Topical Session

Overview of the 5th International Symposium on Probabilistic Methodologies for Nuclear Applications (ISPMNA5) - Further Practical Application of Probabilistic Fracture Mechanics-

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The 5th International Symposium on Probabilistic Methodologies for Nuclear Applications (ISPMNA5) was held on October 7-9, Tokyo. In the symposium, 45 presentations and one keynote were provided, and one panel session was opened to engage in a discussion on a specific topic "Further practical application of probabilistic fracture mechanics (PFM) towards extending probabilistic methods". In this topical session, overview of ISPMNA (Sec. I), the regulatory perspective for PFM implementation (Sec. II), and the efforts on utilization of PFM of the utilities in Japan (Sec. III) will be presented.

I. Overview of ISPMNA

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Risk-Informed decision-making supported with probabilistic approaches in nuclear applications has gained great interest in many countries. With the goal to re-assess typically overly conservative deterministic approaches and informed allocation of available resources, those methods aim to better represent complex systems and provide science-based predictions involving modelled degradation process for long-term operation. They offer the decision makers quantitative estimates of the risks and uncertainties involved via robust and proven mathematical and other methods. Such considerations require various regulatory agencies to reevaluate their paradigms and regulatory frameworks while ensuring coherent and defensible approach to nuclear safety.

Over ten years ago, the International Symposium on Probabilistic Methodologies for Nuclear Applications (ISPMNA) was initiated in Canada to address the need for a platform on probabilistic methodologies involving international technical experts, nuclear regulators, vendors, and other stakeholders of the nuclear industry. This biennial event has evolved over time with more countries represented, emerging new methodologies such as Artificial Intelligence and Machine Learning and the expansion of nuclear applications considered beyond the initial interest in Probabilistic Fracture Mechanics.

The need for open dialog and considerations for different perspectives remains particularly relevant with renewed interest in nuclear generated power and the introduction of new advanced reactor designs including small modular reactors (SMRs). The symposium evolves with time but retains its initial objective, which is to offer an open platform for nuclear regulators, vendors, suppliers and academia from all over the world to share, discuss and evaluate lessons learned from applications of probabilistic methodologies to better understand and assess complex interactions and ensure nuclear safety.

II. Regulatory Perspective for PFM implementation

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II.1 Background

In Japan, the Nuclear Regulation Authority (NRA) was established in 2013 based on the lessons learned from the TEPCO Fukushima Daiichi Nuclear Power Plant accident, and conservative regulatory standards based on deterministic methods were enforced.

The NRA then hosted the IAEA's Integrated Regulatory Review Service (IRRS) mission in 2016, and based on the mission results, the inspection system was renewed reference to the US Reactor Oversite Program (ROP) in 2020. This led to the use of probabilistic methods, and their use is spreading, including the adoption of PRA in safety improvement assessment of licensee.

Probabilistic fracture mechanics (PFM) is known as a method to provide quantitative predictions of failure frequency, etc., considering uncertainties, based on technical basis such as mathematical models and plant data, by assuming the existence of cracks in the same way as deterministic fracture mechanics, and can be used as a decision-making tool using risk information. It is also expected to be used as a method to quantitatively explain the safety margin of a generally conservative deterministic approach.

II.2 Examples of PFM use in regulatory activities

When the NRA conducted a technical evaluation of the JSME Code "Rules on Fitness for service for Nuclear Power Plants" in 2019, it discussed the fact that the extent of inspection of reactor pressure vessel (RPV) is 7.5% of weld lines in Japan, while it is 100% in other countries, and decided to change the extent of inspection from 7.5% to 100% of the weld lines of RPV in Japan as well. One of the reasons for the decision was the results of a quantitative comparison of through-wall cracking frequency (TWCF), which corresponds to core damage frequency in PRA, due to differences in the level of inspection using PFM by JAEA.

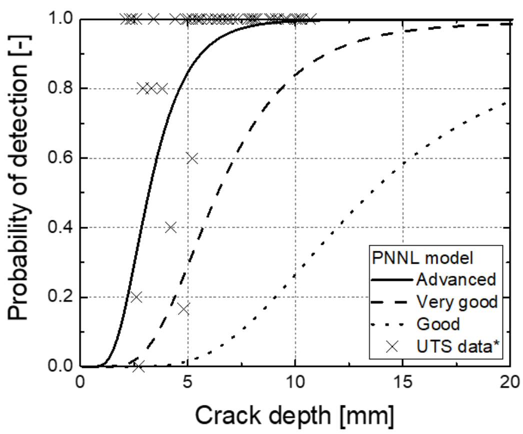

Figure 1. Inspection accuracy evaluation model used in sensitivity analysis [1]

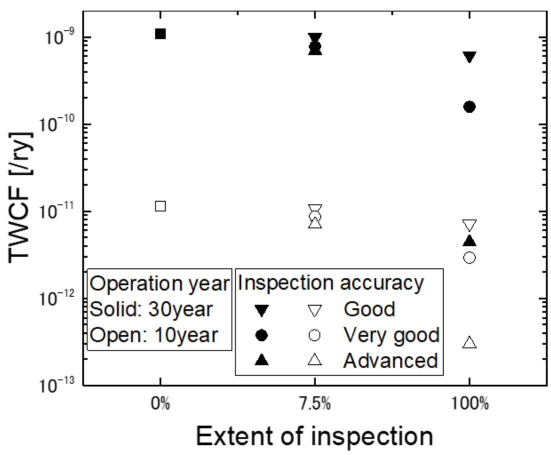

Figure 2. Sensitivity analysis results [1]

In response to the change the extent of inspection, licensees expressed their opinion that they would use the results of 100% inspection of the weld lines of RPV to evaluate risks using PFM and reflect the results in their inspection plans revision. The initiative of PFM is currently being discussed by the Japan Electric Association.

After the licensee's opinion, the NRA has decided to prioritize the evaluation of the licensee's technical basis including the use of PFM of requests for changes to inspection frequency aimed at reducing radiation exposure. The NRA is currently preparing to accept requests for changes to inspection frequency from licensees.

II.3 PFM Research at NRA

From its establishment through 2019, the NRA commissioned the JAEA to develop the PFM Code PASCAL for RPVs, PASCAL-SP for piping with cracks due to stress corrosion cracking and fatigue, and PASCAL-EC for piping with thinning. In addition, from 2023, the JAEA has begun developing a coupled method for thermal-hydraulic and PFM which considers the uncertainties of thermal-hydraulic behaviors in a PFM evaluation method for PTS evaluation.

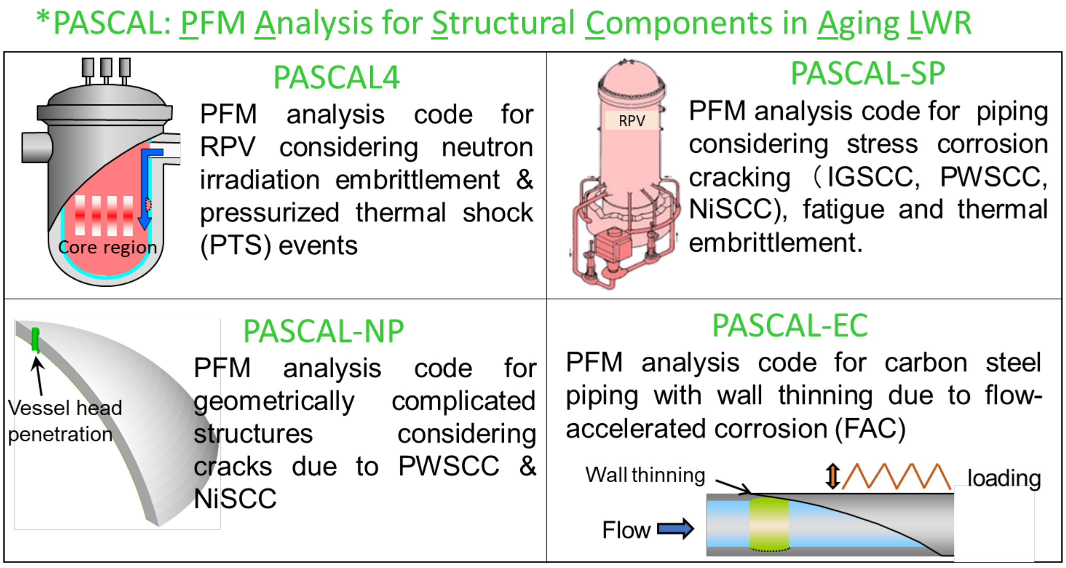

Figure 3. Outline of PASCAL series

II.4 Regulatory Perspective for PFM implementation

Currently, there are no probabilistic acceptance criteria under Japanese regulations, so PFM is expected to be used primarily as a method for comparing risks relatively.

During discussions at the Study Team on Continuous Safety Improvement in 2021, the NRA expressed the view that it was necessary to continue discussion on safety goals, and that while there were benefits to continuing the discussion, but it was not necessarily worth setting safety goals.

In 2024, the University of Tokyo and the JAEA established a committee to discuss about safety goals, led by a former Chairman of the NRA, and discussions on safety goals have just begun.

Considering these circumstances, it is expected that the use of probabilistic methods will become more widespread in Japan in the near future.

III. Japanese utilities approaches to implement PFM

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III.1 INTRODUCTION

PFM is a methodology that enables to quantify the allowable margin and risk level of component integrity, thereby enabling optimization of maintenance program and providing an insight on enhancing safety level of Nuclear Power Plants (NPPs).

In the United States, implementation of PFM on Pressurized Thermal Shock (PTS) evaluations has been progressing since the mid-1980s. It has also been applied to the optimization of In-Service Inspection (ISI) program.

In Japan, even before the Fukushima Daiichi nuclear accident, the evolution of irradiation embrittlement in RPVs had become apparent in some plants, leading to an increasing demand for PFM implementation and subsequent research and development efforts has been made. However, the progress had somewhat stagnated due to the long suspension of plant operation to comply with a new regulatory requirement following the accident. As a result, the application of PFM to NPPs in Japan has been extremely limited. The rare case of PFM implementation was that it demonstrated the failure frequency of the RPVs calculated by PFM was shown to be negligibly small in comparison with the Core Damage Frequency (CDF) calculated by Probabilistic Risk Assessment (PRA) during the regulatory review of the submittal to comply the new regulatory requirement [2].

However, in recent years, many PWR plants have restarted operation, and the restart of BWR plants is also approaching. Additionally, the increase in number of aging plants in Japan and the trends to expand the application of PFM in wider component in other countries have once again increased the demand for PFM.

One catalyst for this resurgence is the NRA decision to expand the inspection coverage for ISI on the RPV shell welds from 7.5% to 100%. In order to minimize radiation exposure through the optimization of inspection program, utilities have declared their intention to utilize PFM to the Nuclear Regulation Authority (NRA) [3].

Furthermore, the current PTS evaluation is based on deterministic approaches, relying on certain conservatisms such as flaw assumptions, transients, fracture toughness, and other individual parameters. Consequently, it is difficult to quantify the safety margin of the RPVs and to identify the influence of each parameter on the integrity of RPVs. By utilizing PFM, it becomes possible to quantitatively assess the risk of RPVs failure, thereby considering adequate acceptance criteria. Also, it can be used to determine the validity of the revised evaluation methodology.

III. 2. Targets for implementation of PFM and current approaches of the utilities

III. 2.1. Targets for implementation of PFM

Currently, Japanese utilities are working to apply PFM on NPPs components. For the case of BWR utilities, they are considering to apply PFM on optimizing inspection coverage of the RPV shell welds. For PWR utilities, they are considering to quantify the margin of current deterministic PTS evaluation methods and introduce PFM methodology into PTS evaluation to establish adequate acceptance criteria.

III. 2.2. Current approaches of the utilities

Regarding implementation of PFM, utilities have compared RPV failure frequency of two versions of JEAC4206, established a guideline to calculate RPV failure frequency, performed trial evaluation of actual RPV, surveying PFM analysis in the US and round-robin analyses of different organizations, and engaged in discussions with stakeholders such as NRA and JAEA. The current approaches of the utilities are described in this section.

III. 2.2.1 RPV failure frequency comparison of two versions of JEAC4206

In order to quantify the allowable margin of the PTS evaluation method based on deterministic fracture mechanics specified in JEAC4206, the RPV failure frequency (through-wall cracking frequency) corresponding to the acceptance criteria of JEAC4206 was calculated by PFM code [4]. Then, the result was compared with the acceptance criteria in the United States. The maximum allowable irradiation embrittlement level (neutron fluence) of a representative PWR plant's RPV in Japan was calculated for both the 2007 and 2016 versions of JEAC4206. Then, the through-wall cracking frequency corresponding to the neutron fluence of the RPV was calculated by PFM code FAVOR developed in the US. The results showed that the through-wall cracking frequencies of the both versions were differed but both were well below the acceptance criteria 1×10^{-6} [per reactor-year] which serves as the basis for the PTS screening criteria in the US. It was confirmed that the acceptance criteria of PTS evaluation methods for both versions of JEAC4206 were more conservatively set than the PTS screening criteria in the US.

III. 2.2.2 Establishment of a guideline to calculate RPV failure frequency

In order to implement PFM on RPV integrity evaluation, it is preferred to establish standardized methods for calculating the failure frequency of RPVs. The utilities engaged in discussions with the other domestic stakeholders within the Fracture Toughness Committee of the Japan Electric Association (JEA) and established JEAG4640-2018 "Guideline for Calculating Failure Frequency of Reactor Pressure Vessel Based on Probabilistic Fracture Mechanics".

III. 2.2.3 Trial evaluation of actual RPV

The trial evaluation was conducted for a representative Japanese BWR plant's RPV, namely unit 1 of the Kashiwazaki-Kariwa Nuclear Power Station. The RPV has axial weld that are subjected to circumferential stress in the core region. As a result of the evaluation considering conservative assumptions, such as an expected operating life of 60 EFPY, it was confirmed that RPV failure frequency (Through-Wall Cracking Frequency) was on the order of 10^{-12} [per reactor-year], which is sufficiently lower than the acceptance criteria in the US (1×10^{-6} [per reactor-year]).

III. 2.2.4 Surveying and round-robin analysis

In the United States, PFM has been applied on the risk evaluation of actual component. Therefore, BWR utilities surveyed EPRI's practice in performing PFM analysis. A round-robin analysis was conducted for the RPV of Kashiwazaki-Kariwa Nuclear Power Station unit 7 (ABWR) with participation of EPRI and TEPSYS. Both organizations employed the same PFM code FAVOR developed in the US. As a result, the RPV failure frequency of both organizations were almost consistent, confirming that PFM evaluation conducted by domestic organization was on par with that in the U.S.

Furthermore, within the working group on practical application of PFM established in CRIEPI, a round-robin analysis including the comparison of different PFM codes such as FAVOR and PASCAL and sensitivity analysis of various input parameters were conducted by participating organizations. Currently, these activities are focusing on PWR plants, and there are future plans for BWR plants as well.

III. 2.2.5 Discussions with Japanese stakeholders

The utilities has begun sharing stakeholder needs to implement PFM on actual component with Japanese stakeholders (utilities, vendors, regulatory agency, research institutes, etc.) at the Fracture toughness committee of the JEA where these stakeholders are participating. Utilities are planning to share the results of the case studies and discuss technical details in preparation for implementation of PFM on actual component.

III. 3. Future works

The following are identified as future works:

- Based on the results of the sensitivity analysis, it is necessary to identify the parameters that have the greatest impact, and to prioritize the acquisition of domestic values for these parameters. Therefore, it is necessary for utilities to reach a common understanding with Japanese regulator especially on the scope of domestic data acquisition. For example, whether or not to obtain the flaw density of Japanese RPV materials and the amount of the material to be investigated.
- It is necessary to establish detailed evaluation methods to implement PFM on Japanese NPPs. Also, allowable acceptance criteria (failure risk) that can be applied to Japanese NPPs should be determined based on mutual understanding of the utilities and the regulatory authority.

III. 4. CONCLUSION

Japanese utilities are continuing an effort to implement PFM on actual plant components while actively collaborating with Japanese and international stakeholders.

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