Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999



# The Design Standard for Strain limitation in Japanese Demonstration FBR Design

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ABSTRACT

DDS (Demonstration plant Design Standard; the structural design standard at elevated temperature for the Japanese demonstration fast breeder reactor) has been provided based on the design standard for MONJU called BDS. As the results, DDS is consistent with another design standard, but the appropriateness of the limitations proper to DDS, the ratchet evaluation methods and so on, have been confirmed with the theoretical and the analytical inspections. Especially, the evaluation method of the thermal ratchet caused by movement of the sodium level has been confirmed both with the experiment and with the analysis. In this paper, the overview of the strain limitation in DDS is described.

## 1. JAPANESE DEMONSTRATION FAST BREEDER REACTOR

Japanese Demonstration Fast Breeder Reactor (DFBR) is under development by Japan Atomic Power Company (JAPC) under the sponsorship from the electric power industry.

DFBR is a 660MWe sodium cooling FBR plant. It has a rector vessel (about 10m diameter) and the three coolant systems, and each vessel is connected with the top-entry piping. The maximum coolant temperature is about 550℃ and the maximum pressure is about 1.0MPa in the primary circuit. The components in the primary circuit is made of 316FR stainless steel (reducing carbon and adding nitrogen to type 316 stainless steel) to improve the creep-fatigue strength.

FBR components are subjected to relatively low pressure and high temperature, so the secondary stress caused by thermal transition and the temperature distribution is more noticeable rather than the primary stress.

## 2. THE STRAIN LIMITATION IN DDS

In designing the FBR components, the prevention of the large inelastic deformation caused by the combination of the primary stress and the secondary stress is important to keep their structural integrity, and the strain limitation is provided in DDS. The strain limitation in DDS also has the additional purposes for prevention of the creep rapture, of the buckling and collapse and so on.

The strain limitation in DDS is described in the following, and Figure-1 shows the evaluation flow of the strain limitation.

## 2.1 The overview of the strain limitation in DDS

In this limitation, the inelastic strain is evaluated by the summation of three types of strain, the enhanced creep strain $\varepsilon_{EC}$, the ratcheting strain $\varepsilon_{R}$ and Elastic follow-up strain $\varepsilon_{EF}$, and the total inelastic strain under the operating condition Ⅰ, Ⅱ, Ⅲ and the test is limited to the following criteria.

- For the membrane (averaged) strain through the thickness : 1%
- For the linearized surface strain through the thickness : 2%

Each of the above three strains can be basically evaluated with the elastic analysis (route-1 in figure-1). If the conservativeness of the evaluation can be proved by other method for example the experiments, the complete inelastic evaluation (route-2 in figure-1) and the partial inelastic evaluation (which is only for the evaluation of ratcheting strain (route-3 in figure-1)) can be used.

In the case that the stress obtained from the elastic analysis can be classified as an elastic region which is called "Sa limitation", the behavior of the material can be considered to be elastic, so the accumulated inelastic strain can be ignored. In the other case, the each of the above three strain components (i.e. accumulated inelastic strain) must be evaluated. The evaluation method for each strain component are described in the section 2.2～2.4.

In the case of evaluating with the elastic analysis, the integrated inelastic strain must be expected conservatively based on the results of the elastic analysis. In DDS, the strain limitation for the inelastic strain is given with elastic analysis considering the characteristics of the operating condition of DFBR. Especially, the increasing of the strain caused by the elastic follow-up must be considered carefully, so the secondary stress is provided to be re-classified appropriately.

## 2.2 The evaluation of the enhanced creep strain

In DDS, to evaluate the enhanced creep strain conservatively, it can be evaluated by regarding the uniform stress which is larger than the initial membrane stress as the membrane stress (called "core stress") which is loaded through the all thickness.

The enhanced creep strain can be evaluated with the equation (1). The first term in this equation expresses the strain caused by the stress in the operation condition Ⅰ and Ⅱ, and the second term expresses that the increasing of the strain caused by the increasing of the core stress in the case that the larger stress is loaded.

The above philosophy is in accordance with ASME section NH.

$$\varepsilon_{EC} = \sum_i \{\varepsilon_c(\sigma_0)\}_i + \sum_j \frac{\sigma_{cj}^2 - \sigma_0^2}{E\sigma_0} \qquad \text{Eq. (1)}$$

Where, $\sigma_0$ is the appropriate core stress, $\sigma_{cj}$ is the stress which exceed $\sigma_0$.

## 2.3 The evaluation of the ratcheting strain

In DDS, the ratcheting strain is admitted instead of evaluating it in detail, and the evaluation method of ratcheting strain is extended to the ratcheting region. There are several mechanisms of the ratcheting strain, and evaluation method for the each mechanism that supposed under the DFBR conditions are provided in DDS.

Table-1 show the ratchet mode treat in DDS. As shown in that table, the ratchet evaluation methods in DDS enable to evaluate the ratcheting strain due to the combination of the primary stress and the secondary stress and it caused only by the secondary stress. Where, the evaluation method for latter is added in DDS.

The appropriateness of these evaluation methods has been confirmed by the inelastic analyses concerning to the representative components of DFBR shown in figure-2～4.

The evaluation method for each mechanism is described in the followings.

### 2.3.1 The ratchet due to the combination of primary stress and secondary stress

In DDS, the evaluation methods for the two types of the ratchet mode in this category are provided. One is the well-known Bree type ratchet, which is caused by the combination of the primary membrane stress and the secondary bending stress. Another is the membrane-membrane type, which caused by the combination of the primary membrane stress and the secondary membrane stress. The latter evaluation method enables the appropriate treatment of the secondary membrane stress.

The original model of the Bree type ratchet is based on the flat plate subjected to the constant primary membrane stress and the secondary bending stress. The ratcheting strain per cycle for this mode is given by equation (2).

$$\Delta\varepsilon = Z(X,Y)\,\sigma_y/E \qquad \text{Eq. (2)}$$

Where, Z is a function expressed by the primary membrane stress parameter X and the secondary bending stress parameter Y. $\sigma_y$ is yield stress and E is Young's modulus.

On the other hand, the original model of the membrane-membrane type ratchet is based on the flat plate subjected to the constant primary membrane stress and the secondary membrane stress. Figure-5 shows the mechanism of this type ratchet. The cyclic secondary membrane stress $\sigma_{rmt}$ is loaded on the line between point A and B, and when stress exceeds the elastic range, the plastic strain corresponding to intensity of stress is occurred. Then, the plastic strain in the direction of the secondary stress is canceled because the same strain is produced during the loading and unloading, but the strain in the direction of the primary stress is not canceled, and the strain in this direction increases in every cycle. Based on the above mechanism, the membrane-membrane type ratcheting can be evaluated by equation (3). In DDS, this equation is improved by considering the temperature effect to $S_y$.

$$\Delta\varepsilon = \frac{3s_2}{2-s_2}(Y_2 + s_2 - 2)\frac{S_y}{E} \qquad \text{Eq. (3)}$$

Where, $Y_2$ is secondary membrane stress parameter, $s_2$ is the function expressed by the primary stress and the secondary stress. $S_y$ is yield stress and E is Young's modulus.

The stress condition in a real component can not be expressed as the above simple model. So, the conservativeness of the evaluation is kept by expressing the stress as stress intensity, adding the above two type ratcheting strain and so on. Furthermore, the primary membrane stress parameter X is expressed including the primary bending stress, and the secondary bending stress in evaluation of the Bree type ratchet is expressed including the secondary membrane stress.

2.3.2 The ratcheting caused by the secondary stress :

In DDS, the evaluation methods for the two types of the ratchet mode in this category are provided. One is the thermal ratchet caused by movement of the sodium level, and another is the secondary membrane type ratchet (or Sn' limitation). The former is applied to the membrane part of the components (for example the vessel wall) and the ratcheting strain is caused by the cyclic thermal stress due to the temperature distribution which is uniformly in the circumferencial direction and has a incline in the axial direction. This condition corresponds to it around the sodium level in the reactor vessel in DFBR.

Figure-6 shows the deformation behavior under the condition that the temperature distribution moves. Figure-6(b) shows the stress-strain relationship corresponding to movement of the temperature distribution shown in figure-6(a). In this time, the ratcheting strain per cycle is expressed by the equation $\Delta\varepsilon = \alpha\Delta T - 2\sigma_y/E$, and because the circumferencial membrane stress is expressed by the equation $\tau_m = E\alpha\Delta T$, the simplified evaluation equation for the thermal ratchet caused by movement of the sodium level is given by equation (4).

$$\Delta\varepsilon = 2(\sigma_m - \sigma_y)/E \qquad \text{Eq. (4)}$$

Furthermore, the following equation for this type ratchet is provided in DDS by considering the effects of the primary stress and the bending stress, and the effects of the moving distance of the temperature distribution and so on.

$$\Delta\varepsilon = AZ\sigma_y/E \qquad \text{Eq. (5)}$$

Where, A is a function of the height of the sodium level motion, and Z is a function expressed by the primary membrane stress parameter X and the secondary bending stress parameter Y. $\sigma_y$ is yield stress and E is Young's modulus.

Figure-7 shows the applicable region of this evaluation equation and the coefficient A.

The evaluation equation of secondary membrane type ratchet (or $S_n'$ limitation) is applied to the parts which is not membrane part of the components. The increasing of the strain caused by the secondary membrane stress, which exceeds the shakedown stress, can be evaluated by equation (6). This equation is based on the mechanism of the membrane-membrane type ratchet.

$$\Delta \varepsilon = 2(S_n' - \overline{3Sm})/E \qquad \text{Eq. (6)}$$

Where, $S_n'$ is sum of primary and the secondary stress except thermal bending stress.

The upper value of the secondary membrane stress is also limited by this evaluation

$S_n'$ limitation is given by equation (7), and this limitation has the role of the limitation of the stress intensity of primary and secondary membrane stress, similar to the secondary membrane type ratchet.

$$S_n' \leq \overline{3Sm} \qquad \text{Eq. (7)}$$

## 2.4 The evaluation of the elastic follow-up strain

In DDS, the elastic follow-up strain is evaluated separately as the components of the inelastic strain, and evaluation equation (8) is provided.

$$\Delta \varepsilon = \begin{cases} \alpha|\Delta T| \\ |\alpha_a T_a - \alpha_b T_b| \end{cases} \qquad \text{Eq. (8)}$$

The upper equation is for the case that the origin of the stress is the temperature difference, and the lower is for the case that the origin of the stress is the difference of the thermal expansion.

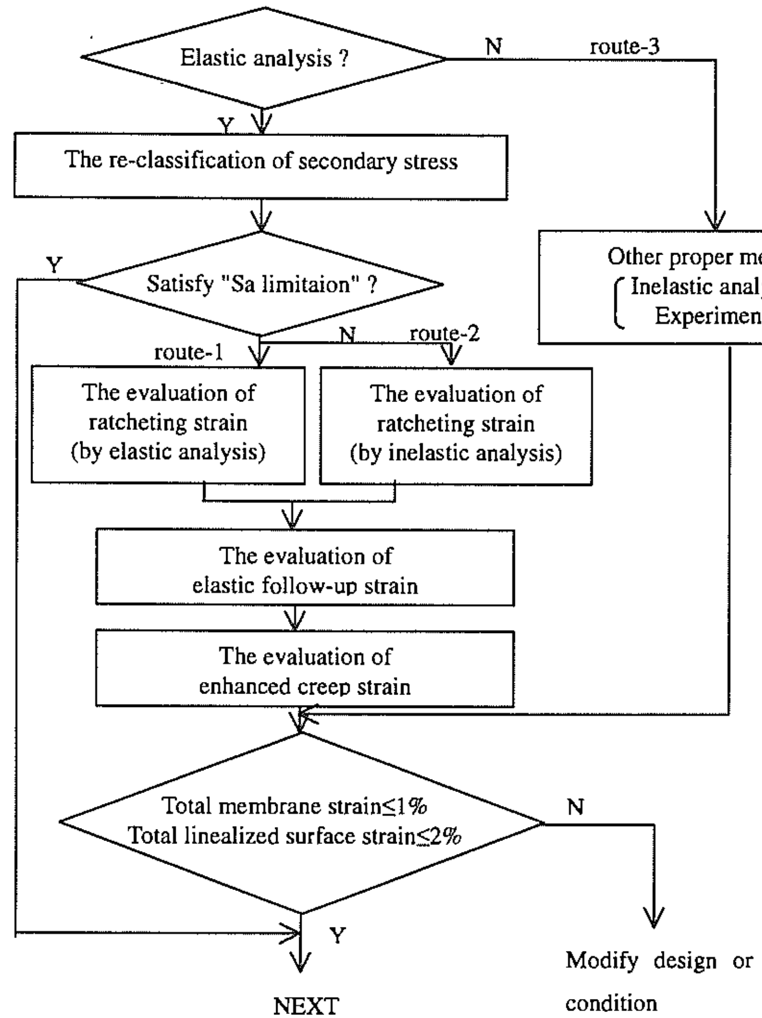
# 3. SUMMARY

Demonstration plant Design Standard for the Japanese demonstration fast breeder reactor including the strain limitation has been provided in 1998. With present DDS, the inelastic strain including the ratcheting strain can be evaluated conservatively. In the future, further improvement of the rationality and the accuracy of the evaluation will be performed.

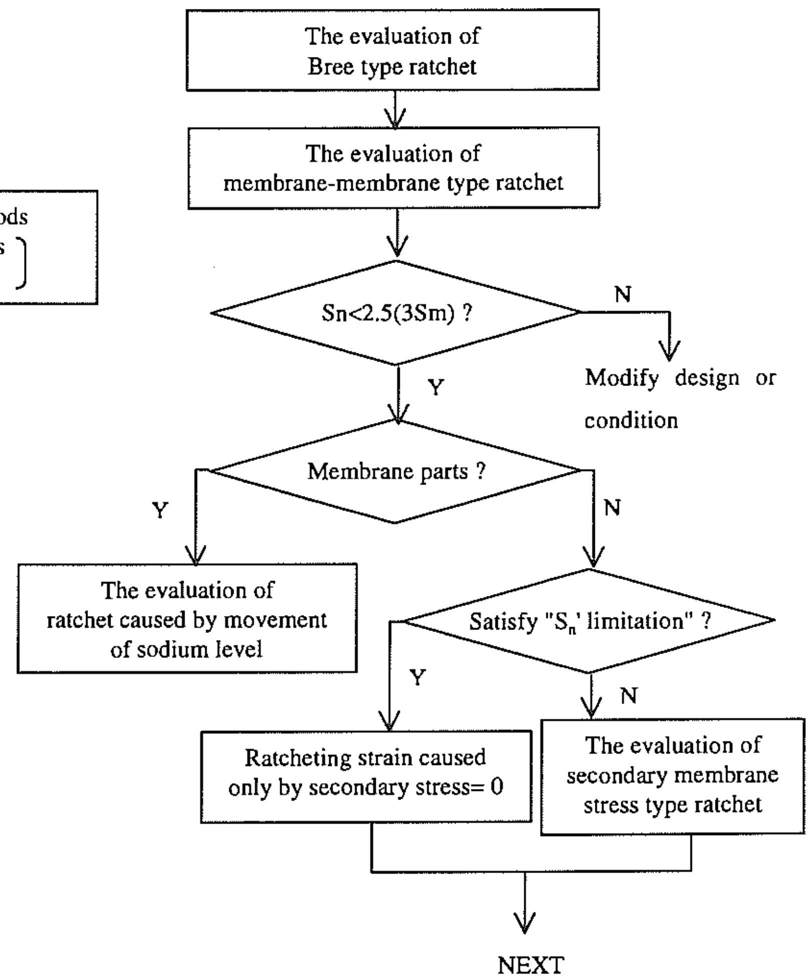

# ACKNOWLEDGEMENTS

Activities in this study has been performed as a part joint research and development projects for DFBR under the sponsorship of nine Japanese electric power companies, Electric Power Development Co., Ltd. and the Japan Atomic Power Company.

The authors would like to express their sincere gratitude to researchers and engineers of JNC, CRIEPI for the fruitful comments and discussion.

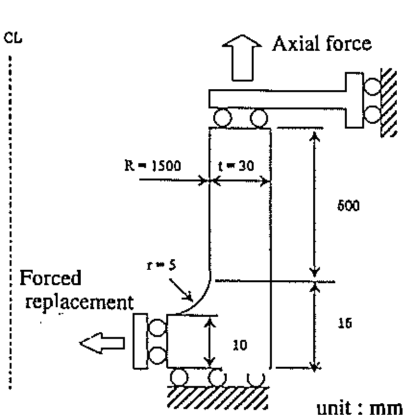



(a) The evaluation flow of the strain limitation in DDS

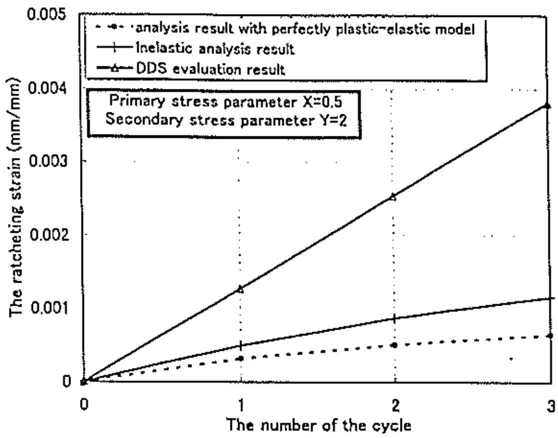



(b) The evaluation flow of the ratcheting strain in DDS

Figure-1 The evaluation flow of the strain limitation in DDS

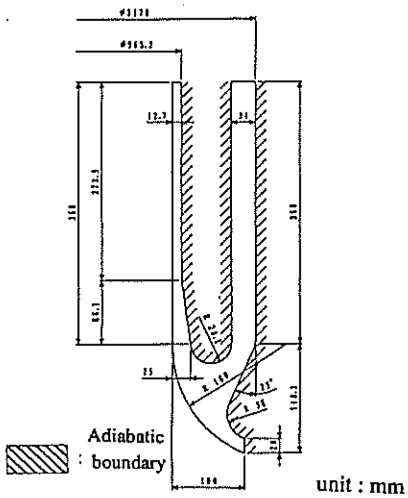



(a) model

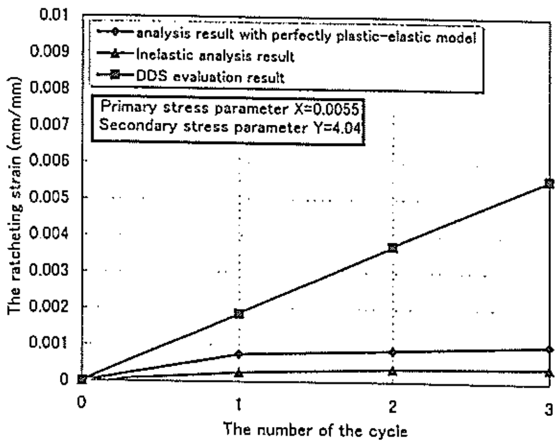



(b) analysis results

Figure-2 The ratchet analysis result concerning to the cylinder with discontinuity




(a) model




(b) analysis results

Figure-3 The ratchet analysis result concerning to the Y piece

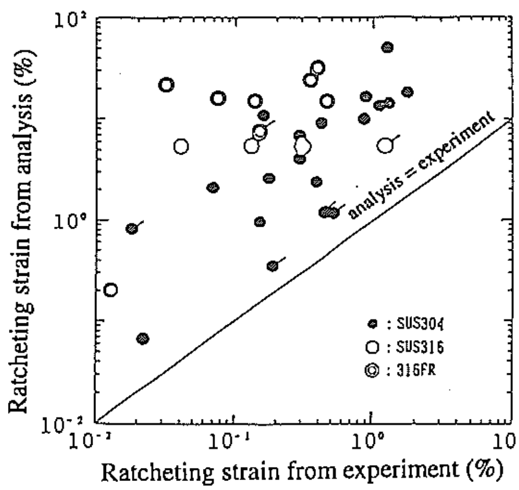



Figure-4 The analysis result concerning to ratchet caused by movement of sodium level

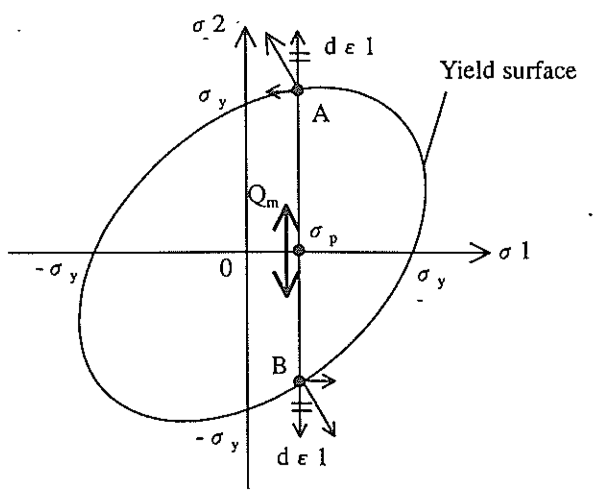
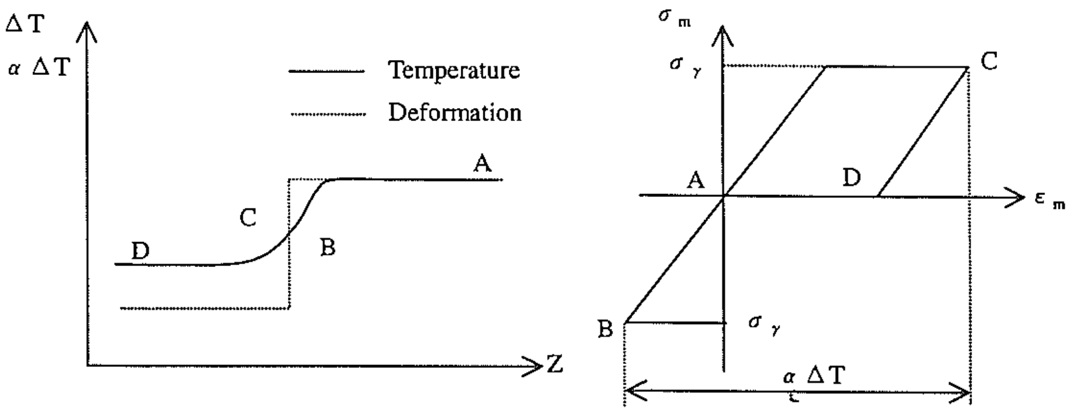
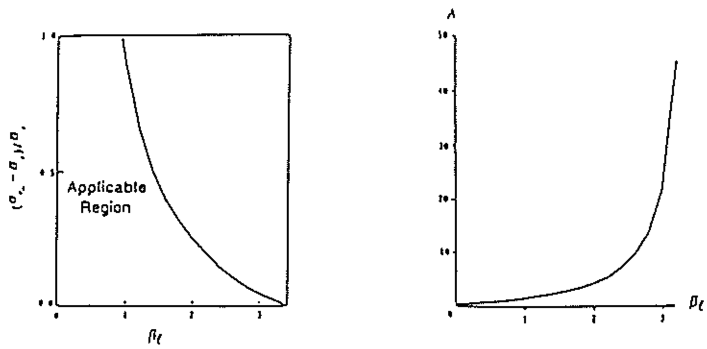



Figure-5 The mechanism of the membrane-membrane ratchet




(a) Temperature distribution and the deformation (b) The relationship between stress and strain

Figure-6 the deformation behavior under the movement of the temperature distribution




(a) Applicable region (b) Coefficient A

Figure-7 The evaluation method of ratchet caused by movement of sodium level

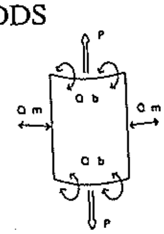
Table-1 The ratchet mode which can be evaluated by DDS

| Primary stress \ Secondary stress | | Membrane stress | | Bending stress | |
|---|---|---|---|---|---|
| | | Axial | Circumferencial | Axial | Circumferencial |
| Membrane stress | Axial | — | ○ | ○ | △ |
| | Circumferencial | ○ | — | — | ○ |
| Bending stress | Axial | | △ | △ | △ |
| | Circumferencial | △ | | △ | △ |

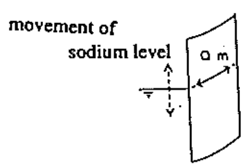
○ : There is a evaluation model in DDS

△ : Considered by replacing the stress with the equivalent stress

— : no model, but confirmed with the inelastic analysis



Bree type ratchet




Ratchet caused by movement of sodium level