Structural Integrity Assessment of Nuclear Energy Systems

原子力エネルギーシステムの構造健全性評価

Nuclear energy uses nuclear fission reactions such as uranium to generate energy. Nuclear energy is a very effective way to solve the problems of resource depletion, energy security, and global warming. However, the Fukushima Daiichi accident in 2011 caused a stalemate over Japan's plans for a new nuclear power plant. On the other hand, many nuclear power plants in Japan have aging issues. To achieve the energy structure in the "Fourth Basic Energy Plan", at least the current operating or standby reactors must be safe and hope to operate safely.

The structural integrity of the reactor pressure vessels (RPV) is an important part of nuclear power plant safety. The RPV contains the reactor core and coolant, which is regarded as irreplaceable. In addition, the RPV is known to be exposed to neutron irradiation that makes the RPV steels brittle. When a large amount of coolant water is injected into the reactor at a loss-of-coolant accident (LOCA), the reactor vessel is rapidly cooled down concurrently with the pressurized thermal shock (PTS) loadings. In this situation, the cold plume may form near the inner surface of the RPV, leading to the RPV walls under high-stress conditions. Since the RPV steel usually becomes brittle under the environment of neutron irradiation, the high-stress that occurred at the PTS events may lead the RPV to fracture. It is therefore necessary to understand the performance of RPVs during the PTS loading for keeping the integrity of RPVs.

Maintenance management refers to taking preventive measures and improving the reliability of the system through the experience of accidents. According to the concept of maintenance management, the research topic of this paper is to maintain the existing aging reactor pressure vessels to prevent damage to the reactor pressure vessels due to pressurized thermal shock events.

The current RPV maintenance management in Japan is mainly based on JEAC 4206 and JEAC 4201 to evaluate the structural integrity of active RPVs. Based on the results of the integrity assessment, it is determined whether to continue operating the nuclear power plant or to cease operation for RPV maintenance. However, there are two problems with current maintenance management. One is that the RPV structural integrity assessment of JEAC 4206 uses a simple spatial one-dimensional model for deterministic assessment. However, in principle, the deterministic method only makes a two-way assessment of whether the material has broken (that is, whether the RPV has fracture). Even if the RPV is not fractured, it is not certain whether it can rest assured, and it cannot quantify the integrity of the RPV. Another one is that part of the effect of neutron irradiation embrittlement of JEAC 4201 on the fracture behavior of materials is based on rules of thumb. The accuracy of the rule of thumb is unknown. In order to solve these two problems, the research purpose of this paper is to improve the method of structural integrity assessment of RPV. At the same time, the new assessment methods are used to properly maintain and manage aging RPVs and contribute to improving the integrity of the nuclear energy systems.

In order to improve the methodology of structural integrity assessment, it is necessary to appropriately evaluate both the environmental conditions in which the RPV is located and the current state of materials that deteriorate with age. If the irradiation embrittlement fracture of RPV is taken into consideration, the former is an improvement of the stress intensity factor K_{I}, and the latter is an improvement of the material fracture toughness value K_{IC}. In order to improve the evaluation of the stress intensity factors K_{I}, the conventional simple spatial one-dimensional structure analysis model (JEAC4206) is not enough, and the evaluation of the three-dimensional structure of RPV needs to be considered. On the other hand, in order to improve the prediction accuracy of neutron irradiation embrittlement of JEAC4201 material to improve the fracture toughness value K_{IC} of the material, it is not a method based on empirical rules, it is necessary to mechanical research based on atomicity assessment of cracks for quantifying the relationship between irradiation defects and fracture.

On the other hand, in order to properly maintain and manage RPV, K_{I} and K_{IC} are evaluated to quantify the use environment and material status, including the ambiguity of the evaluation. Finally, the risk of RPV destruction was quantified based on the degree of overlap between the K_{I} and K_{IC} distributions. Prioritize maintenance activities based on quantified levels of risk. Through reasonable maintenance management, it helps to improve the integrity of nuclear energy systems. Based on these research prospects, I conducted this research and summarized the research work into five chapters.

Chapter 1 is an introduction and describes the background and positioning of this study. It describes world energy issues, Japan's nuclear energy issues, and mentioned about the current status and issues of aging evaluation of reactor pressure vessels. In order to safely maintain the existing aging reactor pressure vessels in Japan, it was pointed out that it was necessary to analyze structural integrity evaluation and computational fluid dynamics (multiphysics simulation), and the mechanistic study from the atomistic evaluation of cracks by molecular dynamics (MD) calculations for quantifying the relationship between irradiation defects and fractures.

Chapter 2 introduces the optimization of RPV maintenance is the target of the study, where an attempt is made to investigate the RPV integrity during PTS loading by employing the probabilistic methodologies. For the probabilistic integrity evaluation, the cold plume cooling effect is considered by using three-dimensional computational fluid dynamics (3D-CFD) and finite element method (FEM) simulations to obtain the spatial distribution of SIF on the RPV during PTS events. The spatial distribution of SIF on the RPV thus obtained could be practically more useful than that obtained by the conventional one-dimensional thermal hydraulic analysis, because the cold plume cooling effect is included. By comparing the distribution thus obtained with the fracture toughness included as a part of the master curve, the conditional failure probabilities of the RPV is obtained. According to the conditional failure probability and the probability of occurrence of cooling water injection when a PTS event occurs, the probability of the occurrence of RPV fracture is obtained. The probability of the occurrence of RPV fracture can be used to quantify the integrity of RPV, providing the possibility to inspect and maintain the priority of RPV. Using the probabilistic methodologies (3D-CFD and FEM) discussed in chapter 2, the priority of the inspection and maintenance will be discussed in chapter 3.

Chapter 3 is the application of the probabilistic methodologies in Chapter 2. Using the probabilistic evaluation methods, the effect of asymmetric emergency cooling injections on the structural integrity of an RPV during PTS loading was investigated using 3D CFD and FEM in Chapter 3. The conventional framework of risk assessment in the architecture with hazard and fragility curves was applied to this issue, and the probability of cooling injection failure, the conditional probability of the RPV fracture, and the probability of the occurrence of RPV fracture was evaluated as a function of the number of injection failures. The probability of the occurrence of an RPV fracture was employed as an index representing the magnitude of the risk of the RPV function loss. Using this risk, a methodology to optimize the maintenance strategy was proposed. Regarding the four-loop RPV, the inspection and maintenance of the emergency cooling injection systems are not considered to be the top priority.

Chapter 4 is part of the improvement of the materials fracture toughness K_{IC} assessment method. In order to prepare for the atomic theory that clarifies the interaction between cracks and irradiated defect, to achieve the ultimate goal of improving the accuracy of fracture toughness K_{IC} values of irradiated materials. In this study, nano-scale cracks were focused and a series of molecular dynamics (MD) simulations were proposed to study the response of nano cracks under tensile load. The α-iron without radiation defects was selected as the model material. The failures of predetermined plane atomic cracks with 11 different lengths under the specified tensile displacement load were studied to observe the fracture process. And the MD simulation results with corresponding solutions obtained through the linear elastic fracture mechanics (LEFM) model (Griffith's criterion) calculations were compared and discussed. According to the comparison results, for the iron material, it speculates that the iron material has a critical crack size (e.g. 50Å). When the crack size is larger than the critical size, the crack propagation meets the Griffith's criterion. When the crack size is smaller than the critical size, the crack propagation does not meet the Griffith's criterion. At this time, the crack size that is too small will cause the stress concentration at the crack tip to disappear, and the iron material will fracture at the theoretical atomic cohesive strength of the material. Furthermore, the energy release rate during crack propagation is also related to the stress concentration factor at the crack tip. When there are irradiation defects in the material, the irradiation defects may affect the stress concentration factor at the crack tip and cause the energy release rate of cracks to change under tensile load. Different from the analysis idea of "predicting the effect of irradiated defects on material properties (resistance to crack propagation) through the rule of thumb", a quantitative analysis idea is proposed here that considers the effect of irradiation defects on the stress concentration factor at the crack tip to quantify the effect of irradiation defects on the energy release rate (driving force for crack propagation). Compared with the existing rules of thumb, this quantitative analysis idea may be more beneficial to improve the prediction of crack propagation in irradiated materials.

Chapter 5 summarizes the results obtained in this study and discuss future prospects.

For this study, the probabilistic evaluation methods have been improved to optimizing the inspection and maintenance of aging RPV. For the improvement of the stress intensity factor K_I assessment method, a structural integrity evaluation method was proposed to "obtain the probability density distribution of the stress intensity factor K_I during a PTS event" through the coupling research method of 3D computational fluid analysis and finite element method. It is expected to optimize the inspection and maintenance of aging nuclear pressure vessels, and improve the integrity of the nuclear energy systems. For the improvement of the material fracture toughness value K_{IC} assessment method, future research can quantify the effect of irradiation defects on the energy release rate by considering the effects of irradiation defects on the stress concentration factor at the crack tip. It provides a new idea for predicting the fracture accuracy of irradiated materials.