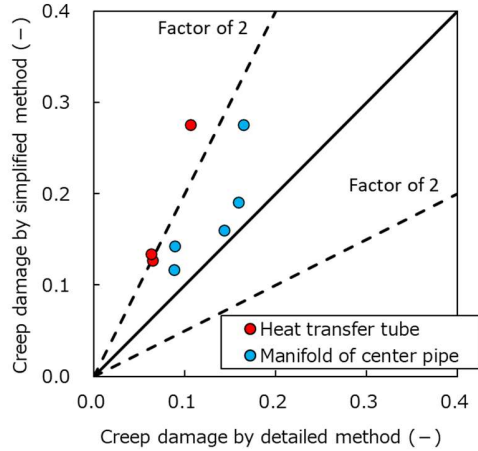


Figure 12. Comparison of creep-fatigue damage by the detailed inelastic FEA and simplified method.

Application example on the influence of stress level and maximum temperature

In a preliminary design of IHX, influences of both a stress level and temperature are of interest to find out both an optimum configuration and operation conditions. The simplified creep-fatigue life evaluation method can be an adequate tool for studying an influence of these parameters. Here trial evaluation was performed for the conditions in Table 2, where primary stress level (PL+Pb)/S0 is kept constant at 0.24; stress range $\Delta\sigma/\sigma_y=(PL+Pb+Q+F)/\sigma_y$ is “0~1.5”; elastic-follow up coefficient is q=3;

post relaxation stress level is the same as the primary stress level. Evaluation results of creep damage for 500,000 hours with 100 cycles of 5,000-hour hold time were depicted in Fig.13, where creep damage is a main factor determining a predicted creep-fatigue life (fatigue damage is negligible). Outline of obtained results is summarized as follows:

- (1) Under the assumption of constant level of $(PL+Pb)/S_0$, difference of creep damage is small between two temperature levels. Although allowable stress S_0 at 850°C is three times higher than that at 950°C , post relaxation stress $(PL+Pb)$ at 850°C is also three times higher than that at 950°C . This is the reason of small difference of creep damage at two temperature levels.
- (2) At both temperature levels, creep damage abruptly increases in the stress range exceeding the yield stress of the material. This comes from the stress-strain hysteresis loop shown in the figure; cyclic elastic-plastic hysteresis loop can cause a cyclic increase of creep damage; elastic shakedown hysteresis loop in the elastic range causes slow increase of creep damage resulting in allowable design area.
- (3) Choice of the primary stress level (same as post relaxation stress level) can be an important factor when discussing the relation between creep damage and maximum temperature.

Table 2 Conditions for the simplified creep-fatigue damage evaluation method.

| Temp. | Stress range $\Delta\sigma_e/\sigma_y$ | Yield stress σ_y (MPa) | Elastic-follow-up coeff. q | Primary stress level $(PL+Pb)/S_0$ | Post relaxation stress $(PL+Pb)/S_0$ | Allowable stress S_0 (MPa) | Young's modulus E (GPa) |
|---------------------|--|-------------------------------|------------------------------|------------------------------------|--------------------------------------|------------------------------|---------------------------|
| 950°C | 0~1.5 | 163 | 3 | 0.24 | 0.24 | 2.13 | 21.3 |
| 850°C | | 175 | | | | 6.38 | 63.8 |

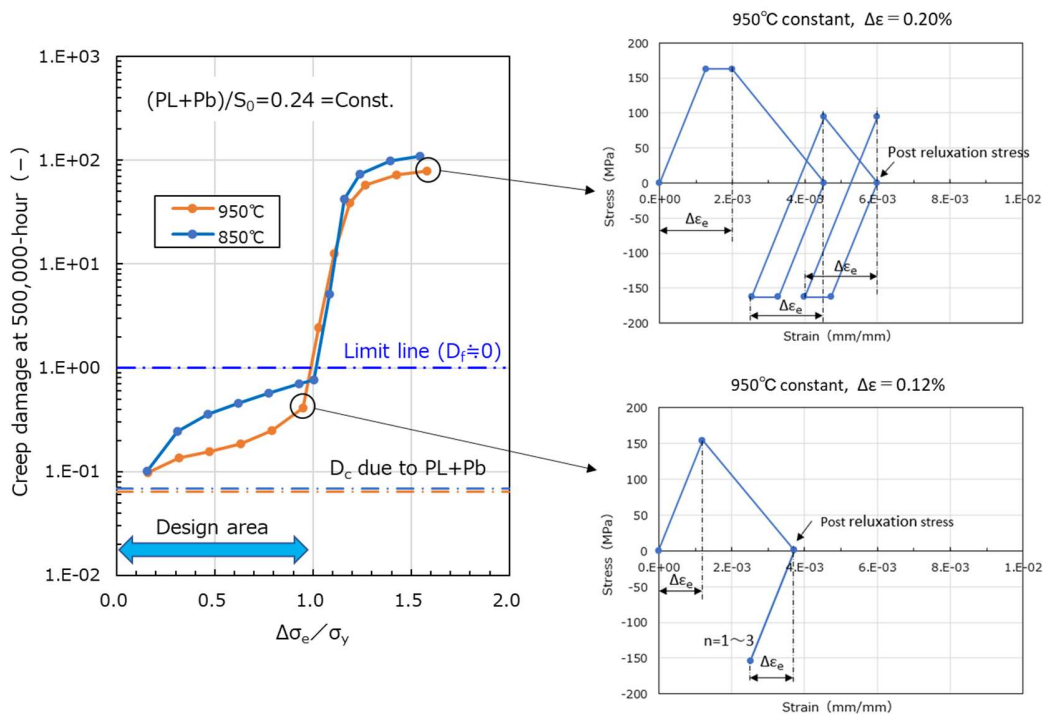


Figure 13. Creep damage by the simplified creep-fatigue damage evaluation method.

CONCLUSIONS

Detailed inelastic analysis was carried out for a helical-type heat transfer tube and a manifold of a centre pipe (made of Hastelloy XR) in IHX of HTGR subjected to 500,000-hour operation (100 cycles of normal start/stop with a hold time of 5000 hours). An applicability of a simplified creep-fatigue evaluation method was discussed, which was based on elastic analysis and reflected features of inelastic behavior of the structures. Obtained results are summarized as follows.

- (1) Inelastic behavior during the cyclic operation was an elastic shakedown with a stress relaxation due to creep during the hold time. An elastic-follow up coefficient q in the relaxation process was conservatively covered by $q=3$, which almost corresponds to the fast reactor standard.
- (2) The post-relaxation stress after hold time almost corresponded to a local primary stress intensity “PL+Pb+F” from elastic analysis. This is different from the fast reactor standard where the post-relaxation stress was considered as the stress level S_g giving creep damage 0.3.
- (3) Based on the strain range “(PL+Pb+Q+F)/E” from a local primary and secondary stress intensity, a uniaxial inelastic hysteresis loop of the material was obtained using the above $q=3$ and the post-relaxation stress. Predicted creep damage from this simplified creep-fatigue life evaluation method coincided with those by detailed inelastic analysis almost by a factor of 2.
- (4) An application example of the simplified creep-fatigue damage evaluation method was shown for two temperature levels of 950°C and 850°C. Elastic stress range showing slow increase of creep damage was found to be an allowable design area. Influence of primary stress level on creep damage at different temperature level is left for further study.

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