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

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Multi-State Physics Modeling (MSPM) integrates multi-state modeling to describe a component degradation process by transitions among discrete states (e.g., no damage, micro-crack, flaw, rupture, etc.), with physics modeling by (physic) equations to describe the continuous degradation process within the states. In this work, we propose MSPM to describe the degradation dynamics of a piping system, accounting for the dependence on the size and location of the Loss of Coolant Accident (LOCA) initiating event of the Reactor Coolant System (RCS) of a Pressurized Water Reactor (PWR). Estimated frequencies of LOCA as a function of break size are used in a variety of regulatory applications and for the Probabilistic Risk Assessment (PRA) of Nuclear Power Plants (NPPs). Traditionally, two approaches have been used to assess LOCA frequencies as a function of pipe break size: estimates based on statistical analysis of field data collected from piping systems service experience and Probabilistic Fracture Mechanics (PFM) analysis of specific, postulated, physical damage mechanisms. However, due to the high reliability of NPP piping systems, it is difficult to construct a comprehensive service database based on which perform statistical analysis. On the other hand, it is difficult to utilize PFM models for calculating LOCA frequencies because many of the input variables and model assumptions are over-simplified and may not adequately represent the true plant conditions. We overcome these challenges and propose a size- and location-dependent LOCA initiating event frequencies estimation by resorting to the novel MSPM modeling scheme. Benchmarking is done with respect to the results obtained with the Generic Safety Issue (GSI) 191 framework that makes use of field data for LOCA initiating event probability calculation.

I. INTRODUCTION

The Loss of Coolant Accident (LOCA) is the loss of coolant due to the break in the primary piping cooling system which makes up the Reactor Coolant pressure boundary. Estimated frequencies of LOCA as a function of break size are used in a variety of regulatory applications and for the Probabilistic Risk Assessment (PRA) of Nuclear Power Plants (NPPs) (Ref. 1). In typical PRAs, LOCAs are divided by size category: small, medium and large. For each category, different strategies of intervention are designed for preventing core damage.

Traditionally, two approaches have been used to assess LOCA frequencies as a function of pipe break size: estimates based on statistical analysis of field data collected from piping systems service experience and Probabilistic Fracture Mechanics (PFM) analysis of specific, postulated, physical damage mechanisms. Due to the high reliability of NPP piping systems, it is difficult to construct a comprehensive service database on the basis of which perform statistical analysis (Ref. 2). Moreover, progress of technology, introduction of new piping material and new piping systems inspection programs may render field data no longer representative for future piping systems reliability assessment and LOCA initiating event frequencies estimation (Ref. 3). On the other hand, it is difficult to utilize PFM models for calculating LOCA frequencies because many of the input variables and model assumptions are over-simplified and may not adequately represent the true plant conditions. This makes it difficult to benchmark PFM models using the available sparse piping failure information (Ref. 4).

Furthermore, accounting for the location of LOCAs has been limited to the so-called "excessive LOCAs", i.e., breaches in the reactor pressure vessel that exceed the capabilities of the Emergency Core Cooling Systems (ECCSs) to prevent core damage (Ref. 1). Despite this, it is witnessed in practical cases that the location of the break can indeed influence the timing and duration of the mitigating action and it is, therefore, an important variable to be considered, but usually it is neglected (Ref. 5).

Recently, a revision of size- and location-dependent LOCA initiating event frequencies, based on service data, has been performed in the Generic Safety Issue (GSI) 191 framework in order to assess the risk of debris formation during LOCAs, that could interfere with the operation of the ECCSs (Ref. 6).

This paper presents the development of a Multi-State Physics Model (MSPM) for size- and location-dependent

LOCAs initiating event probability estimation, including a comparison with the estimation by GSI-191. The MSPM here developed is, conceptually, a Markov Chain Model (MCM) in which the degradation processes (and thus, the transition rates) are described by physic model equations (Refs. 7, 8, and 9). This description by the MSPM is capable of accounting for the break location and size because: i) physic model equations are related with size, materials and operating conditions of the piping system and, therefore, with piping system location; ii) the size of the break is the characteristic dimension that defines the transition among the states of the MSPM. Differently from the other approaches mentioned above, the MSPM directly accounts for changes in the piping systems inspection programs by properly changing the models in itself embedded.

The paper organization is as follows. Section II states the general issue of size- and location-dependent LOCA frequency estimation, as addressed in GSI-191. Section III presents the general characteristics of MSPM in particular focusing on the procedure for estimating the transition rates and, eventually, estimating the LOCA initiating event probability. Section IV presents the results of the application of MSPM to a Pressurized Water Reactor (PWR) piping system and the comparison with the results obtained in GSI-191. Section V presents the conclusions of the work.

II. GSI-191 FOR LOCA PROBABILITY ESTIMATION

The GSI-191 framework expresses the LOCA probability $p_L(c,a,t)$ as (Ref. 6):

$$p_L(c,a,t) = \gamma(c,a,t) \cdot t \qquad (1)$$

where $\gamma(c,a,t)$ is the LOCA initiating event frequency (event/reactor-calendar-year), t is the time variable (year), $c = 1, 2, 3, 4, .., c_o$ are the LOCA categories, i.e., ranges break size x, and a is the component type specified by characteristics like pipe material, degradation mechanisms, inspection programs, etc. .

The following sub-Section II.A describes the approach for estimating the size- and location-dependent LOCA initiating event frequency $\gamma(c,a,t)$.

II.A. GSI-191: Size- and Location-Dependent LOCAs Initiating Event Frequency Estimation

The approach for estimating the size- and location-dependent LOCA initiating event frequency $\gamma(c,a,t)$ as proposed in GSI-191 is based on Eq. (2) (Ref. 6):

$$\gamma(c,a,t) = \sum_a m_a \, \rho(c,a,t) \qquad (2)$$

where m_a is the number of pipes/welds of type a, $\rho(c,a,t)$ is the rupture frequency (rupture/welds-year) of component type a with break size corresponding to the c^{th} category. The rupture frequency $\rho(c,a,t)$ can be estimated by:

$$\rho(c,a,t) = \sum_h \lambda(a,h,t) \Pi(c|a,h) I_{a,h} \qquad (3)$$

where $\lambda(a,h,t)$ is the failure rate (failures/weld-year) for pipe component type a due to degradation mechanism h, $\Pi(c|a,h)$ is the conditional rupture probability to have a break of size corresponding to category c of a pipe component of type a due to degradation mechanism h and $I_{a,h}$ is the integrity management factor that accounts for changes in the inspection and detection strategy of failure mechanism h, in pipe/weld of type a (Ref. 10).

The information needed to evaluate the transition rate $\lambda(a,h,t)$ are, thus:

- Location of debris formation (GSI-191 defines 8 locations);
- Component types (GSI-191 defines 45 component types);
- Number of pipes/welds in the NPP under analysis;
- Number of pipes/welds failures in the NPP under analysis;
- Based on service data, number of piping system components that have been affected by the selected different damage mechanisms;
- Inspection reports and other evidence of any pipe failure or degradation that may influence the plant-specific failure rates.

The $\Pi(c|a,h)$ is evaluated for each one of the 8 locations defined for the evaluation of $\lambda(a,h,t)$ and for each category c, by applying a step-by-step procedure shown in Ref. 6 that makes use of the service data of Ref. 1. Starting from the LOCA category c proposed in Ref. 1 and listed in TABLE I, GSI-191 performs a finer analysis of the influence of break size on the LOCA frequency, where the total number of size categories are 15 (as we shall see in section IV.A, for a LOCA of break size x of category $c = 14$, subjected to the damage mechanism h of thermal fatigue).

TABLE I. LOCA Categories c and Related Break Size x (Ref. 1)

LOCA Category (c)	PRA category	Break size (mm) $X^u > x \geq X^l$
1	Small LOCA	$38 > x \geq 12$
2	Medium LOCA	$76 > x \geq 38$
3	Large LOCA	$170 > x \geq 76$
4		$355 > x \geq 170$
5		$800 > x \geq 355$
6		$1117 > x \geq 800$

III. MULTI-STATE PHYSICS MODELING FOR THE ESTIMATION OF THE SIZE- AND LOCATION-DEPENDENT PROBABILITY OF LOCA INITIATING EVENT

III.A. Multi-State Physics Modeling (MSPM)

The MSPM framework, the degradation is described as a MCM in which the degradation processes (and thus, the transition rates) are described by physic model equations. However, MSPM goes beyond the limitations of MCM that considers only constant rated of transition between the degradation states and exponentially distributed holding times. The underlying model of MSPM is, thus, non-Markovian because the transition rates are time-dependent, and is capable of including the uncertainties due to insufficient knowledge on the physical phenomena and parameters related to and influencing the degradation processes. The transition rates among the degradation states, $\lambda_{i,j}(\tau_{i,j},\overline{\delta})$, are assumed to be functions of the influencing factors $\overline{\delta}$ (i.e., the physical parameters used to model the degradation transition phenomena) and of $\tau_{i,j}$ (i.e., the holding time of the system in state *i*, before arriving to state *j*).

A general MSPM to describe a piping system component affected by the degradation mechanisms h is illustrated in Figure 1 where $\overline{T}=\{S,F,L,R\}$ are the binary states healthy S (i.e., no detectable damage), degraded F and L (i.e., detectable flaw, detectable leak) and rupture R, respectively (Ref. 11). The transition rates between states $\overline{T}$ are denoted as $\lambda_{S,F}(\tau_{S,F},\overline{\delta})$, $\lambda_{S,L}(\tau_{S,L},\overline{\delta})$, $\lambda_{S,R}(\tau_{S,R},\overline{\delta})$, $\lambda_{F,L}(\tau_{F,L},\overline{\delta})$, $\lambda_{F,R}(\tau_{F,R},\overline{\delta})$, $\lambda_{L,R}(\tau_{L,R},\overline{\delta})$, μ and ω (Ref. 12).

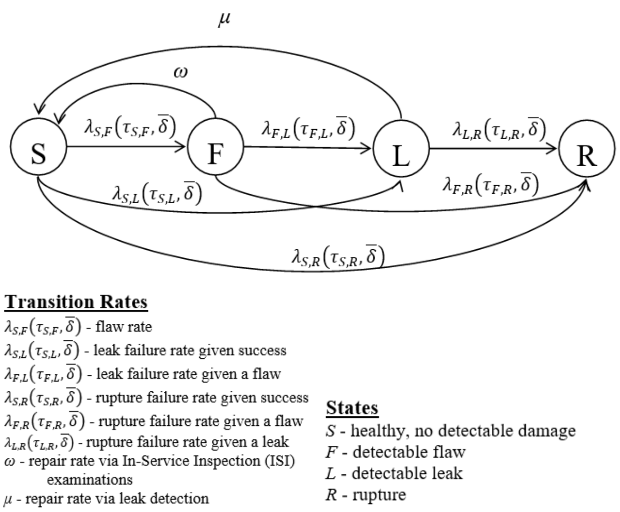

Fig.1. Four-state MSPM configuration describing degradation in piping systems (Ref. 12).

Mathematically, the MSPM consists in a set of differential equations to describe the evolution in time of the state probability vector $\overline{P}(t)=\{p_S(t,\overline{\delta}),p_F(t,\overline{\delta}),p_L(t,\overline{\delta}),p_R(t,\overline{\delta})\}$:

$$\begin{cases}\frac{dp_S(t,\overline{\delta})}{dt}=-\left(\lambda_{S,L}(\tau_{S,L},\overline{\delta})+\lambda_{S,R}(\tau_{S,R},\overline{\delta})+\lambda_{S,F}(\tau_{S,F},\overline{\delta})\right)p_S(t,\overline{\delta})+\omega p_F(t,\overline{\delta})+\mu p_L(t,\overline{\delta})\\ \frac{dp_F(t,\overline{\delta})}{dt}=\lambda_{S,F}(\tau_{S,F},\overline{\delta})p_S(t,\overline{\delta})-\left(\lambda_{F,L}(\tau_{F,L},\overline{\delta})+\lambda_{F,R}(\tau_{F,R},\overline{\delta})+\omega\right)p_F(t,\overline{\delta})\\ \frac{dp_L(t,\overline{\delta})}{dt}=\lambda_{S,L}(\tau_{S,L},\overline{\delta})p_S(t,\overline{\delta})+\lambda_{F,L}(\tau_{F,L},\overline{\delta})p_F(t,\overline{\delta})-\left(\lambda_{L,R}(\tau_{L,R},\overline{\delta})+\mu\right)p_L(t,\overline{\delta})\\ \frac{dp_R(t,\overline{\delta})}{dt}=\lambda_{S,R}(\tau_{S,R},\overline{\delta})p_S(t,\overline{\delta})+\lambda_{F,R}(\tau_{F,R},\overline{\delta})p_F(t,\overline{\delta})+\lambda_{L,R}(\tau_{L,R},\overline{\delta})p_L(t,\overline{\delta})\end{cases} \tag{4}$$

Notice that the four states $\overline{T}$ considered are mutually exclusive and form a complete set: thus, $p_S(t,\overline{\delta})+p_F(t,\overline{\delta})+p_L(t,\overline{\delta})+p_R(t,\overline{\delta})=1$ at any time $t=1,2,\dots,T_{miss}$, where T_{miss} is the mission time of the piping system. The quantification of $\overline{P}(t)$, as explained in (Refs. 12, and 13), is based on the estimation by Monte Carlo (MC) simulation of the τ- and $\overline{\delta}$-dependent transition rates, as we shall see in what follows.

III.B. τ- and $\overline{\delta}$-Dependent Transition Rates Estimation

The transition rates can be expressed as:

$$\lambda_{i,j}(\tau_{i,j},\overline{\delta})=\frac{f(\tau_{i,j}|\overline{\delta})}{R(\tau_{i,j}|\overline{\delta})}\cong\lim_{\Delta\tau\to 0}\frac{F(\tau_{i,j}+\Delta\tau|\overline{\delta})-F(\tau_{i,j}|\overline{\delta})}{\left(1-F(\tau_{i,j}|\overline{\delta})\right)\times(\Delta\tau)} \tag{5}$$

where $\tau_{i,j}$ is the holding time in state *i*, before arriving in state *j*, $R(\tau_{i,j}|\overline{\delta})$ is the reliability of the component of type a at time $\tau_{i,j}$, $f(\tau_{i,j}|\overline{\delta})$ and $F(\tau_{i,j}|\overline{\delta})$ are the probability density function and cumulative distribution function of the holding time between states *i* and *j*, respectively (Ref. 12).

The procedure for estimating the cumulative distribution function $F(\tau_{i,j}|\overline{\delta})$ and the transition rates $\lambda_{i,j}(\tau_{i,j},\overline{\delta})$ is as follows:

1) *Build the physical models that describe the transitions among the different states due to the degradation process h* (e.g., fatigue, thermal fatigue and stress corrosion cracking (SCC)).
2) *Select a characteristic variable x* (e.g. crack depth, crack length, etc.), *that is representative of the degradation process and its threshold value X_{cr}, that triggers the transition from one state to another*: the time $\tau_{i,j}$ at which the system moves from state *i* to state *j* is that at which $x=X_{cr}$.
3) *Sample the values of the parameters $\overline{\delta}$ of the physical models, treated as random variables whose values follow given distributions representing their uncertainties.*
4) *Simulate the degradation process N_c times for estimating the state holding time $\tau_{i,j}$ distributions:* the algorithm for the estimation of the probability density function $f(\tau_{i,j}|\overline{\delta})$ and of the cumulative distribution function $F(\tau_{i,j}|\overline{\delta})$ is sketched in the following pseudo-code, where N_{succ} is the number of MC simulations in which $x\geq X_{cr}$ at time $\tau_{i,j}$ and N_c is the total number of trials. The time space is discretized by choosing a discrete timeline with $\Delta\tau$ as interval size.

Set the threshold dimension X_{cr}, the number of MC repeated trials N_c, the interval time size $\Delta\tau$ and the mission time T_{miss}. Define N_{succ} as a vector of

$T_{miss}/\Delta\tau$ elements, each one representing a discrete step on the timeline equal to $\Delta\tau$.

Consider a physics equation $x = g(\tau, \overline{\delta})$ that models x as a function of τ and $\overline{\delta}$

For $N = 1{:}\, N_c$

$\tau = 0$

Sample physics parameters $\overline{\delta}$ from their distributions

$x = g(\tau, \overline{\delta})$

While $x <= X_{cr}$

$\tau = \tau + \Delta\tau$

$x = g(\tau, \overline{\delta})$

End While

$Nsucc(\tau/\Delta\tau + 1) = Nsucc(\tau/\Delta\tau + 1) + 1$

End For

$f(\tau|\overline{\delta}) = N_{succ}/N_c$

$F(1) = f(1)$

For $N = 2{:}\, T_{miss}/\Delta\tau$

$F(N) = F(N-1) + f(N)$

End For

5) *Estimate the transition rates by applying Eq. (5) with the selected* $\Delta\tau$.

The procedure explained above to evaluate the MSPM transition rates shows that the transition among the states of the MSPM strictly depends on:

- The value of the characteristic dimension x that describes the degradation process h. Thus, the MSPM can be easily tailored to evaluate the probability $p_L(t, \overline{\delta})$ of a leakage phenomenon characterized by a specific break size x, i.e., a LOCA of category c.
- The physical models used to simulate the degradation process (that depends on the degradation mechanism, material, loading and environmental conditions, pipe dimension). Thus, the MSPM can be easily tailored to evaluate $p_L(t, \overline{\delta})$ for a specific component of type a.

The following sub-Sections III.C and III.D present an adaptation of a MSPM already proposed by the authors (Ref. 12) to improve the capability of evaluating the size- and location-dependent LOCA probability.

III.C. A 4 States MSPM Configuration for Size- and Location-Dependent LOCA Probabilities Estimation

The 4 states MSPM configuration shown in Figure 2 is useful for estimating the probability of a LOCA whose leakages phenomena have $x \geq X^l$, where, X^l is the lower bound of the break size of a LOCA of category c (see TABLE II). In this case, $p_L(t, \overline{\delta})$ is the probability of the system to be in state L (i.e., to have a LOCA) at time t, given a break size greater or equal to X^l corresponding to the chosen LOCA category.

The main differences between the model of Figure 1 and this latter are:

- State $L1$ is added to the state space to avoid accounting as leakages all those events having a break size x smaller than X^l. The system enters state $L1$ when the crack reaches a through-wall characteristic and departs from that when $x = X^l$. Otherwise, with the state space of Figure 1, we would not be able to bound the break size x from below, but, rather, we would account as LOCA of category c any leakages of any size.
- State R and the transition between states L and R are deleted: all breaks larger than X^l are accounted as LOCA events of category c (i.e., L becomes an absorbing state).
- The considered piping system is not subjected to severe loading conditions: the transitions between no damage state (S) to Leak (L) and Flaw (F) to Leak (L) are not considered as realistic possible transitions.

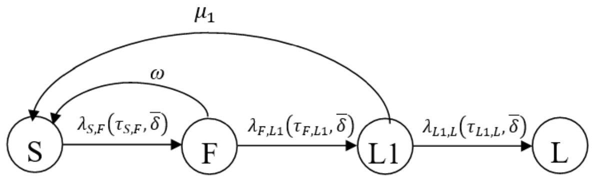

Fig. 2. The 4 states MSPM configuration that can be used for estimating the probability of a LOCA with break size $x \geq X_l$.

III.D. A 5 States MSPM Configuration for Size- and Location-Dependent LOCAs Probabilities Estimation

The 5 states MSPM configuration shown in Figure 3 is useful for estimating the probability of a LOCA whose leakages phenomena have $X^l < x \leq X^u$, where X^l and X^u are the lower and upper bounds of the break size of a LOCA of category c (see TABLE II). In this case, $p_L(t, \overline{\delta})$ is the probability of the system to be in state L (i.e., to have a LOCA) at time t, given a break size belonging to the interval $[X^l, X^u)$ corresponding to the chosen LOCA category c.

A modification of the model of Figure 1 is proposed in Figure 3. The main differences between the model of Figure 1 and this latter are:

- State $L1$ is added to avoid accounting as leakages all those events having a break smaller than X^l, like for the 4 states MSPM of Section III.C.
- The system departs from state L and enters state R when $x = X^u$: state R accounts for all the x larger than X^u, up to a fully-circumferential characteristic of the generated crack. Otherwise, we would not be able to bound the break size from above (as it is not for the 4 states MSPM configuration of Section III.C).
- The piping system considered is not subjected to severe loading conditions: transitions between no damage state (S) to Leak (L) or

Rupture (R) are not considered as realistic possible transition.

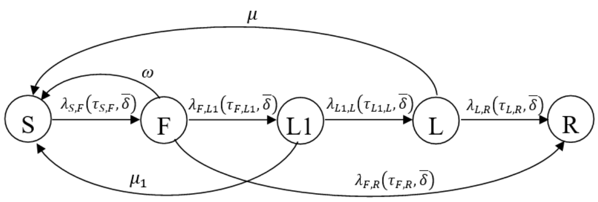

Fig. 3. The 5 states MSPM configuration that can be used for estimating the probability of a LOCA with break size $X^l < x \leq X^u$

IV. APPLICATION TO A PWR PIPING SYSTEM

IV.A. System description

TABLE II. GSI-191 Break Size, LOCA Category and $\gamma(c, a, t)$ for Component of Type 7B Subjected to Thermal Fatigue (Ref. 6)

Component location	Damage mechanism (h)	Pipe Diameter (mm)	Break size (mm) $X^u > x \geq X^l$	c	$\gamma(c,a,t)$
Class 1 medium bore pipe of a RHR	Thermal fatigue	203	$19.05 > x \geq 12.7$	1	2.78E-6
			$25.4 > x_x \geq 19.05$	2	1.67E-6
			$38.1 > x \geq 25.4$	3	1.18E-6
			$50.8 > x \geq 38.1$	4	7.48E-7
			$71.9 > x \geq 50.8$	5	4.01E-7
			$101.6 > x \geq 71.9$	6	1.67E-7
			$107.7 > x \geq 101.6$	7	8.5E-8
			$143.76 > x \geq 107.7$	8	7.41E-8
			$152.4 > x \geq 143.76$	9	3.79E-8
			$171.45 > x \geq 152.4$	10	3.31E-8
			$182.9 > x \geq 171.45$	11	2.52E-8
			$215.6 > x \geq 182.9$	12	2.22E-8
			$254 > x \geq 215.6$	13	1.06E-8
			$287.3 > x \geq 254$	14	1.16E-8
			$x \geq 287.3$	15	9.11E-9

The proposed MSPM configurations for size- and location-dependent probability estimation of LOCA probability estimation as presented in sub-Sections III.C and III.D, are here applied to the mixing tee between the hot and cold legs of a RCS of a PWR undergoing thermal fatigue. The results are, then, compared with those provided by GSI-191 for a Class 1 medium bore pipe of a Residual Heat Removal (RHR) system subjected to thermal fatigue (i.e., location 7 and component type $a = 7B$ (Ref. 6)). This component has been selected to benchmark the MSPMs results because it is characterized by pipe diameter, degradation mechanisms h (thermal fatigue), operating conditions and location similar to the mixing tee. MSPM is applied to evaluate the propability $p_L(t, \overline{\delta})$ of a break size corresponding to the LOCA category $c = 14$. The GSI-191 pipes characteristics and $\gamma(c, a, t)$ are reported in TABLE II.

IV.B. τ- and $\overline{\delta}$-Dependent Transition Rates Estimation

The τ - and $\overline{\delta}$ -dependent transition rates are estimated as follows (for further details, please refer to (Ref. 12)):

- $\lambda_{S,F}(\tau_{S,F}, \overline{\delta})$: the variable that characterizes the transition between states S and F is the total equivalent strain rate (ε_{eq}^{tot}) (Ref. 14). We suppose that the system enters state F experiencing a circumferential crack.
- $\lambda_{F,L1}(\tau_{F,L1}, \overline{\delta})$: the variable that characterizes the transition between states F and $L1$ is the crack radial depth x (Ref. 15). The system enters state $L1$ when the crack reaches a through-wall radial characteristic depth ($X_{cr} = 9\ mm$).
- $\lambda_{F,R}(\tau_{F,R}, \overline{\delta})$: the variable that characterized the transition between states F and R is the crack radial depth x (Ref. 16). The system enters state R when the radial propagation of a fully-circumferential crack reaches a through-wall characteristic depth ($X_{cr} = 9\ mm$).
- $\lambda_{L1,L}(\tau_{L1,L}, \overline{\delta})$: the variable that characterizes the transition between states $L1$ and L is the crack circumferential length x. The system enters state L when $x = X_{cr} = X^l$. The initial crack dimension is $x = 28\ \mu m$ (Refs. 17, and 18).
- $\lambda_{L,R}(\tau_{L,R}, \overline{\delta})$: the variable that characterizes the transition between states L and R is the crack length x. The system enters state R when $x = X_{cr} = X^u$. The initial crack dimension is $x = X^l$.

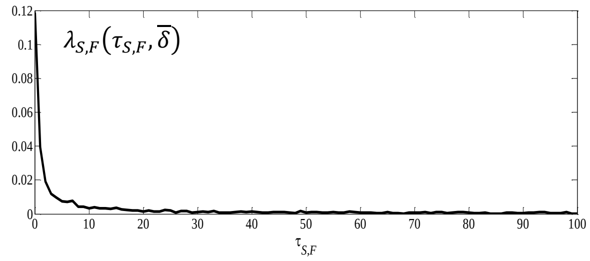

Fig. 4. Transition rate from state *S* to state *F*.

Figures 4-8 show the MC-based estimated (see Section III.B) of the τ- and $\overline{\delta}$-dependent transition rates $\lambda_{S,F}(\tau_{S,F}, \overline{\delta})$, $\lambda_{F,L1}(\tau_{F,L1}, \overline{\delta})$, $\lambda_{F,R}(\tau_{F,R}, \overline{\delta})$, $\lambda_{L1,L}(\tau_{L1,L}, \overline{\delta})$, $\lambda_{L,R}(\tau_{L,R}, \overline{\delta})$, respectively.

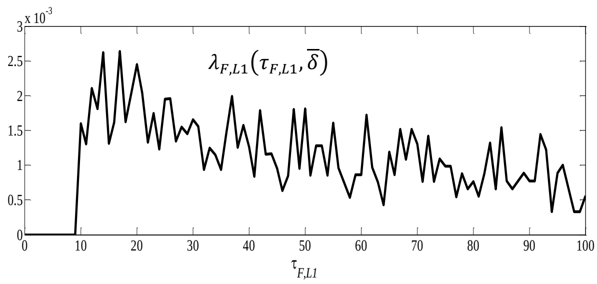

Fig. 5. Transition rate from state *F* to state *L1*.

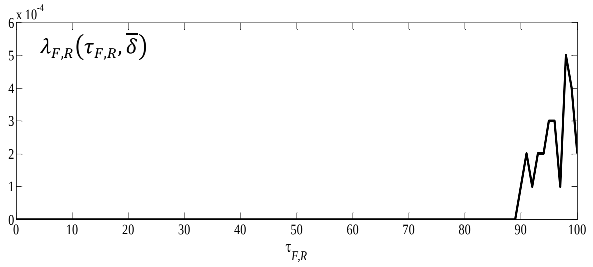

Fig. 6. Transition rate from state *F* to state *R*.

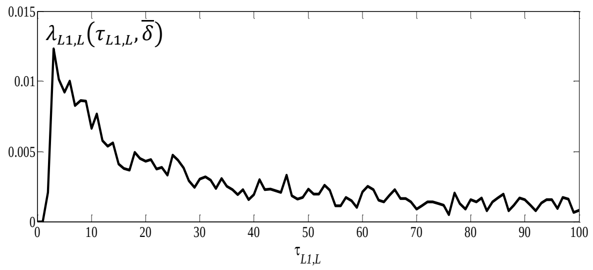

Fig. 7. Transition rate from state *L1* to state *L*.

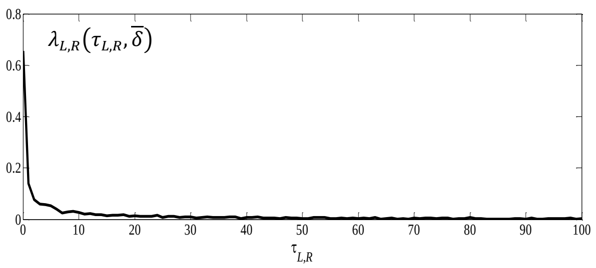

Fig. 8. Transition rate from state *L* to state *R*.

Looking at the transition rates distribution, it is possible to conclude that:

- If a crack onset is experienced, it occurs in the early stage of the component life (as shown in Figure 4).
- The transition rate distribution $\lambda_{F,L1}(\tau_{F,L1},\overline{\delta})$ shows a discontinuity from $\lambda_{F,L1}(9,\overline{\delta}) = 0$ to $\lambda_{F,L1}(10,\overline{\delta}) = 0.0016$ and the largest values for $10 \leq \tau_{F,L1} \leq 20$ years (Figure 5). This leads us to conclude that the radial crack that propagates across the piping wall needs at least 10 years to reach a through-wall circumferential characteristic depth.
- The transition between states *F* and *R* is driven by negligible values for $\lambda_{F,R}$ (Figure 6): this is reasonable due to the unlikely event of having a pipe rupture without being preceded by any leakage phenomena. On the other hand, the transition between states $L1$ and L, as well as the transition between states L and R, are driven by values of $\lambda_{L1,L}$ (Figure 7) and $\lambda_{L,R}$ (Figure 8) that have larger values in the early stage of component life and, thus, cannot be neglected; this means that, once a crack reaches a through-wall characteristic depth, its propagations is likely to happen abruptly and catastrophically.

IV.C. Comparison of the 4 States and 5 States MSPM Configurations with GSI-191

A first comparison between the MSPM configurations and GSI-191 results is made by assuming that the values of the repair transition rates ω and μ are those originally proposed in Ref. 11:

$$\omega = \frac{P_I P_{FD}}{(T_{FI}+T_R)} = 2\times10^{-2}/yr$$

(Components are assumed to have a 25% chance (P_I) of being inspected for flaws detection every 10 years (T_{FI}), with a 90% detection probability (P_{FD}); detected Flaws are repaired in 200 h (T_R=200 h/8760 h/ year)).

$$\mu = \frac{P_I P_{LD}}{(T_{LI}+T_R)} = 7.92\times10^{-1}/yr$$

(Components are assumed to have a 90% chance (P_I) of being inspected for leak detection every 1 years (T_{LI}), with a 90% detection probability (P_{LD}); detected Leaks are repaired in 200 h (T_R=200 h/8760 h/ year).

This hypothesis for ω and μ can be considered reasonable because:

- The transition between states *S* and *F* accounts for the same degree of degradation as in Ref. 11 and is described by the same physical model and settings of Ref. 12. Therefore, ω is equivalent to that of Ref. 11.
- Despite that the transitions between states F and $L1$ and $L1$ to L account for different degrees of degradation than the transition between states F and L described in Ref. 11, states $L1$ and L still model leakages phenomena whose detection capabilities can be considered equivalent to those proposed in Ref. 11. Therefore, μ is the same as in Ref. 11.

Figure 9 shows the probability $p_L(t,\overline{\delta})$ as estimated by the 4 and 5 states MSPM configurations (stars and dots, respectively), as well as the probability $p_L(14,a,t)$ calculated with GSI-191 (triangles).

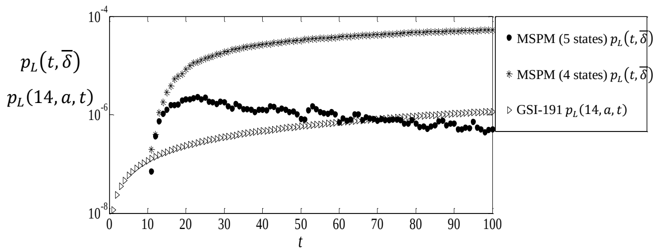

Fig. 9. $p_L(t,\overline{\delta})$ estimated by the 4 and 5 states MSPM configurations and $p_L(14,a,t)$ estimated by GSI-191.

Figure 9 highlights that the 4 states MSPM configuration overestimates the probability to have a LOCA of class 14, whereas, the 5 states MSPM configuration, even if closer to the GSI-191 than the 4 states, shows a decreasing trend, due to the fact that state L is not an absorbing state but, rather, a transition between states L and R is still allowed.

Furthermore, Figure 9 shows that the probabilities $p_L(t,\overline{\delta})$ obtained with the 4 and 5 states MSPM configurations (dots and stars, respectively) differ from $p_L(14,a,t)$ (triangles) from the early stage of the piping system operation: below 10 years, the estimated probability $p_L(t,\overline{\delta})$ would lead to a relaxation of maintenance/repair efforts, with cost savings when relying on the MSPM results rather than on GSI-191, whereas, at larger times, the probability $p_L(14,a,t)$ is underestimated (~2 orders of magnitude) with respect to $p_L(t,\overline{\delta})$, with possibly significant risk associated to this underestimation.

One could argue that these advantages (i.e., relaxation of maintenance efforts and avoidance of any risk underestimation) of MSPM with respect to GSI-191 are due to an improper setting of μ and ω. To dispel any possible doubt, a parameter identification procedure has been followed by fitting the 4 and 5 states MSPM configuration results to the curve of the GSI-191.

Figure 10 shows, the best fitting results of the $p_L(t,\overline{\delta})$ estimated by the 4 states MSPM configuration with the $p_L(14,a,t)$ provided by GSI-191. The best set of parameters are found to be $\omega = 0.5\times2\times10^{-2}/yr$ and $\mu = 4\times7.92\times10^{-1}/yr$. We can draw the following insights:

- except for the first 20 year, the estimated probability $p_L(t,\overline{\delta})$ would lead to a relaxation of maintenance/repair efforts, with cost savings when relying on the MSPM results rather than on GSI-191; the trend in the first 20 years of $p_L(t,\overline{\delta})$ can be explained by looking at the transition rate from F to $L1$ (Figure 5), from which it is evident that the system cannot enter state $L1$, and thus L, until $t = 9\ years$ (e.g., for $t < 9\ years$, $\lambda_{F,L1}(\tau_{F,L1},\overline{\delta})$ is equal to 0).
- The best-fit identified value for ω can be explained by looking at Figure 5: it shows that it is likely for the system to leave state F in $9 < t < 20\ years$ in which $\lambda_{F,L1}(\tau_{F,L1},\overline{\delta})$ shows larger values. Thus, the reduction of ω with respect to Ref. 11 can be explained by the reduced probability of the system to be in state F with respect to the hypothesis made in Ref. 11, that reduces also the probability of detecting a Flaw (i.e, ω).
- The larger value of μ with respect to the original setting is due to a larger occurrence probability of a Leakage of type $L1$, that favors the detection capability (i.e, μ).

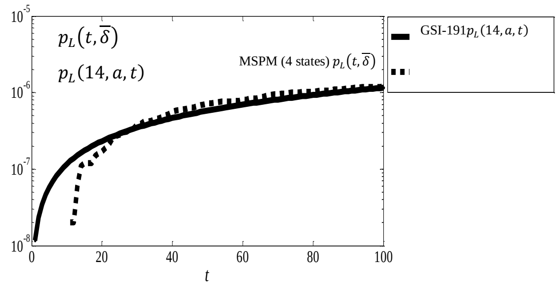

Fig. 10. Best fitting of the 4 states MSPM configuration $p_L(t,\overline{\delta})$ with $p_L(14,a,t)$ of GSI-191.

Finally, Figure 11 shows the best fitting results of the $p_L(t,\overline{\delta})$ estimated by the 5 states MSPM configuration with the $p_L(14,a,t)$ provided by GSI-191. The best set of parameter values is found to be $\mu = 4\times7.92\times10^{-1}/yr$ and $\mu_1 = 7.92\times10^{-1}/yr$. This result allows for some consideration:

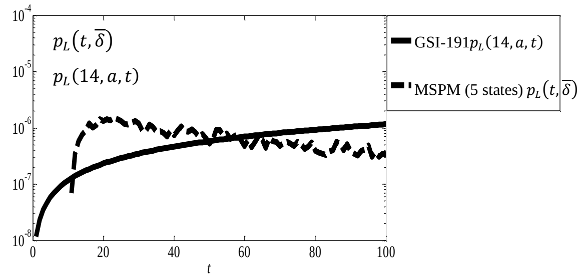

Fig. 11. Best fitting of the 5 states MSPM configuration $p_L(t,\overline{\delta})$ with $p_L(14,a,t)$ of GSI-191.

- The larger value of μ with respect to the original setting can be explained by a larger the size dimension than in Ref. 11: such a large break size dimension favors the detection capability (i.e, μ).
- μ_1 takes the same value proposed in Ref. 11, and it is 4 times smaller than the one set for the 4 states MSPM configuration; this is due to the fact that the 5 state MSPM configuration accounts for the possibility for the system to move from state F to state R, reducing the probability to have a leakage before break and, thus, reducing the capability of detecting the leakage itself.

V. CONCLUSIONS

Two different configurations of MSPM have been developed to estimate the size- and location-dependent LOCA initiating event probability. The two configurations of the MSPM have been applied to a piping system of a Reactor Coolant System (RCS) of a Pressurized Water Reactor (PWR) undergoing thermal fatigue and benchmarked with the results of the Generic Safety Issue (GSI) 191 framework.

The comparison of the GSI-191 with the novel MSPM configurations shows that with more realistic assumptions and consistent exploitation of the available knowledge (data and models), the latter method gives larger probabilities of occurrence of a leakage/rupture in the piping system, than the GSI-191. This difference in the estimates can be significant from the risk point of view as this could be underestimated, with all associated consequences. This shows the importance of finding “modeling ways” to include all the knowledge and information available (in the form of data, models, expert judgments, etc.) for a well-informed-as-possible, faithful-as-possible description of the real degradation and failure mechanisms. Finally, another advantage of the MSPM for piping systems failure probability quantification is its applicability to assess the reliability of newly designed NPP components when lacking field data.

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