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DEVELOPMENT PLAN OF FAILURE MITIGATION TECHNOLOGIES FOR IMPROVING RESILIENCE OF NUCLEAR STRUCTURES

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ABSTRACT

The objective of this research is to develop the fracture control technology that can mitigate failure consequences under Beyond Design Basis Events (BDBE) for nuclear plants. The fracture control technology reduces the load and energy of the equipment and mitigates the progress into the catastrophic failure mode, which has a large impact on safety, by preceding the minor failure mode that has a small impact on safety. There are next three issues in this plan.

(1) Technology for mitigating failure consequence at extremely high temperatures

At extremely high temperatures, the elastic plastic creep deformation of the material becomes significant and the stresses and loads in the structure are redistributed. The authors propose a methodology for mitigating failure consequence to ductile fracture and creep rupture, which is a failure mode with a large impact on safety, by preceding the deformation with a small impact on safety.

(2) Technology for mitigating failure consequence against excessive earthquakes

In the event of an excessive earthquake, the rigidity of the piping and vessels decreases due to plastic deformation of the material and damage to some of the supporting structures.

Utilizing the fact that it becomes difficult to transmit vibration energy from the outside when the natural frequency of the system is lower than the input frequency, energy transmission is reduced by prioritizing plastic deformation and support damage that have a small effect on safety. The authors propose a methodology for mitigating the collapse, which is a failure mode with a large impact on safety, and the subsequent expansion to break.

(3) Methodology for improving reactor structure resilience

The failure consequence mitigation technology developed in (1) and (2) above is applied to the reactor structure of the next-generation reactor to show the effect of improving resilience. In addition, we will draw up guidelines for improving resilience by applying failure consequence mitigation technology to a wide range of actual reactor structures, and encourage the society to implement this mitigation technology.

INTRODUCTION

As shown in figure 1, the risk reduction approach differs between a design basis events (DBE :small damage, high probability) and BDBE (large damage, low probability). In system safety design, based on the concept of defence in depth (IAEA,2016), consequent mitigation measures are taken by portable equipment and accident management (AM) for BDBE.

On the other hand, in the conventional reactor structural design(ASME,2021), the prevention of failure to DBE should be applied to the BDBE (load with high uncertainty such as very high temperature at the time of severe accident and excessive earthquake). Rational approach is different between DBE and BDDBE (Kasahara and Sato, 2017). In order to realize more rational approach, the purpose of this project is to propose an innovative structural strength technology that mitigates failure consequence.

Specifically, even if failure occurs, it mitigates the consequence to the failure mode that affects safety. Its concept is explained in figure. 2, where the resistance to the deterioration of safety performance is increased, and the performance can be recovered by utilizing the time allowance created there, so that the resilience to safety is improved.

Here, resilience is the system's ability to adjust its functions before, during, and after changes and disturbances (such as BDBE in a nuclear reactor), which allows the system to respond to unexpected or unexpected situations (Erik Hollnagel, David D. Woods and Nancy Leveson, 2006). The ability to maintain the required operation (cooling, confinement, etc. in a nuclear reactor) .

As one of the nuclear system research and development projects of the MEXT, Japan, "Development of failure mitigation technologies for improving resilience of nuclear structures" was planned until FY2023. The objective of this research is to develop the fracture control technology that can mitigate failure consequences under Beyond Design Basis Events (BDBE) for nuclear plants.

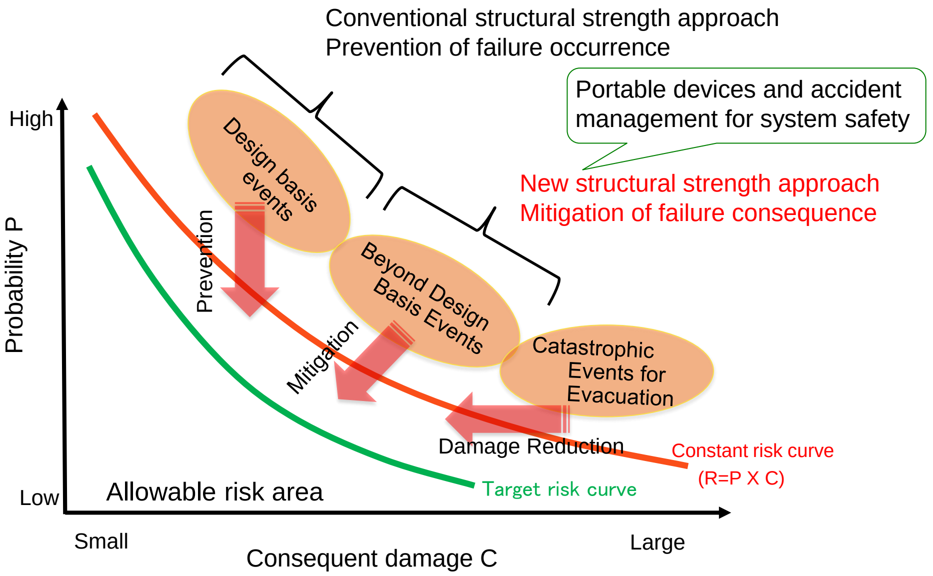


Figure 1. New structural strength approach for BDBE

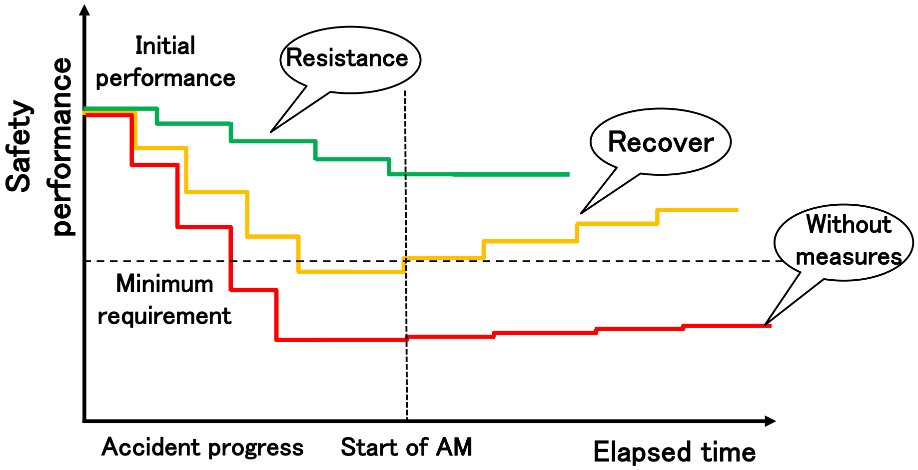


Figure 2. Safety resilience by mitigation of failure consequence

MITIGATION OF FAILURE CONSEQUENCE BY FRACTURE CONTROL

Even if there is no external operation or addition of equipment, the concept of fracture control is used in order to self-control the failure consequence due to the inherent characteristics of the structure. Fracture control reduces the load and energy by initiating a failure mode (deformation, small crack, etc.) that has a small impact on safety, and mitigate consequence to prevent catastrophic faire mode (collapse, break, etc.) that has a large impact on safety (Naoto Kasahara, Takashi Wakai, Izumi Nakamura, and Takuya Sato, 2019). Table 1 shows the variation of the fracture control for plants. In the case of a pressure load, when a small crack penetrates, the pressure drops due to the outflow of the internal fluid, and the rupture of the entire structure can be avoided. An example of a chemical plant is shown in Figure 3. The strength of the connection between the roof of the tank and the side plate is controlled to be lower than that of the side plate and bottom plate. If the internal pressure exceeds expectations for some reason, the connection between the roof and the side plate will break first, and the pressure will release from the gap. As a result, it is possible to mitigate the break of the side plate and the bottom plate due to the pressure and the outflow of the liquid. It is similar to the Leak Before Break (LBB) concept in nuclear power plants.

In the case of its own weight, the load is redistributed due to the deformation, and the other members take charge of the load, so that the load at the site of interest is reduced and failure can be mitigated. In the case of seismic load, the natural frequency decreases when plastic deformation or a part of the support is broken, and when it is lower than the input frequency, vibration energy to be hardly transferred to the structure, and collapse or rupture can be mitigated. In this way, the concept of failure consequence mitigation can be applied to various loads of the reactor structures.

Table 1: Mitigation of failure consequence by structural inherent characteristics (Fracture control)

Loads of nuclear plants	Pressure	Self wight	Earthquake
Preceding failure modes (Small impact on safety)	Small crack penetration	Deformation	Plastic deformation and support failure
Cause of load and energy release	Pressure drop by outflow	Load and stress re-distribution	Increase of frequency ration by flexible structuring
Mitigated failure modes (Large impact on safety)	Ductile fracture, Rupture	Collapse, Break	Collapse, Break

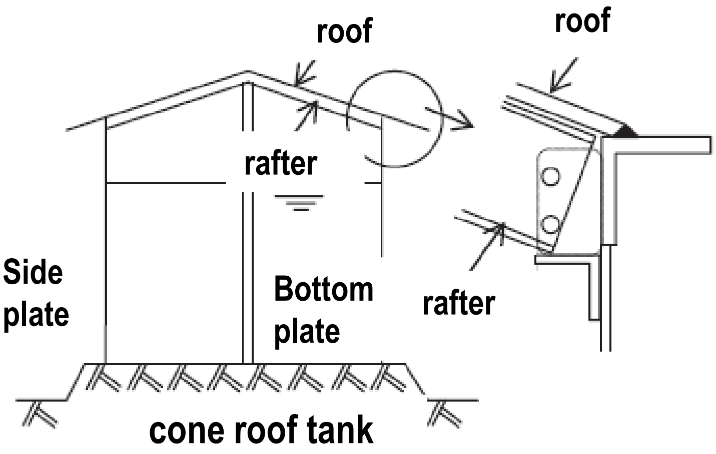


Figure 3. Example of fracture control for excessive pressure of cone roof tank

APPLICATION OF FAILURE CONSECUENCE MITIGATION TECHNOLOGIES TO NEXT GENERATION FAST REACTOR

Since it is an innovative technology different from the conventional one, we will first proceed with research targeting next-generation fast reactors with a high degree of freedom, and then generalize it and apply it to existing reactors.

Specifically, we will improve resilience by applying failure consequence mitigation technology to loss of heat removal system (LOHRS) events, which are important events for the safety of next-generation fast reactors (Naoto Kasahara Edit, 2016)

If the cooling function is lost due to some internal event, the reactor structure becomes very high temperature and the reactor vessel body may creep rupture, and the coolant may be rapidly lost, leading to core meltdown. We will develop a failure consequence mitigation technology for very high temperature conditions (Theme I). A similar scenario is reached when the cooling function is lost due to an external event, an excessive earthquake. For this reason, we will develop a failure consequence mitigation technology against excessive earthquakes (Theme II). Finally, we propose measures to improve the resilience of the reactor structure by applying these damage expansion suppression technologies (Theme III).

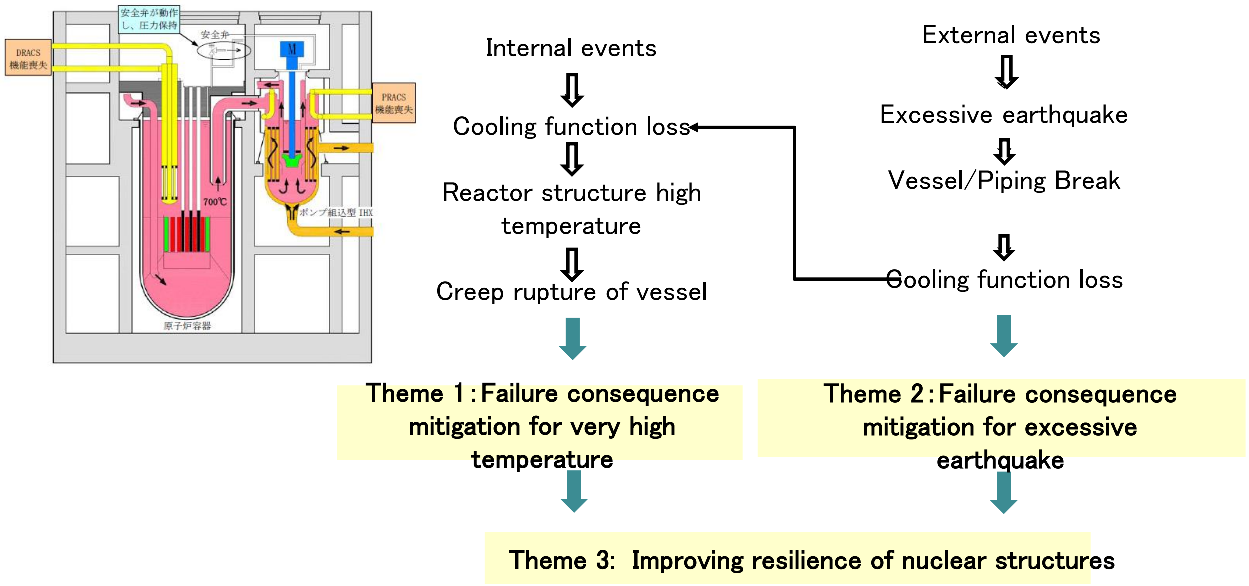
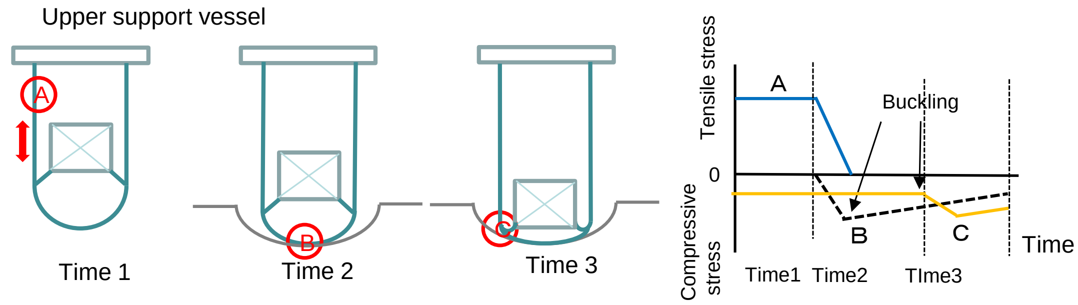


Figure 4. Resilience improvement for Loss of heat removal accidents of fast reactors

MITIGATION OF FAILURE CONSEQUENCE AT EXTREMELY HIGH TMEPERATURE

Regarding the technology for mitigating failure consequence at very high temperature conditions, stress is redistributed by initiating elastic-plastic creep deformation that has a small effect on the cooling function and mitigate consequence to collapse or rupture that has a large effect on the cooling function (Masato Murohara, Akira Yamazaki, Takuya Sato and Naoto Kasahara, 2021)

As a specific example, when the fast reactor vessel (upper supported as in Figure4) becomes extremely hot at the time of an accident, the material softens and deforms due to its own weight. When lower head contacts to the floor as in Figure 5 (Time 2), the maximum stress portion moves from the cylinder portion A to the lower head portion B. Furthermore, the core support structure continues to support the core by behaving stably even after buckling, and the consequence to core exposure is mitigated by lowering the core. In order to realize the above technique, it is necessary to show that the load bearing capacity is maintained even after the lower head comes into contact with the floor and buckles, and that the lower head (portion B) does not break from the load capacity. In addition, it is necessary to show that even if the core support structure buckles and deforms, it does not lead to break of the coolant boundary (portion C).



At ultra-high temperatures, the material softens and deforms due to its own weight.

Due to the load redistribution, the maximum stress portion changes from A to B to C, and the stress decreases (uniformizes).

Figure 5. Failure consequence mitigation for very high temperature of fast reactors

MITIGATION OF FAILURE CONSEQUENCE AGAINST EXCESSIVE EARTHQUAKES

The left graph of figure 6 is the relation between frequency ratio (input frequency / natural frequency) and displacement response magnification. When the frequency ratio becomes larger than 1, the inflow of vibration energy from the outside is reduced due to the phase delay.

Regarding the technology for mitigating failure consequence against excessive earthquakes, by preceding the deformation that has a small effect on the cooling function and the failure of the pipe support structure, the vibration energy transfer from the building is mitigated. That mitigate failure consequence of the vessel and piping to collapse and break that have a large effect on the cooling function.

As a specific example, when the fast reactor vessel receives an excessive earthquake, the frequency ratio rises by more than 1 due to buckling deformation, and the energy inflow from the building is mitigated. We presented a way to maintain cooling function without buckling consequence to boundary break. Furthermore, when the cooling system piping receives an excessive earthquake, the frequency ratio of the piping system rises more than 1 due to damage to the piping support structure. A method was proposed to maintain the cooling function by mitigating consequence to the collapse and break of the piping body (Nakamura, I., and Kasahara, N., 2020).

In order to realize the above technology, deformation does not lead to fracture after buckling of the vessel due to dynamic load, and in a piping system with multiple natural frequencies and support structures, damage to the support structure causes collapse of the piping system. It is necessary to show that it does not lead to break.

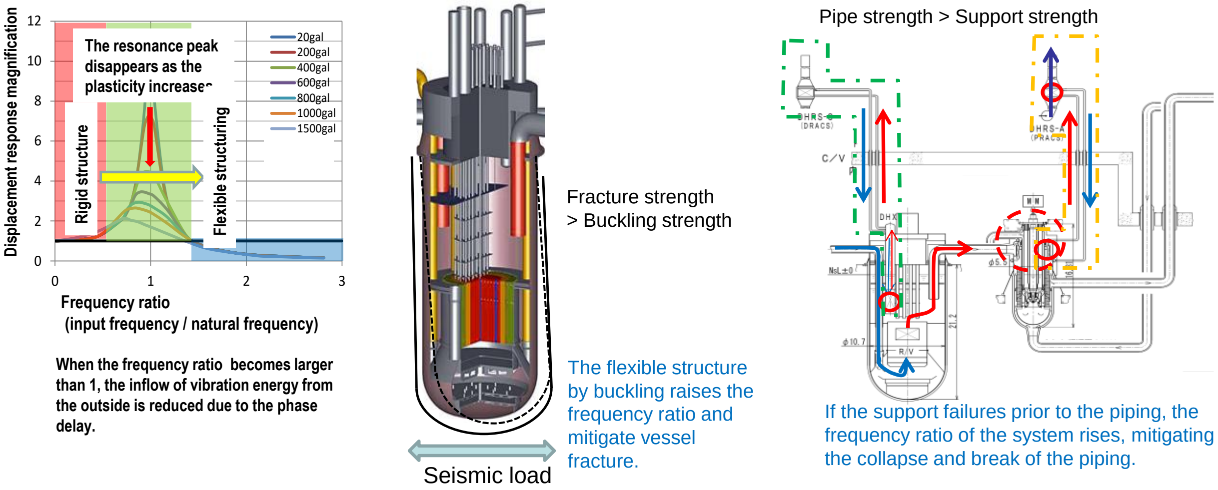


Figure 6. Failure consequence mitigation for excessive earthquake of fast reactors

IMPROVING RESILIENCE OF NUCLEAR STRUCTURES

To visualize the effectiveness of the resilience improvement by the failure consequence mitigation technologies, not only the core meltdown probability but also the resilience indicators (safety function margin and time margin) are adopted. For considering time effects with uncertainty, the dynamic PRA method in which the plant dynamics analysis code and the event tree are coupled by the Continuous Markov Monte Carlo methods (CMMC) as in figure 7. In fact, we created a visualization program and confirmed its function through trial application to the heat removal failure system (LOHRS) event, which is an important safety event for next-generation fast reactors.

In addition, we conducted a three-dimensional structural analysis of the reactor vessel and guard vessel focusing on the deformation behaviour at very high temperatures for next-generation reactors. Based on the results, it was proposed that reducing the pressure load and additional cooling by accident management would be effective in improving the resilience of the next-generation reactor by utilizing the time allowance produced by the failure consequence mitigation.

In order to generalize the concept of improving reactor structure resilience by failure consequence mitigation and apply it to various reactor types including light water reactors, "Reactor Structure Resilience Improvement Guidelines for Beyond Design Basis Events" is planned. The system safety is the superordinate concept of the structural field as a countermeasure for BDBE. Therefore, it is proposed that the guidelines have hierarchical configuration consists of "basic guidelines for performance requirements" and "individual guidelines for requirements" that are consistent with the safety field. As elemental technologies to support guidelines, best estimate methods are suitable for BDBE instead of conservative methods for DBE (Naoto Kasahara and Takuya Sato, 2017).

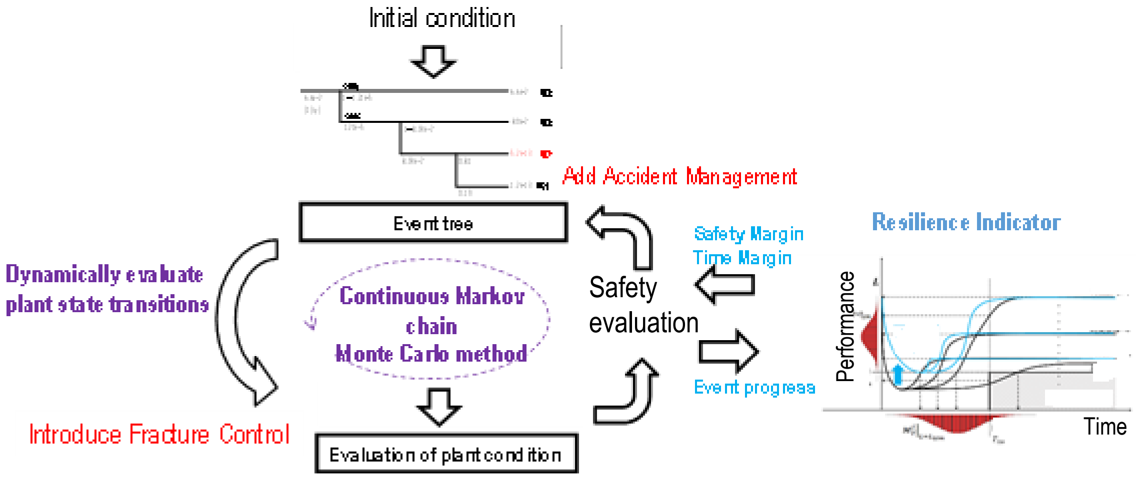


Figure 7. Quantitative evaluation of resilience improvement by the dynamic PRA with resilience indicator

CONCLUSION

The research plans to develop the fracture control technology that can mitigate failure consequences under Beyond Design Basis Events (BDBE) was explained for improving resilience of nuclear plants.

The target of the conventional structural strength technology aimed at preventing the occurrence of failure. Here, targeting the behaviour after the occurrence of failure, the load and energy of surrounding components are reduced by leading the failure mode with less impact on safety, and safety is achieved. Develop innovative structural strength technologies that mitigate failure consequence into catastrophic failure modes that have a large impact on safety. In addition, in order to promote social implementation, the developed technology will be applied to the next-generation reactor structure on a trial basis to show the effectiveness of fracture control. Finally, by integrating the knowledge of the results, we will make guidelines for mitigating the deterioration of safety performance in the event of a nuclear reactor accident, facilitating recovery, and improving resilience.

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