PASCAL Code Series: JAEA’s PFM Codes

Kunio ONIZAWA
Japan Atomic Energy Agency (JAEA)

October 24, 2014

International Symposium on
Improvement of Nuclear Safety
Using Probabilistic Fracture Mechanics

The Welding Hall, Tokyo, Japan

This presentation includes results obtained under the contract between the Nuclear Regulation Authority of Japan and JAEA.
Contents

- Introduction
- Development of PASCAL Codes
- PASCAL Codes: Outlines, main features and some results
  - PASCAL Ver. 3: RPV Integrity
  - PASCAL-SP: Piping Integrity
  - PASCAL-NP: PWSCC & NiSCC Growth
  - PASCAL-EC: Wall Thinning due to FAC
- Summary

*PASCAL: PFM Analysis for Structural Components in Aging LWR*
After the severe accidents in Fukushima-daiichi NPPs, the safe long-term operation of nuclear power plants has become more and more important.

Accordingly the measures for aging degradation to maintain or improve the function and performance of systems, structures and components in the plant, are necessary.

On the other hand, risk information including failure probability of components are to be utilized to maintain and improve the safety level of the NPPs.

We have been performing researches on the evaluation methods based on probabilistic fracture mechanics (PFM) to predict the effect of material degradation for long-time operation on the plant risk.

- Technical basis for safety improvement and probabilistic risk assessment
- Quantification of safety margin, relative difference in different standards
- Application to the optimization of inspection interval and degree, prioritization of inspection, etc.
Concepts of PFM

RPV (Corebelt Region) Integrity

Piping Integrity

Fracture by Deterministic method
Main Features of PASCAL Codes

- Failure Probability Evaluation Based on Domestic Regulatory Framework and the Latest Information using PFM for Major Components in NPPs

  - Based on Domestic Codes and Standards
    - JSME Rules on Fitness-for-Service
    - JEA Codes on Fracture Toughness

  - Latest Information on Fracture Mechanics Analysis
    - Stress Intensity Factor Calculation
    - Master Curve Method
    - Multiple Cracks Treatment

  - Probabilistic Models based on Domestic Data
    - Fracture Toughness $K_{lc}$ and $K_{la}$ curves
    - Crack Growth Rate (Fatigue and SCC)
## Development of PASCAL Codes

<table>
<thead>
<tr>
<th>Components</th>
<th>Aging / Loading</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV</td>
<td>Irradiation Embrittlement / PTS</td>
<td>PASCAL</td>
<td>PASCAL2</td>
<td>PASCAL3</td>
</tr>
<tr>
<td>Piping</td>
<td>IGSCC / Residual Stress, Earthquake</td>
<td>PRAISE</td>
<td>PASCAL-EQ</td>
<td>PASCAL-SP</td>
</tr>
<tr>
<td>RPV and Piping</td>
<td>PWSCC NiSCC / Residual Stress</td>
<td>PASCAL-SC</td>
<td>PASCAL-SP</td>
<td>PASCAL-NP</td>
</tr>
<tr>
<td>Piping</td>
<td>Flow Accelerated Corrosion / Operation, Earthquake</td>
<td>PASCAL-EC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PASCAL Codes

- PASCAL ver. 3 for RPV Integrity
  - ✔️ Brittle Fracture during PTS events
  - ❖ International Round Robin analyses
  - ❖ Studying the standardizing, verification, utilization

- PASCAL-NP for Ni-based Alloys and Welds
  - ✔️ PWSCC and NiSCC in Ni-based Alloys and Welds
  - ❖ Studying the applicability to various cracks, Improvement of Initiation model, case studies

- PASCAL-SP for Piping Integrity
  - ✔️ Crack Growth due to SCC and Fatigue in Primary Piping
  - ❖ Benchmark analyses with the other domestic codes.
  - ❖ Studying the applicability to the seismic safety analyses

- PASCAL-EC for Wall Thinning of Piping
  - ✔️ Wall Thinning due to FAC in Carbon Steel Piping
  - ❖ Applied to the analysis on the Mihama-3 accident
  - ❖ Improvement on the analysis functions
Probabilistic Fracture Assessment for Reactor Pressure Vessels during Various Transient Loadings

PASCAL version 3
• Probabilistic Fracture Mechanics (PFM) analysis is quite useful for the structural integrity/reliability assessment of aged components containing a crack/cracks.

• A PFM analysis code for the structural integrity assessment of RPV during PTS has been developed in JAEA, named **PASCAL**: PFM Analysis of Structural Components in Aging LWR.

• PASCAL ver. 3 evaluates the conditional probability of failure of a reactor pressure vessel (RPV) under transient loading conditions such as pressurized thermal shock (PTS).

• Using the latest version of PASCAL, some sensitivity analyses were performed for model RPVs during typical PTS events.
PTS (Pressurized Thermal Shock)

- ECCS water injection under pressure cools inner surface and then produces high tensile stress. → PTS
- The difference in thermal expansion coeff. between cladding and base metal makes stress discontinuity.
- Cladding may yield due to tensile pressure and thermal stresses under severe transient.

- High tensile stress due to internal pressure and thermal stress
- Irradiation embrittlement

Core

RPV

ECCS water injection

Overlay cladding (Austenitic stainless steel weld)

Base metal (Ferritic low alloy steel)
Structural Integrity Assessment for RPV during PTS

Current Approach: **Deterministic**!
Ref.: JEAC 4201 and 4206
Structural integrity is maintained if $K_I$ is smaller than $K_{IC}$ in deterministic approach.

However there are large uncertainties in $K_I$ and $K_{IC}$.

Each calculation of the integrity evaluation is performed in deterministic fracture mechanics approach.

The fracture probability is calculated from the number of fractured vessels and number of samples of all.
**Outline of PASCAL3 for PTS Assessment**

### Main flow chart

- **Start**
- Data input
- Crack sampling
- Calculation of the probability of detection by non-destructive inspection
- Sampling of chemical compositions, fluence, \( RT_{NDT} \), \( K_Ic \), and \( K_Ia \)
- **Evaluation of crack growth**
  - Total number of crack
  - CPI
  - CPF
- Evaluation of the conditional probability of crack initiation and through-wall cracking (fracture)
- End

### Flow chart of crack growth

- **Start**
- The end of transient
- Update the time of transient
- Crack initiation
  - Yes
  - Vessel failure
    - Yes
    - Recalculation of \( \Delta RT_{NDT} \) and deviation of \( K_Ic \) and \( K_Ia \)
    - No
    - Crack arrest
      - Yes
      - End
      - No
      - No
  - No
- No
- Yes
- End
Main Features of PASCAL3

- Prediction of Irradiation Embrittlement
  - JEAC4201-2007 (2013 addenda)

- Stress Intensity Factor Calculation
  - Overlay cladding is considered.
  - Influence Function Method developed by CEA for through-cladding surface crack and JSME FFS for embedded crack

- Fracture Toughness
  - Statistical Model based on $K_{IC}$ and $K_{IA}$ Data from Japanese RPV Steels

- Probability of Detection by NDE
  - POD Model developed statistically based on Domestic NDE Project Results

- Consideration of Inhomogeneous Properties in Heat Affected Zone adjacent to Welds
  - Crack Initiation/Growth Model in Inhomogeneous HAZ
Conditional probabilities of crack initiation and through-wall cracking can be calculated by PASCAL3 code using basically the default conditions listed below.

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_i$ for thru-clad surface crack</td>
<td>Influence function method by CEA</td>
</tr>
<tr>
<td>$K_i$ for embedded crack</td>
<td>JSME FFS Code</td>
</tr>
<tr>
<td>$K_{lc}$ and $K_{la}^*$ equation</td>
<td>Statistical distribution model</td>
</tr>
<tr>
<td>$RT_{NDT}$ shift equation</td>
<td>JEAC 4201 equation</td>
</tr>
<tr>
<td>Chemical composition</td>
<td>Cu, Ni</td>
</tr>
<tr>
<td>Failure criterion</td>
<td>$K_{lc}/K_{la}$ and plastic collapse</td>
</tr>
<tr>
<td>Warm pre-stress</td>
<td>No crack initiation after and below the maximum SIF during PTS</td>
</tr>
<tr>
<td>Decrease in upper shelf toughness</td>
<td>JEAC 4201 equation</td>
</tr>
</tbody>
</table>

*K_{la} model is under development
# Analysis conditions for model RPV Nos. 1 to 3

| RPV No. | Embrittlement prediction | Fracture toughness $K_{ic}$ | Chemical comp. (average wt.%)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>JEAC4201-2007</td>
<td>Japanese Weibull (PFM)</td>
<td>B: Cu 0.16, Ni 0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JEAC4206-2007 (DFM)</td>
<td>W: Cu 0.14, Ni 0.80</td>
</tr>
<tr>
<td>2</td>
<td>10CFR50.61a</td>
<td>ORNL Weibull (PFM)</td>
<td>B: Cu 0.16, Ni 0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASME Sec.XI (DFM)</td>
<td>W: Cu 0.14, Ni 0.80</td>
</tr>
<tr>
<td>3</td>
<td>JEAC4201-2007</td>
<td>Japanese Weibull (PFM)</td>
<td>B: Cu 0.16, Ni 0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JEAC4206-2007 (DFM)</td>
<td>W: Cu 0.19, Ni 1.08</td>
</tr>
</tbody>
</table>

(B: Base metal, W: Weld metal)

### Diagrams

**Ratio of conditional probability of fracture to the crack initiation (LBLOCA):**

**Relationship between deterministic temperature margin and CPI:**
International PFM Round Robin Analyses

- DFM and PFM Analyses for PTS events
- 12 Participants from China, Japan, Korea and Taiwan
- PFM Code: PASCAL2, WinPraise, Own codes
- Major Conclusion drawn from RR;
  - Although the calculated probabilities of vessel failure have a good agreement in general, there are some variation between participants, which is apparently caused by the difference of stress and stress intensity factors among participants due to the selection of different input parameters for analysis, and use of different probabilistic software packages.
Ongoing Work for PASCAL3

- Study on Applicability to Regulation, Codes and Standards
  - Sensitivity Analyses on Inspection Performance, Safety Margin Quantification, etc.
- Improvement of Analysis Functions and Models
  - SIF Calculation, $K_{la}$ model, etc.
- Research on Utilization of PASCAL3
  - Guideline for standardized procedures of PFM analysis
  - Selection of typical input data and analysis functions of PASCAL3
  - Verification of PASCAL3
- International PFM Round Robin Analysis
  - Proposed Phase 2 Problems to Asian Countries as an Activity within the PFM Sub-committee
Probabilistic Fracture Mechanics Analysis Code for Ni-based Alloy welds PASCAL-NP

(NP: NiSCC and PWSCC)
To properly assess the structural integrity with considering the scatters of parameters related to PWSCC and NiSCC, we developed a probabilistic fracture mechanics analysis code for Ni-based alloy welds, named PASCAL-NP.

PFM Analysis of Structural Components in Aging LWR - NiSCC / PWSCC
Main causes for PWSCC and NiSCC

<table>
<thead>
<tr>
<th></th>
<th>PWSCC</th>
<th>NiSCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>PWR</td>
<td>BWR</td>
</tr>
<tr>
<td>Material</td>
<td>Ni-based alloy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>base / weld metal</td>
<td></td>
</tr>
<tr>
<td>Stress</td>
<td>Welding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface machining</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Operating loads</td>
<td></td>
</tr>
</tbody>
</table>

- It is difficult to detect PWSCC and NiSCC in weld metal by using UT.
- Therefore, it is important to develop analytical models of not only crack growth but also crack initiation for PWSCC and NiSCC.

Monte Carlo Simulation

1. Setting the analytical conditions
   - Piping and weld geometry
   - Operating condition, etc.

2. Sampling random valuables
   - Crack initiation
   - CGR
   - Residual stress distribution, etc.

3. Calculation of incubation time

4. Evaluation of crack growth behavior

5. Failure judgment (Leak and Break)

6. Statistical output (Failure probabilities)

Start

End of sampling ?
Crack types treated in PASCAL-NP:

- PWSCC in VHPs
- NiSCC in CRD housings

<table>
<thead>
<tr>
<th>Crack types no</th>
<th>Orientation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Hoop</td>
<td>Inner surface</td>
</tr>
<tr>
<td>1</td>
<td>Axial</td>
<td>Inner surface</td>
</tr>
<tr>
<td>2</td>
<td>Hoop</td>
<td>Outer surface</td>
</tr>
<tr>
<td>3</td>
<td>Axial</td>
<td>Outer surface</td>
</tr>
<tr>
<td>4</td>
<td>Hoop</td>
<td>Through wall</td>
</tr>
<tr>
<td>5</td>
<td>Radial, Axial</td>
<td>In weld metal</td>
</tr>
</tbody>
</table>

PASCAL-NP has functions to evaluate crack growth behaviors for these types of cracks and to calculate failure probabilities considering features of PWSCC and NiSCC.
Calculation model

\[ t_i = \frac{t_{i0}}{i_\theta \times i_\sigma \times i_m} \times \alpha_i \]

Temperature and ECP

\[ i_\theta = A_\theta (ECP) \times \exp (-Q_i / RT) \]

Material

Manufacturing process (hot or cold work)

Chemical composition (Cr contents)

Thermal treatment

PWSCC in weld metal

NiSCC in weld metal

Cumulative distribution function (-)

Scatter of incubation time, \( \alpha_i \)

Exp. \quad Ref.

-100 mV_{\text{SHE}}

0 mV_{\text{SHE}}

+190 mV_{\text{SHE}}

Temp. = 288 \degree C

\( t_i \) (h)

\( t_i \) (h)

\( t_i \) (h)

Exp. \quad Prediction (\( \alpha_i = 1 \))

Exp. \quad Prediction (\( \alpha_i = 1 \))
SCC Growth Behavior in Ni-base Alloy/Welds

- PWSCC CGR in dissimilar welds

- CGR of PWSCC in weld metal
  - 325 °C (Exp.)
  - 318 °C

- CGR of NiSCC in weld metal
  - 0 mV<sub>SHE</sub> (Exp.)

- Boric acid corrosion rate (0.04 mm/year)
  - Low alloy steel
  - Ni-base alloy weld metal
  - Ni-based alloy base metal

- Leak

- SIF, \( K_I \) (MPa\( \sqrt{m} \))
  - \( \frac{d\alpha}{dt} \) (m/s)
Step 1: Leak probability evaluation

Radial crack initiation and growth in weld metal (welds)

Hoop stress distribution

PWSCC initiation growth

Crack type: 5
(Radial, in weld metal)

σ_H = 379 MPa > σ_{th} (250 MPa)

Hardened depth due to grinding = 100 μm

Total number of nozzles = 69
Leak probability ≈ 1.4%

Nozzle

Leak position

Buttering

J-groove welds

Cladding

Temp. = 318 ºC


Step 2: Break probability evaluation

Hoop crack initiation and growth in base metal (nozzles)

Axial stress distribution

PWSCC initiation growth

σ_A = 389 MPa > σ_{th} (250 MPa)

Hardened depth due to machining = 100 μm
At 11 EFPY, PFM analysis results agreed with leak detection data.
 Improvement of Analysis Functions and Models
- SIF Calculation Method for High Aspect-ratio Crack
- SCC Initiation Model
- SCC Growth Rate Hybrid Model
- Fatigue CGR model, etc.

Research on Utilization of PASCAL-NP (Future work)
- Selection of typical input data and analysis functions of PASCAL-NP
- Verification of PASCAL-NP
Probabilistic Failure Assessment for Welded Joints in Piping

PASCAL-SP

(SP: SCC at Welded Joints of Piping)
Many Stress Corrosion Cracks (SCC) Have Been Observed at Some Piping Joints Made by Austenitic Stainless Steel in BWR Plants

SCC Degrades Structural Integrity of Piping

Assessment of the Structural Integrity at Aged Piping

Deterministic Approaches Have Been Used
Qualitative Approaches Whether Failure or Not Based on Empirical Values

Possible Uncertainties and Scatters
- Material Properties
- Crack Initiation and Growth
- Residual Stress Distribution
- Accuracy of Flaw Detection and Sizing
- Occurrence and Magnitude of Earthquake, etc

Probabilistic Fracture Mechanics (PFM) Approach is More Suitable to Evaluate the Structural Integrity of Piping
Analysis Flow of PASCAL-SP Code

Start

Analytical Condition
- Environment, Geometry
- Operating Stress, Residual Stress, etc.

Analytical Condition Setting

Sampling of Random Variables

Random Variables
- Residual Stress
- Crack Growth Rate
- Accuracy of Flaw Detection and Sizing, etc.

Simulation of Plant Operation

Monte Carlo Simulation
- Applied Loads: Operating Stress, Residual Stress

Crack Growth Evaluation

Failure Judgment
- Leak
- Break

Operating Time

Occurrences of Event
- In-Service Inspection (ISI)
- Earthquake
- Transient event

Evaluation of Failure Probabilities

Stop
Probabilistic Model for the Position of SCC Initiation

Modeling based on Field Data and the Approach of NISA

Observed Data for $L$ are Regressed to Normal Distribution

Statistical Modeling for $L$

Relation between Position of Crack Initiation $L$ and Crack Depth Reaching Boundary between Base and Weld Metal $d_c$

Cumulative Distribution

$d_c = \bar{d}_c + 2\sigma$

$\bar{d}_c = 1.0 L + 5.7$

$d_c = \bar{d}_c + 3\sigma$

$\bar{d}_c = 1.0 L + 3.0$

Fitted to Normal Distribution

Probabilistic Modeling of Relation between $L$ and $d_c$
Crack Growth Model on SCC in Type 316L

Crack Growth Model based on the NISA Approach

- Crack Growth is evaluated by 2 steps, from (1) Heat Affected Zone (HAZ) to (2) Weld Metal Zone.
- Crack Growth Rate
  1. HAZ → CGR Diagram of Sensitized Type 304
  2. Weld Metal Zone → CGR Diagram of Type 316L (Low Carbon)
- Crack Growth Rate Switches from (1) to (2) at Crack Depth $d_c$.

Probabilistic Model for Crack Growth Rate to Follow Log-Normal Distribution Referring to JSME FFS Code Diagram and its Original Data

**Sensitized Type 304**
- Average (Avg)
  - JSME FFS
  - Avg + 2$\sigma$
  - Avg - 2$\sigma$

**Type 316L**
- JSME FFS
- Average (Avg)
  - Avg + 2$\sigma$
  - Avg - 2$\sigma$

**$\sigma$: Standard Deviation**
Accuracies of flaw detection and sizing at in-service inspection is an important factor to evaluate failure probability.

In-Service Inspection by JSME FFS Code

Operating Time

Flaw Detection
Some models exist, but they are based on old experimental data.

Flaw Sizing
No flaw sizing models exist.

New models were established by regression analyses of data from the Ultrasonic Test & Evaluation for Maintenance Standards (UTS) project in Japan.

Flaw Detection (SCC)

Sizing of Flaw Depth (TOFD Method)
Uncertainties and scatters of residual stress distribution may affect SCC behavior.

Possible Uncertainties and Scatters in Welding Condition
- Heat Input
- Welding Velocity, etc

Uncertainties and Scatters of Residual Stress Distribution
- We Assumed Uncertainties and Scatters Follows Normal Distribution.

Outline of Modeling

Experiments of Welded Pipe Joint
- Record of Welding Conditions
- Evaluation of Uncertainties and Scatters of Residual Stress

Modeling Uncertainties and Scatters of Residual Stress Distribution

Parametric FEM Analyses verified by the Experiments
- Establishing Database Including Uncertainties and Scatters

Database
Example of Residual Stress Distribution

Residual Stress Database by Parametric FEM Analyses Concerning Heat Input and Welding Velocity

- 250A Sch. 80 pipe butt weld by submerge arc welding
- Heat input: ~20.7 (kJ/cm)
- Welding velocity: ~0.00113 (m/s)

Through-thickness residual stress distribution @ $L = 1$ mm

Standard Deviation
Failure Judgment

Piping system including welding lines

SG1  SG2  SG3  ...  Segment (SG) consisting of several welding lines is defined.

Intact

Failure Judgment of Single Welding Line

Leak
When cracks grow through the wall and the leak from the crack is detectable

Break
When applied stress exceeds the failure stress

Maintenance and Replacement (MR)
When the crack detected at ISI is judged to be significant by the evaluation method of JSME FFS Codes

Evaluation of Entire System Failure Probability
1. Probability of Single Welding Line
2. Probability of Segment
**Application of PFM analysis Results**

1. **Benchmark Analysis**
   - Confirmation of the reliability of the PFM analysis codes through the benchmark analyses on SCC and fatigue → presented by Dr. Li

2. **Quantification of safety margin**
   - Deterministic assessment
     - Safety factor is used based on the knowledge.
     - Assessment if the piping will break or not.
   - Comparison
   - Probabilistic assessment by PFM
     - Best estimate method considering the uncertainties and scatter of material properties, stress distribution, CGR, NDE accuracy
     - Failure probability considering the aging degradation is evaluated.

3. **Seismic Safety Analysis**
   - Failure probabilities and fragility curves of aged pipes
     - Presented by Dr. Li
Ongoing Work for PASCAL-SP

- Improvement of Analysis Functions and Models
  - SIF Calculation Method for High Aspect-ratio Crack and Through-wall Crack
  - SCC Initiation Model
  - Low Probability - High Confidence Calculation, etc.

- Modification to include Thermal Aging Degradation
  - Two Parameter Method, etc.

- Research on Utilization of PASCAL-SP (Future work)
  - Selection of typical input data and analysis functions of PASCAL-SP
  - Verification of PASCAL-SP
Structural Reliability Assessment of Wall-thinned Piping

PASCAL-EC

(EC: Erosion and Corrosion)
Examples in USA・・・>30 events (PWR／BWR)

- PWR Feedwater Piping・Elbow・Shell (Rupture):
  - Oconee-2, Surry-1&2, ANO-1, Loviisa-1, Millstone-2&3, Fort Calhoun, Point Beach-1
- PWR Feedwater System (Leak):
  - Oconee-3, Zion-1, San Onofre-2, Callaway
- PWR Feedwater Piping Wall Thinning:
  - Trojan, Surry-2, Diablo Canyon
- BWR Feedwater Heater Shell Failure:
  - Dresden, Pilgrim, Susquehanna
- BWR Drain Piping・45° Elbow Leak:
  - Vermont Yankee, LaSalle

PWR Secondary Piping Rupture: Mihama Unit 3
- Failure Probability Analysis Code for Carbon Steel Pipe Thinned due to Erosion/Corrosion developed at JAEA: **PASCAL-EC**

- Wall thinning rate: Kastner’s equation
  - Parameters with uncertainties (Chemical comp., Water chemistry, Temperature, etc.) are treated as probabilistic ones. Failure probability is calculated by Monte Carlo simulation
  - Probabilities to reach the minimum required thickness and rupture as a function of operation time

- Failure analysis is performed using applied loads (pressure, design bending moment). Leakage and/or rupture are calculated as a function of operation time, i.e. progression of wall thinning.
  - Failure diagram developed at JAERI based on the experiments
  - Applicable to seismic loading considering fatigue and ratcheting

* **PFM Analysis of Structural Components in Aging LWR – Erosion / Corrosion**

Analysis flow of PASCAL-EC
● Statistical Analysis of Wall Thinning due to E/C based on Experiments and Prediction by Kastner

● Average Difference and Standard Deviation for Log-normal Distribution of Kastner’s eq. (single phase flow): 3.2 and ~2.4

● These values are used for probabilistic analysis for wall thinning rate calculation.
Wall Thinning Behavior of Secondary Piping at Mihama Unit 3

- Calculated Wall Thinning with varying pH values and measured thickness at the piping lines A and B

![Graph showing wall thinning behavior over operating years with predictions and measured values at different pH cases.]

- Prediction based on Initial wall thinning rate
- Prediction by PASCAL-EC
- Measured value at A
- Measured value at B
- Low pH case
- Mean pH case
- High pH case
Probabilistic analysis results by PASCAL-EC

- Case Study of wall thinning at Mihama unit 3
- Results obtained from data scatter in previous figure
  - Log-normal distribution with std. dev. of 2.4
• Improvement of Analysis Functions
  ➢ Wall Thinning Prediction based on Measured Data
  ➢ Probabilistic Model, etc.

• Research on Utilization of PASCAL-EC (Future work)
  ➢ Selection of typical input data and analysis functions of PASCAL-EC
  ➢ Verification of PASCAL-EC
PFM analysis codes PASCAL series have been developed for the application to the regulation, codes and standards.

The PASCAL series have various target components with aging degradation such as neutron irradiation embrittlement, SCC fatigue and wall thinning as follows;
- Reactor Pressure Vessel Corebelt Region
- Nickel Alloys and the Welds
- Primary Piping Welded Joints
- Carbon Steel Piping

These codes have been published and are being updated and verified for standardizing the PFM analysis methods.

Based on the analysis results for various portions of components and piping, PFM analysis technique is highly expected for the risk quantification for safety improvement, optimization of inspection, review and quantification of safety margin, etc.
How to get PASCAL Codes

● Access PRODAS Website
  ➢ http://prodas.jaea.go.jp/
  ➢ JAEA Program and Database Retrieval System

● Users’ Manual
  ➢ PASCAL Ver.3
  ➢ PASCAL-NP
  ➢ PASCAL-SP
  ➢ PASCAL-EC