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THREE-DIMENSIONAL STRUCTURAL ANALYSIS FOR ENHANCING RESILIENCE OFNEXT-GENERATION NUCLEAR STRUCTURES UNDER EXTREMELY HIGH TEMPERATURE CONDITIONS

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ABSTRACT

To enhance resilience of next-generation nuclear structures, it is necessary to develop design methodology that mitigates impacts of failure caused under extremely high temperature conditions which might lead to a severe accident. In this study, three-dimensional structural analyses of a loop-type sodium-cooled fast reactor (SFR) Monju as a typical SFR plant have been conducted to understand its deformation behavior of a reactor vessel (RV) and guard vessel (GV) which are important nuclear structures. This analysis has also aimed to identify the areas which should be focused to mitigate impacts of failure. A postulated event sequence was a protected loss of heat sink event, which may cause all decay heat removal systems to lose their functions immediately after reactor shutdown. The RV and GV temperatures were increased up to 900 °C over 24 hours to simulate the event sequence. The structural analysis showed;

- Both RV and GV deformed downward as the temperature increased. The GV bottom came into contact with an aseismic support located under the GV, and then the lower part of RV came into contact with the lower part of GV.
- The upper part of the RV body, the inlet nozzle area, and the GV lower part were identified as the areas that developed relatively great equivalent inelastic strain (plastic and creep strain). These correspond to the areas on which should be focused for damage prevention against extremely high temperatures.
- The integrity evaluation using the fracture criteria showed that the equivalent inelastic strains (plastic and creep strain) at the identified areas did not exceed the fracture criteria. It means these areas would not develop ductile fracture within a temperature up to 900 °C and in the calculation time of 24 hours.
- Great stress and relatively high equivalent inelastic strain (plastic and creep strain) were generated on the GV bottom. This result suggests that no discontinuous section of the RV and the GV bottom is recommended to avoid the fracture of the RV and the GV bottom in order to enhance the resilience.
- Stress on the RV upper part which was initially high at a low temperature was relaxed by creep behavior as the temperature rose.
- Stress on the inlet nozzle area peaked at 2 hours (600 °C) was reduced by creep behavior as the temperature rose.
- Deformation and contact behavior at the RV and GV bottom area did not influence to the fracture of the RV.
- Extreme high temperature deformation behavior induced by thermal expansion and gravitational force would not be concerned in the temperature range up to 900 °C and in the calculation time of 24 hours.

INTRODUCTION

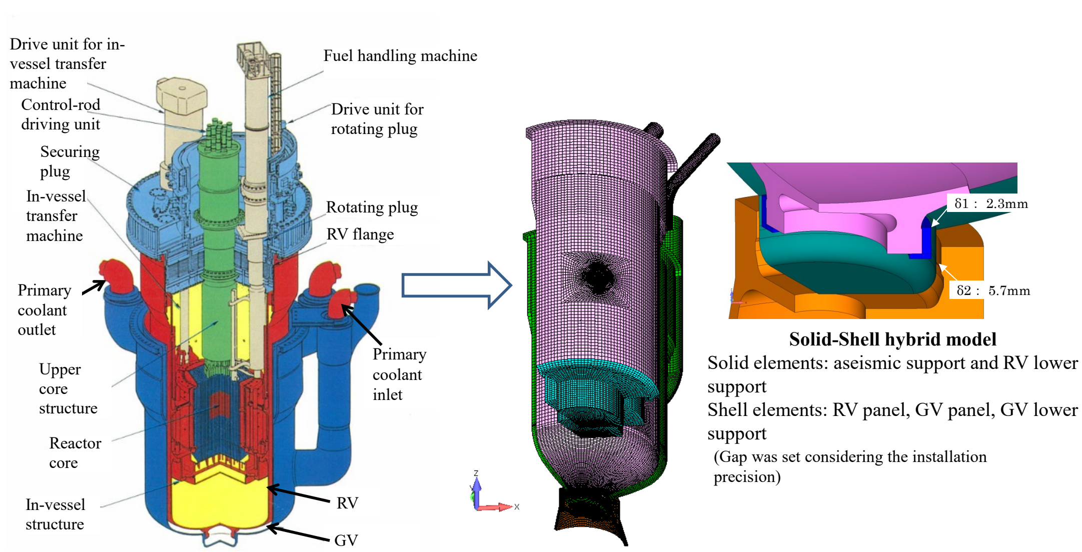
As the lessons learned from the TEPCO Fukushima Daiichi nuclear power plant accident, countermeasures for Beyond Design Basis Events (BDBE) have been recognized to be important for nuclear safety (Hatamura et al., 2014, IAEA 2015). However, previous efforts in the structural strength fields focused mainly on design basis event (DBE) area. There are few activities and are no suitable approaches for the BDBE area from the structural design point of view. Kasahara et al. (2017, 2019, 2020) has proposed a new mitigation approach for BDBE in the structural strength field. Several structural evaluations in severe accidents were conducted for light water reactors (LWRs) (e.g. Katsuyama et al., 2015). In the past SFRs, a reactor vessel (RV) has been regarded as failure below the boiling temperature of coolant due to creep failure under accident conditions of loss of heat removal system (JAEA 2015, Onoda et al., 2016). On the other hand, for next-generation nuclear structures, especially for sodium-cooled fast reactors (SFRs), identification of RV failure mode and evaluation of RV structural resilience were needed to enhance design approach for BDBE accident management (Onoda et al., 2021). To enhance structural resilience of SFRs, it is necessary to develop design methodology that mitigates impacts of failure caused under extremely high temperature conditions which might lead to a severe accident.

In this study, a three-dimensional structural analysis of the RV and guard vessel (GV) of a loop-type SFR, Monju, reinforced with anti-seismic lower support structure has been conducted to understand its deformation behavior and to identify the areas which should be focused to mitigate impacts of failure under an extremely high temperature condition. The postulated initiating event for the extremely high temperature condition is a protected loss of heat sink (PLOHS) event, which may cause all decay heat removal systems to lose their functions immediately after reactor shutdown.

ANALYSIS CONDITIONS

Analysis model

The structural analysis used a general-purpose finite element analysis code, FINAS/STAR, to model the RV, GV, and aseismic support, as shown in Figure 1 (Mitsumoto et al., 2019).



Example of an RV with anti-seismic lower support structure (Monju)

Figure 1. Three-dimensional analysis model

Topical structural features of RV and GV are shown below;

- RV and GV are hanged from upper deck floor.
- Three primary system piping is symmetrically connected to RV shell.
- Seismic horizontal displacement of RV and GV are restricted by a narrow gap of lower support structure of aseismic support.

And, topical feature of analysis model is shown below;

- RV, GV, aseismic support, and a part of the primary coolant pipes were modelled considering interaction between the structures.
- 1/3 sector model
- Number of nodes in the structure: 109,015
- Number of elements: 101,390
- Extremely high temperature material property equations and physical property values were used (JSME 2016, Onizawa et al., 2019)

In this study, 2 cases of structure model are conducted to focus on the influence of lower support structure. Case 1 is with aseismic support model, and Case 2 is without aseismic support model.

Postulated event sequence and analysis conditions

In this study, a postulated event sequence was the PLOHS event, for which analysis conditions are shown below;

- Pipe failure causes loss of all cooling functions and results in PLOHS.
- The RV body temperature continues to rise for 10 hours from 530 °C to 900 °C (initial temperature + 370 °C). Temperature gradient is not changed since the occurrence of the event (see figure 2). Since then, 900 °C is kept till 24 hours for this calculation.
- The GV temperature is the same as the RV body temperature.
- Internal pressure of the primary system is constant assuming the piping failure (pressure difference between the inside and the outside of RV is 0).

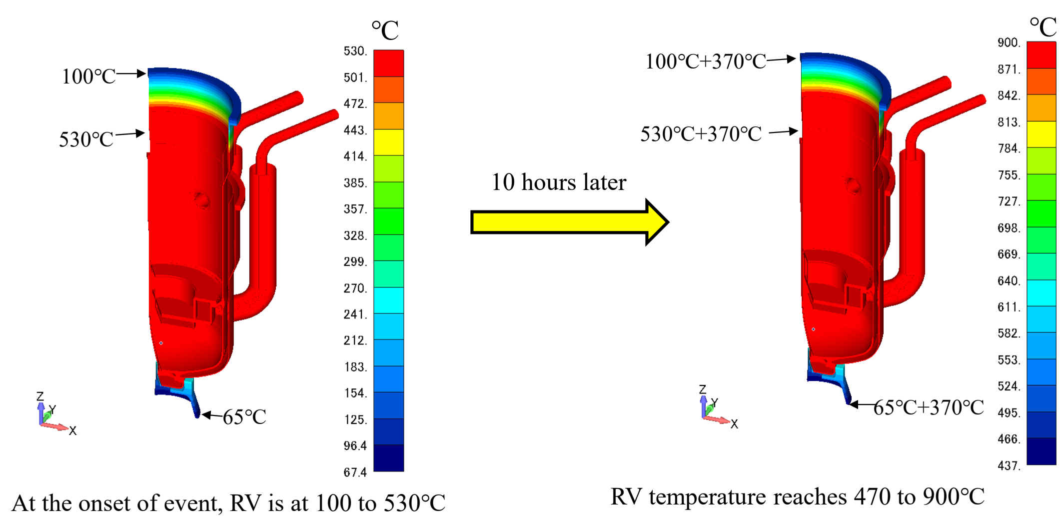


Figure 2. Temperature distribution condition

In these conditions, a matter of concern is extreme high temperature deformation behaviors induced by thermal expansion and gravitational force. Deformation and contact behavior of RV and GV bottom area may influence to the fracture of RV. From the view point of accident management in SFRs, maintaining RV sodium level in the long term is a key safety function to enhance resilience of next-generation nuclear structures. The fracture of RV lower part is more severe than the fracture of RV upper part, because of its difficulty of accident management measures.

Failure evaluation method

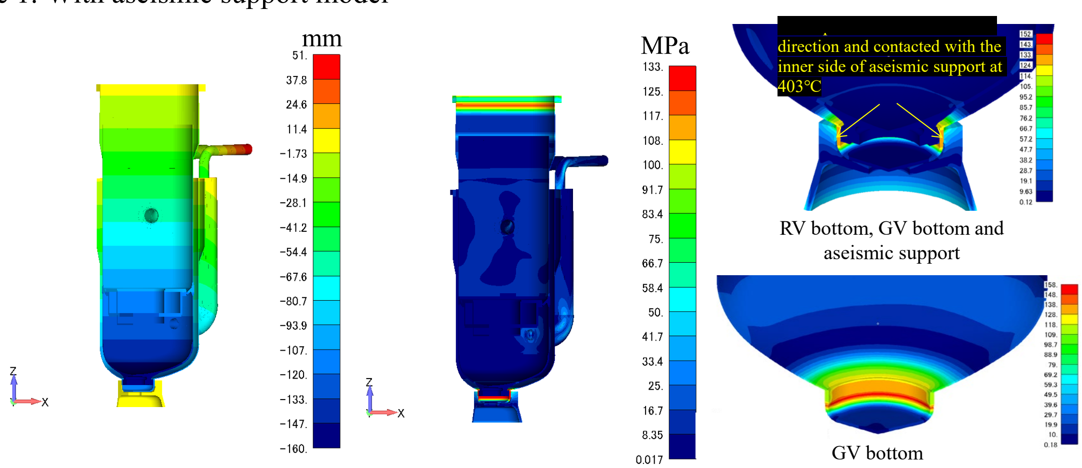
Ductile fracture was evaluated using ASME's "Boiler & Pressure Vessel Code Section VIII Rules for Construction of Pressure Vessels Division 2 Alternative Rules" (ASME 2021), although its applicability to the event postulated here is yet to be proven. In this study, allowable strain limit was used for the fracture criteria (equations (1)) with a correction coefficient β=0.47, based on JSME criteria, although the reliability of the criteria would be improved based on future experimental studies. Failure evaluation compared the fracture criteria with the equivalent of anelastic strain. The equivalent of anelastic strain was obtained from the analysis results of plastic strain and creep strain using von-Mises criterion.

$$\varepsilon_L = \beta \cdot \varepsilon_{Lu} \cdot exp\left[-\left(\frac{\alpha_{sl}}{1+m_2}\right)\left(\left\{\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e}\right\}-\frac{1}{3}\right)\right] \quad (1)$$

β	:	correction coefficient (ASME standard: 1, JSME standard: 0.47)
σ_e	:	equivalent stress: $\sigma_e = \frac{1}{\sqrt{2}} \cdot \sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}$
$\sigma_1, \sigma_2, \sigma_3$	:	main stress
α_{sl}	:	0.6 (if structure is made of stainless steel)
ε_{Lu}	:	single axis fracture ductility : $\varepsilon_{Lu} = m_2 = 0.75 \cdot (1.00 - R)$
R	:	$R = \frac{\sigma_{ys}}{\sigma_{uts}}$
σ_{ys}	:	yield stress
σ_{uts}	:	tensile strength

ANALYSIS RESULTS

(1) Case 1: With aseismic support model



Deformation contour in axial direction

Equivalent stress contour

Figure 3. Analysis results at 530 °C (Case 1)

Figure 3 shows the analysis results of initial condition at 530 °C. GV expanded in circumferential direction and contacted with the inner side of aseismic support at 403 °C.

Figure 4 shows the analysis results at 900 °C at 10 hours. GV deformed downward, and aseismic support deformed upward, contacting with each other on the bottom (The gap between them at room temperature: 235 mm). GV bottom contacted with the aseismic support at 549 °C at 0.5 hours. Sides of RV bottom and GV bottom contacted at 600 °C at 2 hours. Great stress was generated the contact surface between the aseismic support and GV bottom and the upper part of RV.

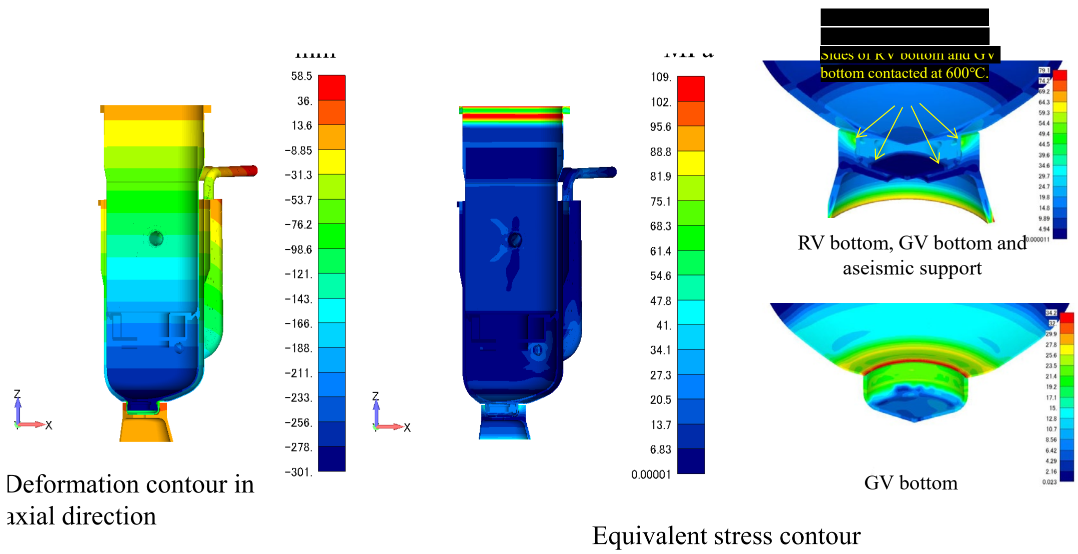


Figure 4. Analysis results at 900 °C (Case 1)

(2) Case 2: Without aseismic support model

Figure 5 shows the analysis results at 900 °C at 10hours. GV deformation behavior was almost same as Case 1. Sides of RV bottom and GV bottom contacted. But great stress of bottom part of RV and GV was not appeared, because of lack of the aseismic support.

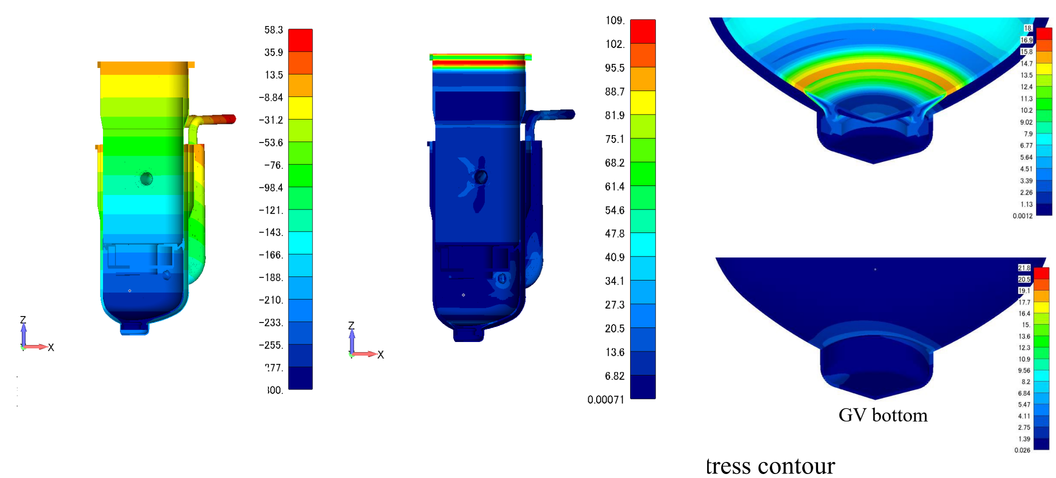


Figure 5. Analysis results at 900 °C (Case 2)

DISCUSSION

Structural integrity analysis based on equivalent anelastic strain

Figure 6 shows structural integrity analysis based on equivalent inelastic strain (plastic and creep strain) of Case 1. From the analysis results, the upper part of the RV body, the inlet nozzle area, and the GV lower part were identified as the areas that developed relatively great equivalent inelastic strain (plastic and creep strain). These correspond to the areas on which should be focused for damage prevention against extremely high temperatures. These areas were identified, but the integrity evaluation using the fracture criteria showed that the equivalent inelastic strains (plastic and creep strain) at the identified areas did not exceed the fracture criteria nevertheless. It means these areas would not develop ductile fracture within a temperature of up to 900 °C and in the calculation time 24 hours. On the other hand, RV, GV and aseismic support contacted with each other on the bottom. And, great stress and relatively high equivalent anelastic strain were generated on the GV bottom. This result suggests that no discontinuous section of the RV and the GV bottom is recommended to avoid the fracture of RV and GV bottom in order to enhance the resilience.

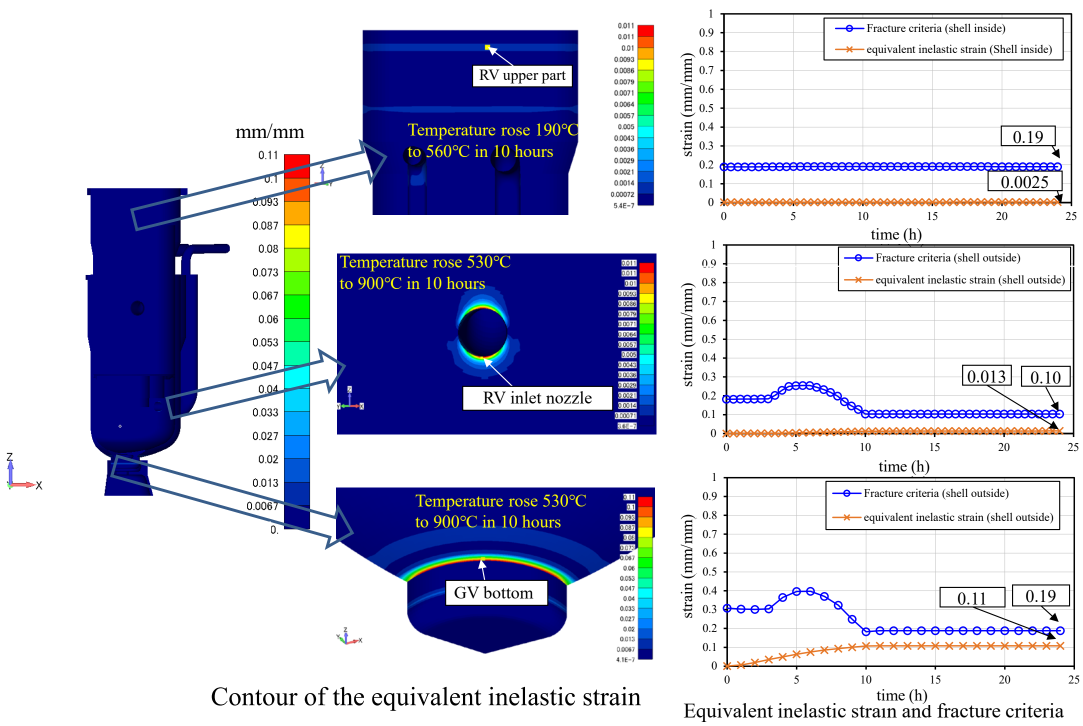


Figure 6. Structural integrity analysis based on equivalent anelastic strain of Case 1

Stress on RV

Figure 7 shows the analysis results of stress on the RV upper part of Case 1. Left side of this figure shows contour of the equivalent inelastic strain (plastic and creep strain). Relatively high equivalent inelastic strain (plastic and creep strain) area is pointed to discuss stress history (ID:26617 and ID:25857). Stress on the RV upper part which was initially high at a low temperature (ID:26617) remained high, whereas stress on the RV upper part which was initially high at a high temperature (ID:25857) was relaxed by creep behavior as the temperature rose.

Figure 8 shows the analysis results of stress on RV inlet nozzle of Case 1. Left side of this figure shows contour of the equivalent inelastic strain(plastic and creep strain). Relatively high equivalent inelastic strain(plastic and creep strain) area is also pointed to discuss stress history (ID:82012). Stress on the inlet nozzle area (ID:82012) peaked at 2h (600 °C) but was reduced by creep behavior as the temperature rose.

These stress histories were pretty much the same as Case 2 (without aseismic support). These results mean that deformation and contact behavior at the RV and the GV bottom area did not influence to the fracture of the RV.

From these results of loop-type SFRs, extreme high temperature deformation behavior induced by thermal expansion and gravitational force would not be concerned in the temperature range up to 900 °C and in the calculation time of 24 hours. In other words, influence of inner pressure of primary system should be confirmed for next step evaluation.

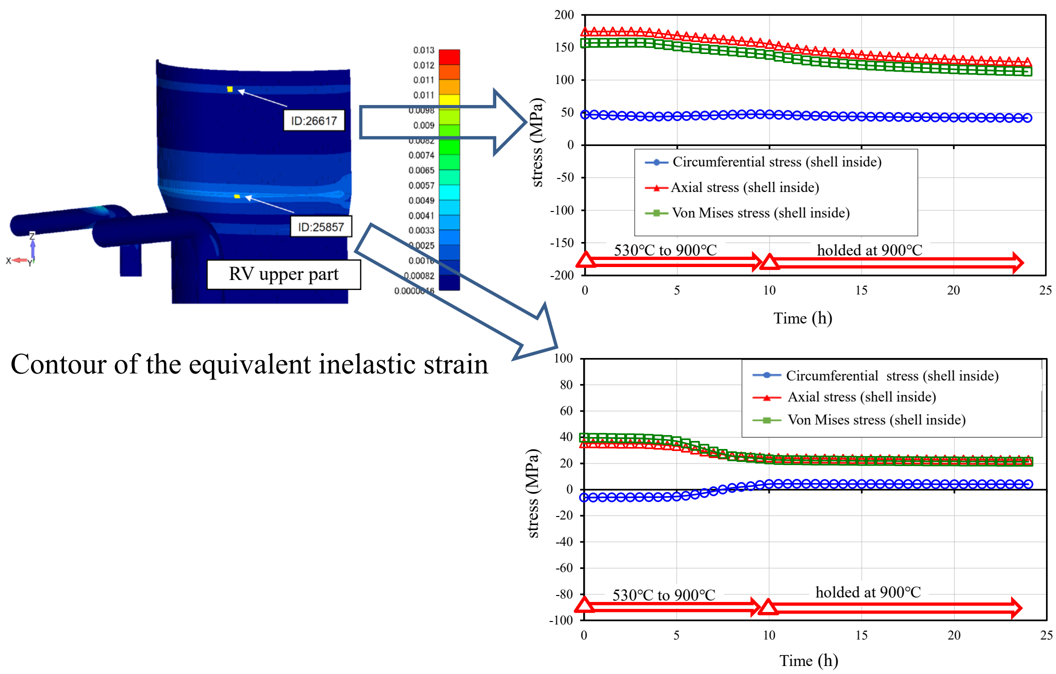


Figure 7. Stress on RV upper part of Case 1

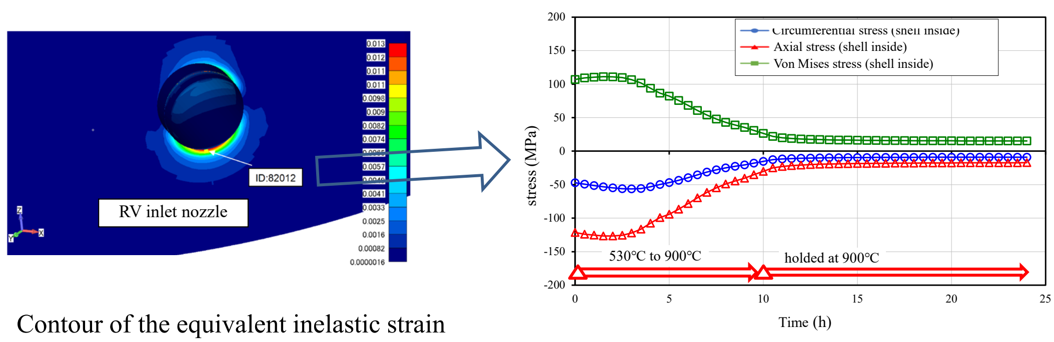


Figure 8. Stress on RV inlet nozzle of Case 1

CONCLUSION

The three-dimensional structural analysis of the typical SFR showed the deformation behaviors and the areas on which should be focused to mitigate impacts of failure caused by extremely high temperature during a PLOHS.

- Both RV and GV deformed downward as the temperature increased.
- The upper part of the RV body, the inlert nozzle area, and the GV lower part were identified as the areas that developed relatively great equivalent inelastic strain (plastic and creep strain). These correspond to the areas on which should be focused for damage prevention against extremely high temperatures.
- The integrity evaluation using the fracture criteria showed that the identified areas would not develop ductile fracture within a temperature up to 900 °C and in the calculation time of 24 hours.
- No discontinuous section of the RV and the GV bottom is recommended to avoid the fracture of the RV and the GV bottom in order to enhance the resilience.
- Stress on the RV upper part which was initially high at a low temperature was reluxed by creep behavior as the temperature rose.
- Stress on the inlet nozzle area peaked at 2 hours (600 °C) but was reduced by creep behavior as the temperature rose.
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From these results of loop-type SFRs, extreme high temperature deformation behavior induced by thermal expansion and gravitational force would not be concerned in the temperature range up to 900 °C and in the calculation time of 24 hours. In other words, influence of inner pressure of primary system should be confirmed for next step evaluation.

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