A MULTI-STATE PHYSICS MODELING FOR ESTIMATING THE SIZE- AND LOCATION-DEPENDENT LOSS OF COOLANT ACCIDENT INITIATING EVENT PROBABILITY

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In PRA, Loss of Coolant Accidents (LOCAs) are categorized with respect to:

- Size
- Location

Both can indeed influence the **timing** and **duration** of the **mitigating action** \(^{[1,2]}\)

For each category, different strategies of intervention are to be designed for preventing core damage.

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Problem Statement: LOCAs in FTs/ETs

PIPING FAILURE PROBABILITY ESTIMATION

Statistics based on field data

Pros: consolidated approaches that fit real failure data

Cons: lack of data due to the high reliability of nuclear piping system

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Stochastic Model (e.g., Markov Chain Model (MCM))
Probabilistic Fracture Mechanics (PFM)
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Pros: explicit modelling of crack initiation and growth
Cons: 

Probabilistic Fracture Mechanics Model (PFM)

Pros: 
Cons: • Demanding on data for parameters calibration
• No consideration of the the effects of inspections and detection strategies
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Stochastic Model (e.g., Markov Chain Model (MCM))

Cons: explicit modelling of crack initiation and growth

Pros: explicit modelling of the interactions between damage mechanisms and inspection, detection and repair strategies

Probabilistic Fracture Mechanics Model

Cons: • constant transition rates: exponentially distributed holding times not acceptable for components with different geometry, material properties

Pros: • Demanding on data for parameters calibration

• No consideration of the effects of inspections and detection strategies
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PIPING FAILURE PROBABILITY ESTIMATION

Statistics based on field data

Stochastic Model (e.g., Markov Chain Model (MCM))

Probabilistic Fracture Mechanics Model

Multi-state transition setting + scarce data available + Physics modelling

Multi-State Physics Model (MSPM)

Pros: • Feasible also with scarce data • effects of the repair strategy included • Applicable also to new piping systems because the degradation process is described by physical models

Cons: estimation of transition rates can be challenging
The degradation process is described by transitions among discrete states:

- **S**: no detectable damage
- **F**: detectable flaw
- **L**: detectable leak
- **R**: rupture

**The Approach: Multi-State Physics Model (MSPM)**

- The transition rates, $\lambda_{i,j}(t_{i,j}, \delta)$, are assumed to be functions of:
  - The influencing factors $\delta$ (i.e., material properties)
  - The holding times $\tau_{i,j}$

- $P(t, \delta) = \{p_S(t, \delta), p_F(t, \delta), p_L(t, \delta), p_R(t, \delta)\}$

Monte Carlo (MC) simulation framework
The case study

Component: *mixing tee* between the hot and cold legs in the Reactor Cooling System (RCS) of a Pressurized Water Reactor (PWR)

Operating conditions:
- Pressure: 36 bar
- Hot leg water temperature: 180°C
- Cold leg water temperature: 20°C

Piping material: *austenitic stainless steel 304L*
Transition rates evaluation procedure:

1) Build the physical models that describe the degradation process
Degradation mechanism: *thermal fatigue*

- Temperature fluctuation at the inner surface \( r_i \) of the pipe due to turbulent mixing or vortices

  Hypothesis: *sinusoidal transient thermal loading*
1) Degradation mechanism description

Degradation mechanism: *thermal fatigue*

- Temperature fluctuation at the inner surface ($r_i$) of the pipe due to turbulent mixing or vortices

Hypothesis: *sinusoidal transient thermal loading*

\[
\theta(r_i, t) = \theta_0 \cdot \sin(2\pi \phi)
\]
Degradation mechanism: \textit{thermal fatigue}

- Temperature fluctuation at the inner surface ($r_i$) of the pipe due to turbulent mixing or vortices

Hypothesis: \textit{sinusoidal transient thermal loading}

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\textbf{Amplitude} \quad \theta_0

uniform distribution:
- Lower value 0 °C
- Upper value 60 °C
Degradation mechanism: *thermal fatigue*

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\]

- **Amplitude** \(\theta_0\)
  - Uniform distribution:
    - Lower value 0 °C
    - Upper value 60 °C

- **Frequency** \(\phi\)
  - Uniform distribution:
    - Lower value \(10^{-4}\) Hz
    - Upper value \(10^2\) Hz
First degradation step: from No detectable damage $S$ to detectable Flaw $F$

Circumferential Crack Onset
Transition rates evaluation procedure:

1) Build the physical models that describe the degradation process

2) Sample the values of the parameters $\delta$ of the physical models
First degradation step: from No detectable damage \textbf{S} to detectable Flaw \textbf{F}.

\[ \theta(r_i, t) = \theta_0 \cdot \sin(2\pi \phi) \]

Stress distribution:
- radial \( \sigma_r(r) \)
- axial \( \sigma_z(r) \)
- hoop \( \sigma_\theta(r) \)
MC simulation: transition rate evaluation

Transition rates evaluation procedure:

1) Build the physical models that describe the degradation process

2) Sample the values of the parameters $\bar{\delta}$ of the physical models

3) Select a characteristic variable $x$ that \textit{describes the degradation process}
First degradation step: from No detectable damage $S$ to detectable Flaw $F$

Circumferential Crack Onset

$\theta(r_i, t) = \theta_0 \cdot \sin(2\pi \phi)$
Transition rates evaluation procedure:

1) Build the physical models that describe the degradation process.

2) Sample the values of the parameters $\delta$ of the physical models.

3) Select a characteristic variable $x$ that describes the degradation process.

4) Select a threshold value $X_{cr}$ that defines transition among states.
4) Setting of the threshold value $X_{cr}$

First degradation step: *from No detectable damage S to detectable Flaw F*

Circumferential Crack Onset

\[ \theta(r_t, t) = \theta_0 \cdot \sin(2\pi \phi) \]

**Number of thermal cycles to have the crack onset**

- radial $\sigma_r(r)$
- axial $\sigma_z(r)$
- hoop $\sigma_\theta(r)$
4) Setting of the threshold value $X_{cr}$

First degradation step: *from No detectable damage S to detectable Flaw F*

Circumferential crack Onset

$$N_f \quad \tau_{S,F}(\text{years}) = \frac{N_f}{\phi \cdot 3600 \cdot 24 \cdot 365}$$

$$\theta(r_i, t) = \theta_0 \cdot \sin(2\pi\phi)$$

- radial $\sigma_r(r)$
- axial $\sigma_z(r)$
- hoop $\sigma_\theta(r)$

$\varepsilon_{eq}^{tot} \quad N_f$
Transition rates evaluation procedure:

1) Build the physical models that describe the degradation process.

2) Sample the values of the parameters $\delta$ of the physical models.

3) Select a characteristic variable $x$ that describes the degradation process.

4) Select a threshold value $X_{cr}$ that defines transition among states.

5) Simulate the degradation process $N_c$ times for estimating the cumulative distribution function $F(\tau_{i,j} | \delta)$ of $\tau_{i,j}$. 
5) Degradation process simulation for estimating $F(\tau_{S,F} | \delta)$

First degradation step: *from No detectable damage $S$ to detectable Flaw $F$*

![Circumferential crack Onset](image)

- Circumferential crack:
  - $\theta(r, t) = \theta_0 \cdot \sin(2\pi \phi)$
  - Radial $\sigma_r(r)$
  - Axial $\sigma_z(r)$
  - Hoop $\sigma_\theta(r)$

- Number of simulation $N_c = 10000$

- $\tau_{S,F}$

- $F(\tau_{S,F} | \delta)$

- $\varepsilon_{eq}^{tot}$

- $N_f$
First degradation step: from No detectable damage S to detectable Flaw F

Circumferential crack Onset

\[ F(\tau_{S,F}|\delta) \rightarrow \lambda_{S,F}(\tau_{S,F}, \delta) \]
Application to a PWR piping system: developing the MSPM

First degradation step: *from No detectable damage S to detectable Flaw F*

Circumferential crack Onset

\[ \lambda_{S,F}(\tau_{S,F}, \delta) \]

\[ \theta(r_i, t) = \theta_0 \cdot \sin(2\pi \phi) \]

radial \( \sigma_r(r) \)

axial \( \sigma_z(r) \)

hoop \( \sigma_\theta(r) \)

\[ \varepsilon_{eq} \]

\[ \tau_{S,F} \]

\[ N_f \]

\[ F(\tau_{S,F} | \delta) \]
Rupture probability evaluation \( p_R(t, \delta) \)

**Rupture:** crack size reaches the whole circumference

**Hypotheses:**
- the considered piping system is not subjected to severe loading conditions
- repair transition rates are considered constant and the state transition time follows an exponential distribution as in [Fleming, 2004]


Developed MSPM: LOCA probability evaluation

Size and location-dependent LOCA probability evaluation

**LOCA:** Loss of Reactor Coolant Accident due to the breach in the Reactor Coolant pressure boundary

**Hypotheses:**
- breaches of size $254 \, mm < x \leq 287.3 \, mm$ (LOCA category 14) are accounted as leakages
- repair transition rates are considered constant and the state transition time will follow exponential distribution as in [Fleming, 2004]


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Size and location-dependent LOCA probability evaluation

Break size: $254 \, mm < x \leq 287.3 \, mm$

- At early stage, $p_L(t, \delta)$, obtained with the MSPM is smaller than $p_L(14, a, t)$ obtained by GSI-191

- At larger time, the probabilities $p_L(t, \delta)$, obtained with the MSPM, is larger than $p_L(14, a, t)$ obtained by GSI-191

Developed MSPM model: LOCA probability evaluation

- Inappropriate maintenance
- Underestimated risk
Conclusions

Safety assessment of NPPs

Failure probability estimation integrating Physical modelling

• MSPM framework applied to the Size and location-dependent Loss of Coolant Accident (LOCA) probability evaluation occurring in the mixing tee of the RCS of a PWR

• MC simulation framework for the transition rates estimation

• Comparison with benchmark results shows the benefits of introducing physics models not to underestimate the failure probability