28

A PROPOSAL TO DEVELOP A HIGH TEMPERATURE STRUCTURAL DESIGN GUIDELINE FOR HTGR COMPONENTS

K. HADA
HTTR Designing Laboratory,
Japan Atomic Energy Research Institute,
Tokai-mura, Naka-gun, Ibaraki-ken,
Japan

Abstract

This paper presents some proposals for developing a high-temperature structural design guideline for HTGR structural components. It is appropriate that a basis for developing high-temperature structural design rules is rested on well-established elevated-temperature design guidelines, if the same failure modes are expected for high-temperature components as considered in such design guidelines.

As for the applicability of ASME B&PV Code Case N-47 to structural design rules for high-temperature components (service temperatures ≧900°C), the following critical issues on material properties and service life evaluation rules have been pointed out.

(i) no work-hardening of stress-strain curves at high temperatures due to dynamic recrystallization
(ii) issues relating to very significant creep
(iii) ductility loss after long-term ageing at high temperatures
(iv) validity of life-fraction rule (Robinson-Taira rule) as creep-fatigue damage evaluation rule.

Furthermore, the validity of design margins of elevated-temperature structural design guidelines to high-temperature design rules should be clarified.

Solutions and proposals to these issues are presented in this paper. Concerning no work-hardening due to dynamic recrystallization, it is shown that viscous effects cannot be neglected even at high extension rate for tensile tests, and that changes in viscous deformation rates by dynamic recrystallization should be taken into account. The extention rate for tensile tests is proposed to change at high temperatures. The solutions and proposals to the above-mentioned issues lead to the conclusion that the design methodologies of N-47 are basically applicable to the high-temperature structural design guideline for HTGR structural components in service at about 900°C.

1. Introduction

High-temperature components, e.g., He/He intermediate heat exchangers (IHXs), of HTGRs for nuclear process heat utilization systems are expected to function at service temperatures of 900C or above. Some of Ni-base or Fe-base heat-resistant alloys, e.g., Hastelloy X including Hastelloy XR, Inconel 617 and Alloy 800H, are the candidate structural materials for the high-temperature components. The service temperatures and the materials are beyond the scope covered by elevated-temperature structural design guidelines which are aiming primarily at applying to LMFBR components. Development of a high-temperature structural design guideline, therefore, is one of key issues to establish nuclear process heat utilization systems.

It is appropriate and reasonable that a basis for developing a high-temperature structural design guideline is rested on well-established elevated-temperature design guidelines, if the same failure modes are expected for the high-temperature components. In this paper, applicability of elevated-temperature structural design guidelines to high-temperature components of Hastelloy XR is discussed, and some proposals are presented to solve critical issues on the applicability.

2. Applicability of the Elevated-Temperature Structural Design Guideline

Applicability of elevated-temperature structural design guidelines to the high-temperature components should be discussed from aspects of failure modes of the structural materials and their material properties, as the first step. Furthermore, safety margins for design allowable stresses should be discussed.

2.1 Failure modes of Hastelloy XR

From reviewing material property and structural mechanics testings for Hastelloy XR and operation experiences of high-temperature experimental facilities made of Hastelloy X such as the ERANS High-Temperature Helium Test Loop, OGL-1 of JMTR and HENDEL in JAERI, the following seven modes of failure should be considered for the high-temperature components of Hastelloy XR in service up to about 1000C.

- Ductile rupture from short-term loadings
  The ductilities at tensile rupture exceed about 40% for unaged Hastelloy XR.
- Creep rupture from long-term loadings
- Fatigue and creep-fatigue failure
- Gross distortion due to incremental collapse and ratchetting
- Buckling due to short-term loadings
- Creep buckling due to long-term loadings
- Loss of function due to excessive deformation

It should be noted here that long-term exposures at high temperatures lose the ductilities of Hastelloy XR at room temperature. The ductilities of thermally aged Hastelloy XR, however, still exceed about 10%. Although thermal ageing effects should be considered in structural designing, therefore, thermal ageing does not add new failure mode of brittle rupture.

ASME Boiler and Pressure Vessel Code Case N-47(1) provides guidelines for guarding against these failure modes in elevated temperature range (up to about 800C). Therefore, basic design philosophies of N-47, for example, the primary stress limits, are concluded to be applicable to the service temperature range up to 1000C for Hastelloy XR.

2.2 Material properties of Hastelloy XR

The material properties of Hastelloy XR should be reviewed as shown below, because rules in N-47 for guarding against 7 failure modes are constructed on several assumptions for properties of the materials listed in N-47 and the material properties are changeable with temperature even if the same failure modes are expected at high temperatures.

1) Short-term or tensile property
The short-term rupture ductilities are high even for the aged material, as mentioned above. As for the stress-strain curves, no work-hardening and "waving" are observed at temperatures of about 850C and above, due to dynamic recrystallization, one of viscous flow phenomena as illustrated in Fig. 1.

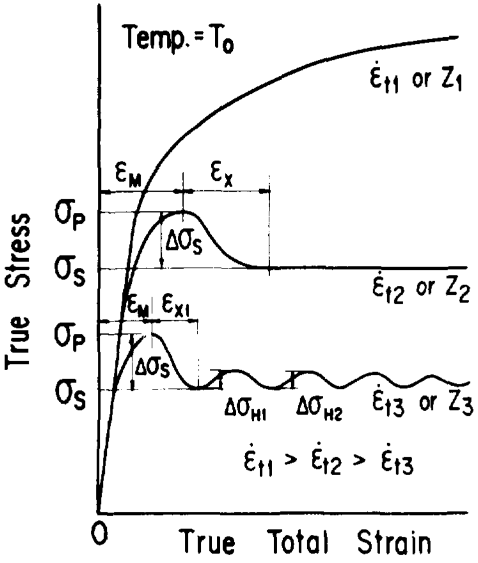


Fig. 1 Schematic Illustration of Stress-Strain Curves under Dynamic Recovery / Recrystallization

2) Creep property
The creep rupture ductilities are high even at longer creep rupture lives, as shown in Fig. 2. Even for Hastelloy XR, creep effects are very significant at temperatures of about 900C and above. Thus, relaxation rates of thermal stresses are so fast at 900C and above that elastically-calculated stresses cannot satisfy the design allowable limits on strain and creep-fatigue damage, as mentioned in another paper by the author et al.(2).

3) Fatigue property
Hastelloy XR is one of cyclic-hardening materials. In the temperature range of very significant creep, however, no cyclic hardening., i.e., constant stress range, is observed under strain rate-controlled fatigue testings at constant total strain ranges, due to very significant viscous flow or creep even at high strain rates.

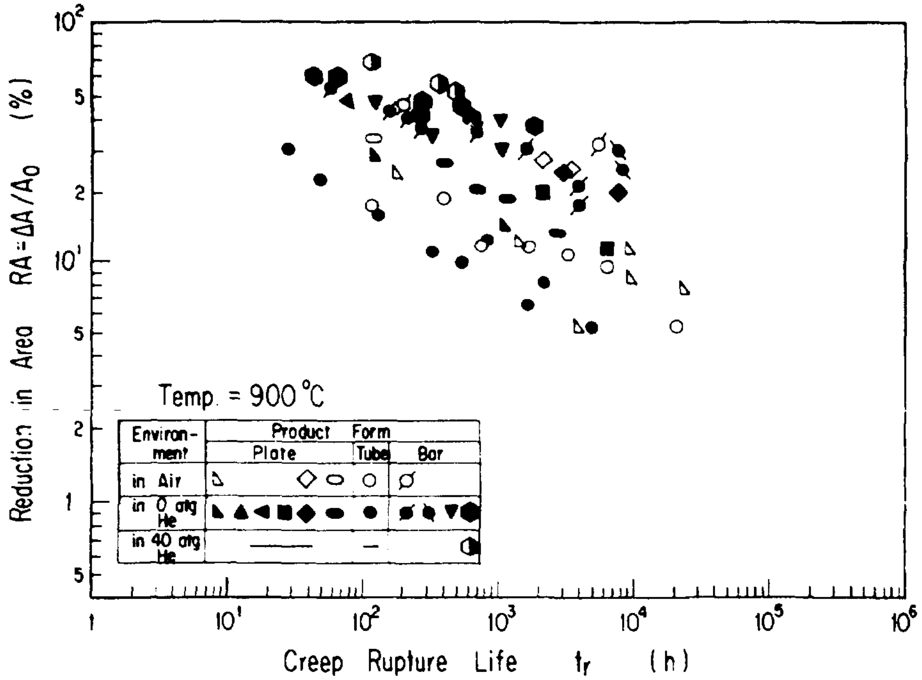


Fig. 2 Creep Rupture Ductility of Hastelloy XR (Temperature = 900°C)

As the concluding remarks, the following critical issues on the material properties of Hastelloy XR should be discussed for the applicability of N-47.

- No work-hardening of stress-strain curves at high temperatures due to dynamic recrystallization
- Issues relating to very significant creep
- Ductility loss at low temperatures after long-term ageing at high temperatures

2.3 Safety margins

Safety margins are defined from failure probabilities of components. The failure probabilities are closely related to variations in material properties, especially to probability distributions of variables defining the variation behavior.

The creep rupture life, one of the governing material properties at high temperatures, is lognormally distributed for Hastelloy XR, as shown in Fig. 3. The lognormal distribution of the creep rupture life is assumed for the materials in N-47. Thus, the basic philosophy of N-47 for defining the safety margins are applicable to the high-temperature structural design guideline.

3. Proposals for the Critical Issues

Of the critical issues on the material properties as mentioned in Chapter 2, dynamic recrystallization and ductility loss due to thermal ageing are discussed here. Structural behavior such as stress relaxation process under very significant creep is able to be predicted by using a sophisticated and accurate inelastic (in particular, creep) analysis method.

3.1 Dynamic recrystallization

Dynamic recrystallization is well-known to be developed under high straining rates at high temperatures in some types of materials, and to cause metallurgical changes in materials and then changes in viscous deformation strengthes, as illustrated in Fig. 1. In this figure, the Zener-Hollomon factor Z is defined as follows,

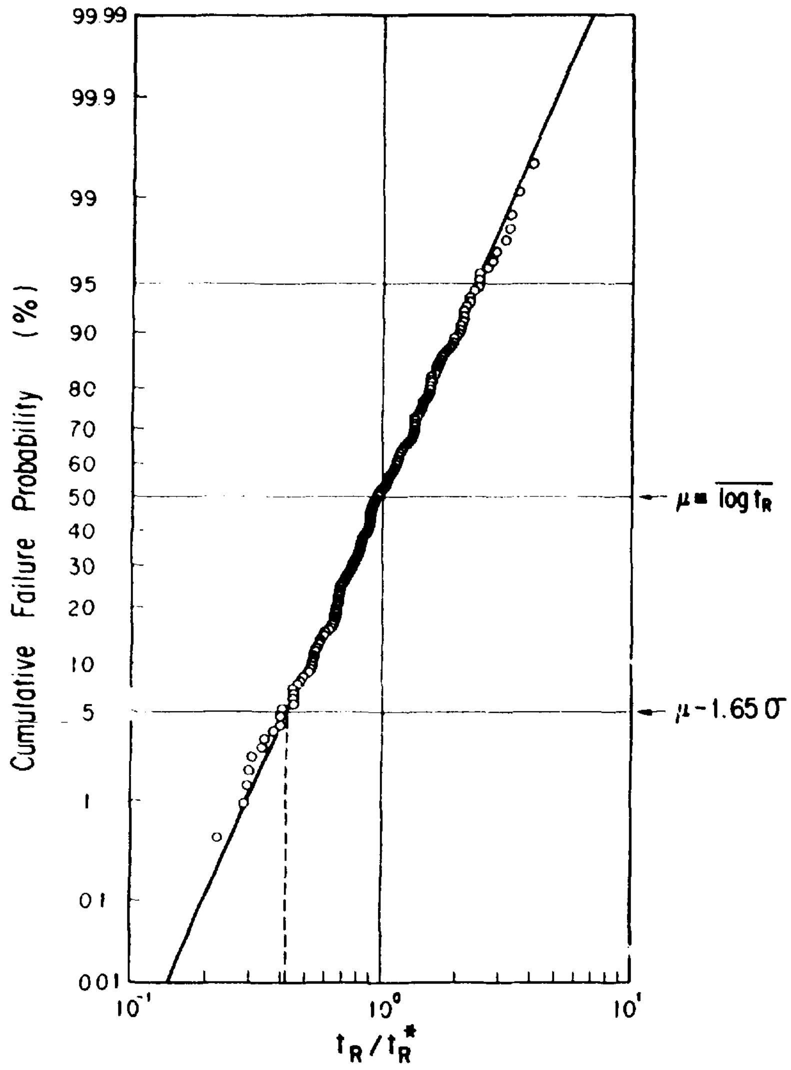
$$Z = \dot{\varepsilon}_t \exp(Q/RT)$$

where $\dot{\varepsilon}_t$ is the strain rate and T the absolute temperature. For Hastelloy XR, the dynamic recrystallization does not occur at slow strain rates observed during creep tests, but does at high strain rates during tensile and fatigue tests. Accordingly, questions as shown below arise associated with the dynamic recrystallization.

Q1)How to define the time-independent design allowable stress limits(Su, Sy and Sm in N-47)

Q2)Structural behavior at high strain rates under dynamic recrystallization

As for Q1, it should be noted that dynamic restoration caused by dynamic recovery and/or dynamic recrystallization is one of viscous flow or creep phenomena. Under the dynamic restoration phenomenon, therefore, yield strength and ultimate tensile strength are expected to change with strain rate as schematically illustrated in Fig. 4. The yield strengthes and ultimate tensile strengthes as the design stress limits are possible to be defined their values obtained at the strain rates of $\dot{\varepsilon}^*_{t,c}$ or above, which are considered the time-independent, plastic property (without creep). The yield strengthes and ultimate tensile strengthes at the strain rates below $\dot{\varepsilon}^*_{t,c}$ should be considered examples of short-term creep properties at constant strain rates under very significant creep.



t_R : experimental creep rupture life data

t_R^* : predicted by average TTP master curve

$(\mu = \overline{\log t_R} = \log t_R^*)$

Fig. 3 Probabilistic Distribution of Creep Rupture Life Data of Hastelloy XR.

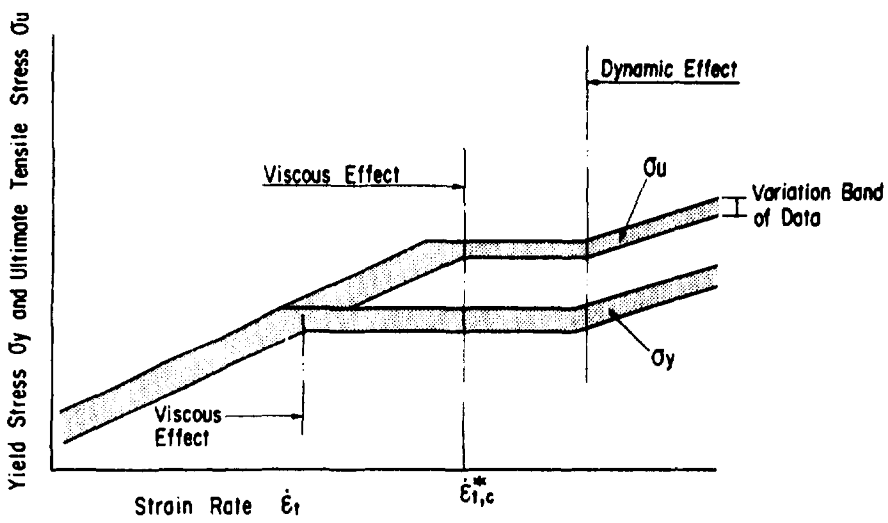


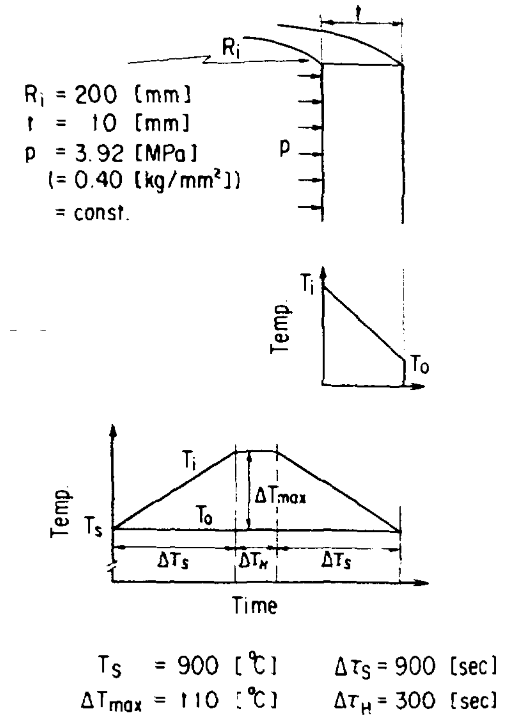
Fig.4 Schematic Illustration of Tensile Strength Dependence on Strain Rate.

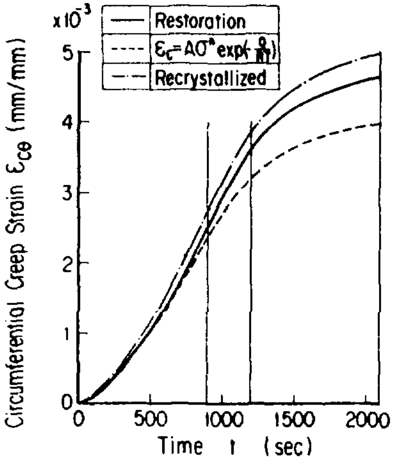
As for Q2, an example of numerically analyzed structural behavior of a thin cylindrical pipe(3) is shown in Fig. 5. In this figure, the solid line shows the structural behavior under dynamic recovery and recrystallization. As the behavior predictions on extremely idealized assumptions, the dashed line shows that under dynamic recovery only, while the chained line does that of the recrystallized material. This figure shows that the structural behavior under dynamic recrystallization can be predicted within those by two extremely idealized assumptions.

3.2 Ductility loss due to thermal ageing

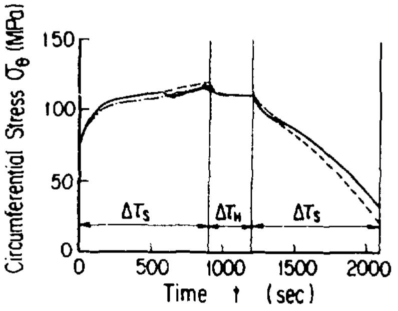
Ni-base superalloys such as Hastelloy XR and Inconel 617 are well-known to lose not only their ductilities but also their fracture toughnesses at low temperatures after long-term thermal ageing. Moreover, thermal ageing is found to reduce fatigue crack growth resistance of Hastelloy XR at low temperatures(4).

Such embrittlement due to thermal ageing should be taken into account for structural safety evaluation on pre-existing flaws in low temperature operating conditions (for example, during reactor shut-down), but haven't necessarily to be done for structural integrity evaluation. Structural





(b) Creep Strain Variation



(a) Stress Variation

(A) Loading Conditions of Cylindrical Pipe

(B) Structural Behavior Variation of Cynnarical Pipe.

Fig. 5 Structural Behavior under Dynamic Recovery / Recrystallization

integrity evaluation on thermal ageing embrittlement, however, should be made of the heat transfer tube bundle structure of the IHX under seismic or fluid-induced vibration conditions if the heat transfer tubes are supported by a type of assembled tube support mechanism. The structural safety and integrity evaluations show that the design of the IHX by JAERI is acceptable for the thermal ageing embrittlement(5).

4. Service Life Evaluation Rules

The discussion on failure modes and material properties and the proposals to the critical issues clarify that N-47, one of the elevated-temperature structural design guidelines is basically applicable to the high-temperature components. Next, the applicability of the design rules of the elevated-temperature design guidelines should be discussed.

Another paper by the author et al.(2) revealed that the accumulated creep damages or creep strains determined the service life of the IHX. Here, the applicability of creep damage evaluation rules is discussed. In N-47, the time-fraction rule is applied to the accumulated creep damage evaluation of elevated-temperature components. The time-fraction rule has the following features.

- safe-side evaluation of creep damage, and in some cases, overconservative,
- the least experimental data required to establish the rule among creep damage evaluation rules proposed, and
- many applications to elevated-temperature components such as IHXs and SGs of LMFBRs.

Furthermore, the time-fraction rule has been applied to one of high-temperature metallic materials, Hastelloy XR, and has demonstrated the safe-side evaluations.(6) Therefore, the creep damage evaluation rule in N-47 can be concluded to be basically applicable to the high-temperature components of Hastelloy XR.

Under very significant creep, however, the time-fraction rule needs accurate stress-time histories, requiring a sophisticated and accurate inelastic analysis method, and this rule does not have any theoretical backgrounds. Designers of the high-temperature components prefer more reasonable damage evaluation rules to the time-fraction rule, because the accumulated creep damages determine the structural life. Other well-known creep damage evaluation rules have the following difficulties in applying to the high-temperature components.

1) Strain-range partitioning rule(7)
   The rule is difficult to apply to hysteresis loops without any plastic strains.
2) Damage rate accumulation rule(8)
   The updated version applicable to multi-axial stress fields has not yet been proposed. Many experimental data are required to establish the rule.

On the other hand, the ductility exhaustion rule(9) has a prospective applicability to high-temperature components as follows,

- to have the theoretical background which can be derived from continuum damage mechanics as shown in Appendix,

- the least experimental data required, and
- creep strains or enhanced creep produced by thermal stresses even under very significant creep can be evaluated without using inelastic analysis method.

5. Concluding Remarks

Discussions on failure modes, material properties and safety margins of Hastelloy XR lead to the conclusion that the elevated-temperature structural design guidelines could be applicable to the high-temperature components in service up to about 1000C. The following critical issues on the applicability are clarified.

- No work-hardening at high-temperatures due to dynamic recrystallization
- Issues relating to very significant creep
- Ductility loss after long-term ageing at high temperatures

Some proposals to these issues are presented in this paper.

Furthermore, the applicability of typical creep damage evaluation rules to the high-temperature components is discussed. The well-established time-fraction rule in N-47 demonstrates the applicability to Hastelloy XR, while the ductility exhaustion rule is shown to be prospective.

Appendix Derivation of Ductility Exhaustion Rule from Continuum Damage Mechanics

The Rabotnov's hypothesis$^{(A-1)}$, a criterion of the continuum damage mechanics, is formulated through the following combination of equations,

$$\frac{d\varepsilon_c}{dt} = \frac{C}{(1-\omega)^{\eta}}\,\sigma^{\alpha} \qquad \text{---- (A-1)}$$

$$\frac{d\omega}{dt} = \frac{D}{(1-\omega)^{\xi}}\,\sigma^{\beta} \qquad \text{---- (A-2)}$$

where ε_c is the creep strain and ω the accumulated creep damage. Now, consider a case where $\eta = \xi$ in the above equations, and then

$$d\omega = \frac{D}{C}\,\sigma^{\beta-\alpha}\,d\varepsilon_c \qquad \text{---- (A-3)}$$

In a case of brittle creep rupture at a constant-load isothermal creep test when the rupture elongation is so small that $\sigma = \sigma_0$ = const., the creep rupture ductility $\varepsilon_{c,r}$ can be expressed as follows,

$$\varepsilon_{c,r}(\sigma = \sigma_0) = \frac{C}{D}\,\sigma_0{}^{\alpha-\beta} \qquad \text{---- (A-4)}$$

Then, Eq.(A-3) can be rewritten as

$$d\omega = \frac{d\varepsilon_c}{\varepsilon_{c,r}(\sigma = \sigma_0)} \qquad \text{---- (A-5)}$$

This is the ductility exhaustion rule.

[Reference]

(A-1) Yu. N. Rabotnov, "Creep Problems in Structural Members", North-Holland Publishing Company, 1969.

REFERENCES

(1) ASME Boiler and Pressure Vessel Code Case N-47-23(1986), ASME, New York.

(2) M. Okubo, K. Hada et al., "Structural Integrity Evaluation of a Helically-Coiled He/He Intermediate Heat Exchanger", presented at IAEA SM on High Temperature Metallic Materials forGCRs, Cracow, Poland June 20-23, 1988.

(3) K. Hada, "Study on Dynamic Restoration from Viewpoints of Structural Design and Evaluation", Proceedings of the 24th Symp. on Strength of Materials at High Temperatures, pp.31- 35, Tokyo, Japan, Dec.9-10, 1986.

(4) Private communication with S. Jitsukawa, JAERI, March 1988.

(5) K. Hada, Unpublished report.

(6) Private communication with H. Tsuji, JAERI, Dec. 1986.

(7) S. S. Manson, G. R. Halford and M. H. Hirschberg, "Creep-Fatigue Analysis by Strainrange Partitioning", Proceedings of First Symp. on Design for Elevated Temperature Environment" pp.12-24, San Francisco, May 10-12, 1971.

(8) S. Majumdar and P. S.Maiya, "A Unified and Mechanistic Approach to Creep-Fatigue Damage", ANL-76-58(1976).

(9) J. F. Polhemus, C. E. Spaeth and W. H. Vogel, "Ductility Exhaustion Model for Prediction of Thermal Fatigue and Creep Interaction", ASTM STP 520, pp.625-636, 1973.

DESIGN REQUIREMENTS FOR HIGH TEMPERATURE METALLIC COMPONENT MATERIALS IN THE US MODULAR HTGR*

A.S. SHENOY, W.S. BETTS
General Atomics,
San Diego, California,
United States of America

Abstract

The modular high temperature gas-cooled reactor (MHTGR) is a 350 MW(t) second generation reactor system design which during normal operation circulates helium with a mixed mean cold and hot temperature of 260°C (500°F) and 690°C (1270°F), respectively. The design incorporates passive design features which allow the plant to be safely shutdown and cooled with no active systems or operator action being required. A key feature of this concept is the capability of the residual heat removal by passive conduction cooldown from the core to the reactor cavity via an uninsulated vessel. The MHTGR uses a number of metallic components. A description of these components and their design requirements are presented in this paper.

1. MHTGR PLANT DESCRIPTION

The MHTGR plant is divided into two major areas: a Nuclear Island (NI) containing the four reactor modules, and an Energy Conversion Area (ECA) containing the two turbine generators. The four reactor modules, each of which produces a thermal output of 350 MW, are cross-headered to feed the two turbine generators operating in parallel.

Within the NI, each reactor module is housed in adjacent, but separate, reinforced concrete structures located below grade. A typical

---

*This is a report of work sponsored by the Department of Energy under Contract No. DE-AC03-88SF17367.