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# Research Activities on Development of Piping Design Methodology of High Temperature Reactors

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## 1. Introduction

In the present paper, the recent research activities on mechanical design and structural integrity assessment of structural components of high temperature reactor and material characterization under high temperature condition are summarized.

Among Generation-IV (GEN-IV) reactors, a Sodium-cooled Fast Reactor (SFR) is considered as most promising candidate reactor in South Korea to reduce the radiotoxicity of spent nuclear fuel. A SFR is operated at high temperature and low pressure compared with commercial pressurized water reactor (PWR), and such an operating condition leads to time-dependent damages such as creep rupture, excessive creep deformation, creep-fatigue interaction and creep crack growth. Thus, high temperature design and structural integrity assessment methodology should be developed considering such failure mechanisms.

In terms of design of mechanical components of SFR, ASME B&PV Code, Sec. III, Div. 5 [1] and RCC-MRx [2] provide high temperature design and assessment procedures for nuclear structural components operated at high temperature, and a Leak-Before-Break (LBB) assessment procedure for high temperature piping is also provided in RCC-MRx, A16 [3]. However, since the procedures given in these codes are not so simple to be used in actual calculations, the computer software needs to be developed. In this context, web-based design and LBB assessment programs have been recently developed in this work. Furthermore, for the accurate LBB assessment, new engineering estimation methods of creep $C^*$ and creep COD rate have also been proposed, and the feasibility of Garofalo's creep model on simulating deformation of Gr. 91 under high temperature has been studied in the present work.

## 2. Development of high temperature piping design method

### *2.1. ASME B&PV code, Sec. III, Div. 5 based design assessment program*

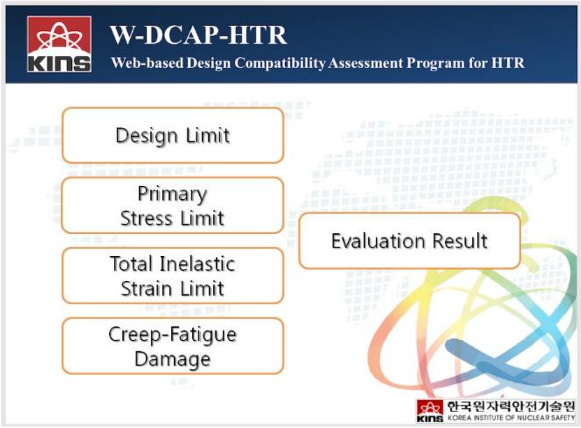


Fig. 1 Main window of W-DCAP-HTR

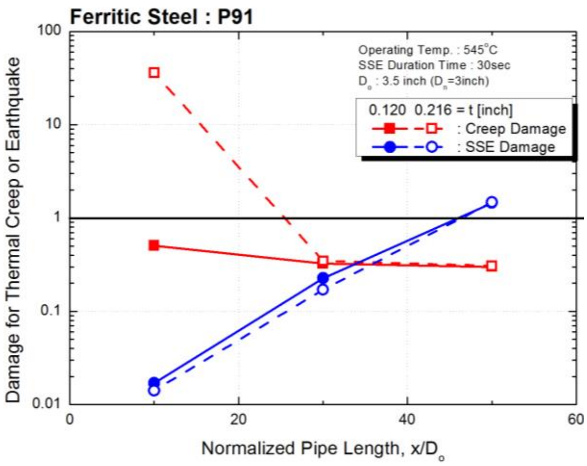


Fig. 2 Creep and SSE damages for P91

Based on ASME B&PV Code, Sec. III, Div. 5, HBB-3200 (Design By Analysis, DBA) procedure, web-based evaluation program, named as W-DCAP-HTR, was developed. As shown in Fig. 1, W-DCAP-HTR is composed of four evaluation modules, i.e., Design Limit, Primary Stress Limit, Total Inelastic Strain Limit and Creep-Fatigue Damage. Since this program was developed based on DBA rule, the detailed finite element analyses should be performed to obtain linearized stress results and strain values. The confidence of this program was validated against the existing SIE ASME-NH program [4] using several benchmark problems.

In fact, the Design By Rule (DBR) procedure for high temperature piping design is not provided in ASME B&PV Code, Sec. III, Div. 5 yet, which results in great difficulties in piping design using ASME Div. 5. So, in the present work, in order to suggest guideline on piping design using DBA procedure in ASME Div. 5, some feasibility analyses were carried out for high temperature elbow system in BOP (Balance of Piping) system based on DBA in ASME Div. 5 together with detailed 3-dimensional finite element analyses. Fig. 2 shows the values of damages due to creep-fatigue and earthquake according to piping length of elbow system. In the Fig. 2, the acceptable ranges of piping length can be determined considering both failure mechanisms simultaneously.

### *2.2. RCC-MRx based assessment program*

RCC-MRx provides two types of design and assessment codes for high temperature structure. Hence, two web-based evaluation programs were developed.

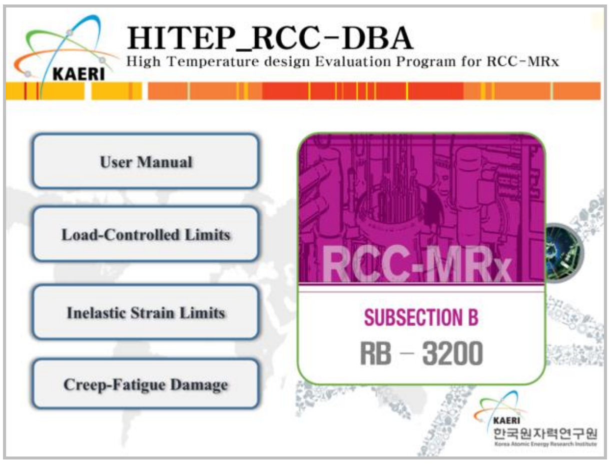


Fig. 3 Main window of HITEP_RCC-DBA

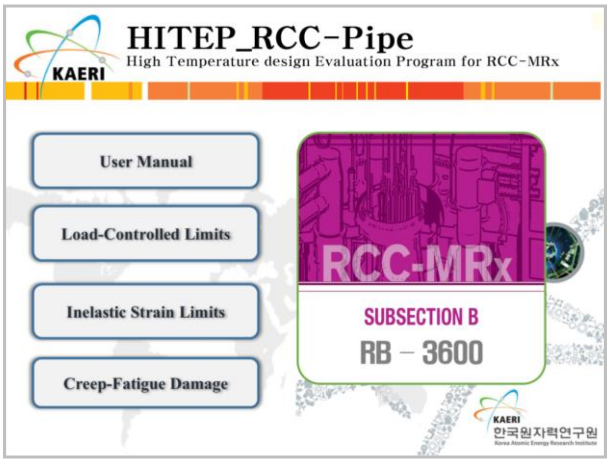


Fig. 4 Main window of HITEP_RCC-Pipe

Firstly, HITEP_RCC-DBA was developed based on RCC-MRx, RB-3200 (DBA) procedure which has similar assessment procedure with ASME B&PV Sec. III, Div. 5, HBB-3200. The second program is HITEP_RCC-Pipe which is based on RCC-MRx, RB-3600 (DBR for piping design). As mentioned previously, although ASME B&PV Code, Sec. III, Div. 5 for high temperature components gives only DBA procedure, the RCC-MRx provides not only DBA rule but also DBR procedure for high temperature piping system. Fig. 3 and 4 show the main window of HITEP_RCC-DBA and HITEP_RCC-Pipe, respectively. These two programs have three evaluation modules, i.e., Load-Controlled Limits, Inelastic Strain Limits and Creep-Fatigue Damage. Self-verification analyses were performed for two programs and additional round-robin based verification will be in progress.

## 3. LBB assessment and creep deformation model for high temperature piping system

### *3.1. Reference stress based flaw assessment for non-idealized through-wall flaws*

For an assessment of a flaw in a component at elevated temperatures, time-dependent fracture mechanics parameters should be calculated to investigate high temperature crack growth and leak rate. Hence, estimations of creep $C^*$-integral for creep crack growth and creep COD rate for leak rate were addressed for non-idealized TWC (Through-Wall Crack) in cylinders under creep condition. Both GE/EPRI and reference stress based methods were newly proposed and $C^*$-integral for non-idealized axial TWC in cylinders can be expressed as follows:

$$C^{*,non-idealized}_{GE/EPRI} = \alpha A a_1 h_1 \left(\frac{R_m}{t}, n, \rho_1, \frac{\rho_1}{\rho_2}\right)\left(\frac{P}{P_L}\sigma_0\right)^{n+1} \quad (1)$$

$$\frac{C^{*,non-idealized}_{ERS}}{J_e^{non-idealized}} = \frac{E\dot{\varepsilon}_c}{\sigma_{ref}} \; ; \; \sigma_{ref} = \frac{P}{P_{OR}}\sigma_0 \quad (2)$$

The proposed estimation schemes based on GE/EPRI and reference stress concepts were validated against finite element results.

### *3.2. RCC-MRx A16 based LBB assessment program*

HITEP_RCC-A16 was developed based on RCC-MRx, A16 procedure. RCC-MRx, A16 provides assessment guide for LBB assessment, creep-fatigue crack initiation and propagation. As shown in Fig. 5, HITEP_RCC-A16 consists of three evaluation modules, i.e., Creep-Fatigue Initiation, Creep-Fatigue Propagation and Leak-Before-Break, which will be validated against MJSAM program.

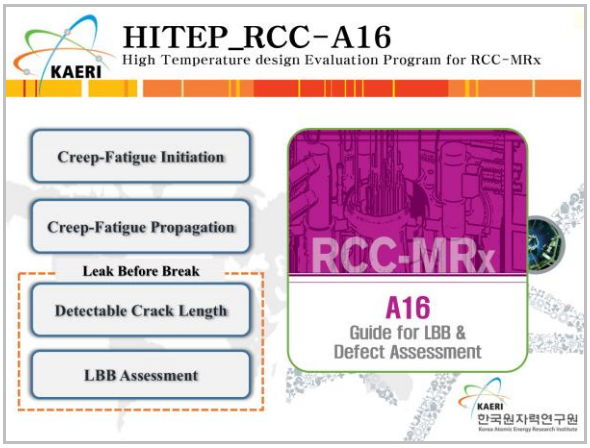


Fig. 5 Main window of HITEP_RCC-A16

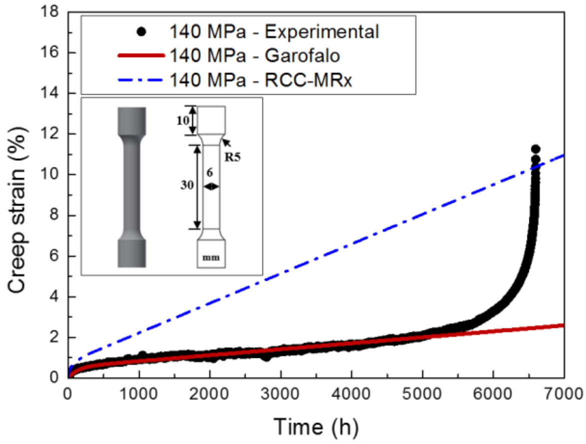


Fig. 6 Comparison of FE results for Garofalo's model with experiment results and RCC-MRx model

### *3.3. Creep deformation characterization for Gr. 91 steel using Garofalo's creep model*

In order to describe the deformation behavior of material of interest at elevated temperature, well-validated creep deformation model is required, which could be used, for instance, to produce isochronous stress-strain curves of materials. RCC-MRx tome 6 provides creep deformation model and its coefficients for Gr. 91 steel. However, creep deformation model given in RCC-MRx gives somewhat overestimated creep deformation compared to actual experimental results. To describe creep deformation behavior of Gr. 91 steel, Garofalo's creep deformation model was employed in the present work, and the equation of Garofalo's creep model is given as follows [5]:

$$\varepsilon = \varepsilon_o + \varepsilon_t[1-e^{-rt}] + \dot{\varepsilon}_{ss}t \qquad (3)$$

The parameters of Garofalo's creep model, i.e., $\varepsilon_t$, $r$ and $\dot{\varepsilon}_{ss}$ were calibrated from the results of tensile creep tests at 600 ℃. Using the calibrated Garofalo's creep model and RCC-MRx creep model, CREEP (user creep material in ABAQUS subroutine) subroutines were developed and detailed finite element analyses were performed for tensile creep tests under six constant tensile loads. Figure 6 compares the experimental results with finite element results both based on Garofalo's model and RCC-MRx creep model. As shown in this figure, the present Garofalo's creep model provides more accurate creep deformation results than RCC-MRx creep model.

## 4. Summary

The recent research activities on developing piping design methodology for high temperature reactors are addressed in this paper.

Three web-based evaluation programs based on the current high temperature codes were developed for structural components of high temperature reactors.

Moreover, for the detailed LBB analyses of high temperature piping, new engineering methods for predicting creep *C**-integral and creep COD rate based either on GE/EPRI or on reference stress concepts were proposed. Finally, the numerical methods based on Garofalo's model and RCC-MRx have been developed, and they have been implemented into ABAQUS. The predictions based on both models were compared with the experimental results, and it has been revealed that the predictions from Garafalo's model gave somewhat successful results to describe the deformation behavior of Gr. 91 at elevated temperatures.

In terms of piping design at elevated temperature, it should be pointed out that, recently, the research activities to come up with either DBR procedure or simple finite element stress/strain analyses procedure for Class A piping system of Korean SFR are in progress.

## REFERENCES

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