2–5 A Nonparametric Bayesian Method for Predicting the Embrittlement of Reactor Pressure Vessels
—Toward Further Reliability of Integrity Assessment in Long-Term Operation—

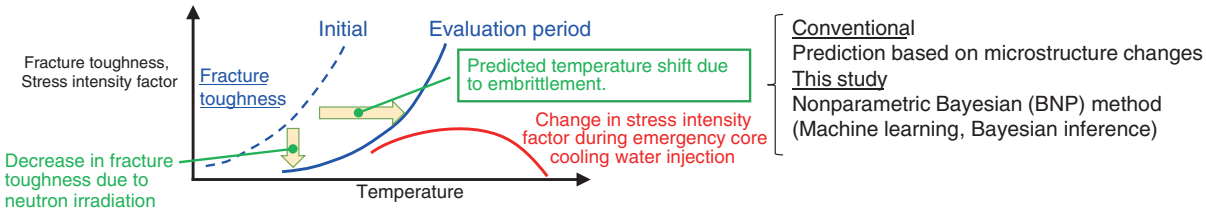

Fig.2-15 Overview of the structural integrity assessment of a reactor pressure vessel (RPV)
Neutron irradiation embrittlement of the steel used in RPVs increase with operating time in light-water reactors. Based on the predicted transition temperature shift (i.e., embrittlement), the fracture toughness should exceed the stress intensity factor caused by the rapid cooling of coolant water.

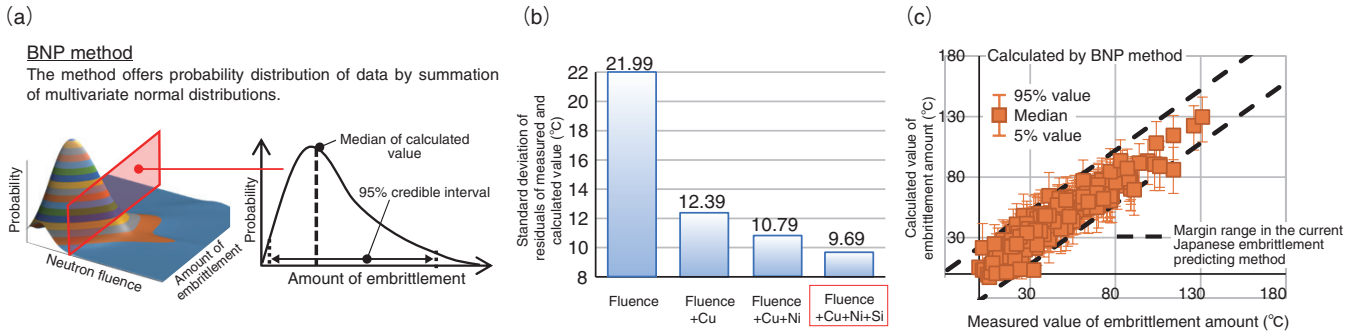

Fig.2-16 Analyses by nonparametric Bayesian (BNP) method
(a) Schematic of the obtained probability distribution. Here, the probability distribution of embrittlement under varying neutron fluence is provided as an example; the corresponding probability distribution of the embrittlement with other variables can be obtained by specifying the arbitrary values for the other factors. (b) The lower standard deviation of the residuals of the calculated and measured values corresponds to better predictability; thus, the accuracy of embrittlement prediction was improved. (c) Using the proposed method confirmed the accuracy of the embrittlement prediction margin established by the current Japanese code.

As the reactor pressure vessel (RPV) is the most important safety-related structural component, its failure should be prevented during operation. As shown in the structural integrity assessment of RPV in Fig.2-15, the fracture toughness of the steel comprising the RPV must exceed the stress intensity factor in the event of rapid cooling caused by the operation of the emergency core cooling system. Neutron irradiation decreases the fracture toughness, which is expressed by a shift in the reference temperature of the nil-ductility transition (ΔRT_{NDT}). It is therefore essential to accurately predict ΔRT_{NDT} during long-term operation. ΔRT_{NDT} is highly dependent on the irradiation conditions and chemical composition of the steel used in the RPV; however, the factors affecting ΔRT_{NDT} need to be understood more precisely to improve the accuracy of ΔRT_{NDT} prediction. It is also important to ensure that the embrittlement prediction margin in the current structural integrity assessment is set appropriately.

Machine learning and Bayesian statistics (i.e., the nonparametric Bayesian (BNP) method) were therefore applied to analyze the factors affecting ΔRT_{NDT} and to evaluate the uncertainties of ΔRT_{NDT} prediction under various irradiation conditions and chemical compositions. Using the BNP method provides the probability distribution of the data by summing the multivariate normal distribution and can quantitatively evaluate the uncertainties of the calculated ΔRT_{NDT} in response to a limited amount of data or scattered data, as shown in Fig.2-16(a).

The developed method was then used to analyze data from pressurized water reactors collected over several decades. Our analysis revealed that the prediction accuracy could be improved by considering the Si content in addition to the Cu and Ni content, which have been documented to significantly affect the ΔRT_{NDT} (Fig.2-16(b)). Furthermore, as shown in Fig.2-16(c), the values including uncertainties obtained by the proposed BNP method were mostly within the currently established margins, thereby confirming the appropriateness of the current Japanese embrittlement prediction method.

Efforts to apply this developed BNP uncertainty evaluation method to the probabilistic structural integrity assessment method are ongoing to quantitatively evaluate the safety margin in the structural integrity assessment that is under development for implementation in Japan.

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Reference

Takamizawa, H. et al., Bayesian Analysis of Japanese Pressurized Water Reactor Surveillance Data for Irradiation Embrittlement Prediction, Journal of Pressure Vessel Technology, vol.143, issue 5, 2021, 051502, 8p.