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Methodology for the Incorporation of Passive Component Aging Modeling into the RAVEN/ RELAP-7 Environment

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1. INTRODUCTION

Passive system, structure and components (SSCs) will degrade over their operation life and this degradation may cause to reduction in the safety margins of a nuclear power plant. In traditional probabilistic risk assessment (PRA) using the event-tree/fault-tree methodology, passive SSC failure rates are generally based on generic plant failure data and the true state of a specific plant is not reflected realistically. To address aging effects of passive SSCs in the traditional PRA methodology [1] does consider physics based models that account for the operating conditions in the plant, however, [1] does not include effects of surveillance/inspection.

This paper represents an overall methodology for the incorporation of aging modeling of passive components into the RAVEN/RELAP-7 environment which provides a framework for performing dynamic PRA. Dynamic PRA allows consideration of both epistemic and aleatory uncertainties (including those associated with maintenance activities) in a consistent phenomenological and probabilistic framework and is often needed when there is complex process/hardware/software/firmware/ human interaction [2]. Dynamic PRA has gained attention recently due to difficulties in the traditional PRA modeling of aging effects of passive components using physics based models and also in the modeling of digital instrumentation and control systems. RAVEN (Reactor Analysis and Virtual control Environment) [3] is a software package under development at the Idaho National Laboratory (INL) as an online control logic driver and post-processing tool. It is coupled to the plant transient code RELAP-7 (Reactor Excursion and Leak Analysis Program) also currently under development at INL [3], as well as RELAP5-3D [4]. The overall methodology aims to:

- Address multiple aging mechanisms involving large number of components in a computational feasible manner where sequencing of events is conditioned on the physical conditions predicted in a simulation environment such as RELAP-7.
- Identify the risk-significant passive components, their failure modes and anticipated rates of degradation
- Incorporate surveillance and maintenance activities and their effects into the plant state and into component aging progress.
- Asses aging affects in a dynamic simulation environment

2. METHODOLGY

In the proposed methodology, the traditional PRA is extended to include dynamic plant condition dependent data from physics based SSC degradation models for which surveillance data are used for periodical updating. In Fig. 1, the proposed interaction of aging models with the plant dynamics within this simulation environment is schematically shown. Solid lines indicate manual or mechanized implementation. Dashed lines indicate additional direct coupling for mechanized implementation.

Initially, at time t=0, plant state as obtained from the plant configuration and state of process variables (Initial Conditions) are fed into *the Plant Simulator*. Plant configuration and component failure rates/probabilities are also fed into the *PRA Code* for the prediction of *Risk Metrics and Importances* at t=T. The variable T is a user specified time interval, possibly chosen to represent the duration of an operating cycle or surveillance intervals as well as to model degradation dynamics adequately.

The Plant Simulator (RELAP-7 code) produces the required thermal-hydraulic/neutronic data to feed into the *Component Aging Model* which is assumed to stay unchanged within the selected time interval T to predict failure rates/probabilities at t=T. In Fig. 1, *The Plant Simulator* operates over two distinctly different time scales: 1) the quasi-steady state condition while the plant is at power during a fuel cycle, and, 2) the dynamic time frame of a reactor shutdown and startup or the transient response of the plant to an accident. For the quasi-steady state condition, it is likely that the thermal-hydraulic conditions will be maintained as constant based on the results of off-line steady-state calculations performed with the Plant Simulator. In the dynamic time frame case, the variability of the operational data is taken in account. Therefore the size of the interval T should be taken as small as possible to improve the fidelity of the analysis while preserving the computational affordability of the simulation. *Initial conditions*/*surveillance data*, including maintenance and repair actions as they affect the plant state, are also updated at each time *T*, as well as *Component Failure Rates/Probabilities* inferred from these data.

At the end of each time interval *T*, the plant state is re-evaluated as it impacts the determination of the plant risk for that time interval. If the predicted *Risk Metrics and Importances* are found inadequate, the surveillance program is updated. As degradation processes continue over the time period the potential will grow that an initiating event of some kind would occur, such as a rupture of a pipe at a weld. Based on the plant condition, the likelihood of an initiating event of this nature will be determined, which will affect the plant risk for that time interval. Similarly, degradation will occur in components that need to operate in response to an initiating event, again affecting the outcome of the risk assessment. Thus, it is necessary not only to project degradation as a function of time but to interpret the impact of a level of degradation on the probability of the occurrence of an initiating event or the impact of a level of degradation on the performance of a component.

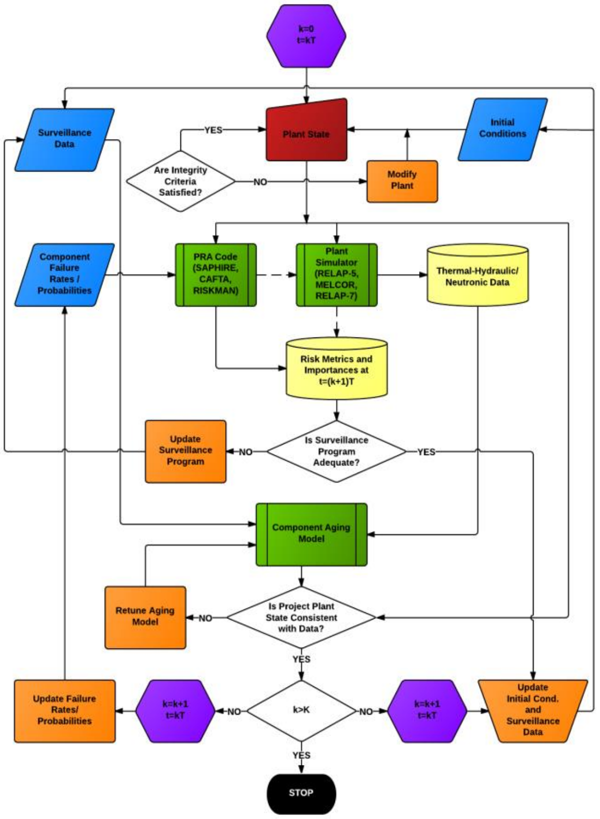

Fig. 1. Proposed PRA methodology

If the predicted *the Plant State* is found to be inconsistent with surveillance data, then the component aging model retuned. Similarly, the results of surveillance performed within a particular time interval could indicate the need to repair or replace a component or structure. Thus, SSCs can be returned to some initial state at which degradation mechanisms will again continue to degrade their performance. The time is incremented by *T* and the process is repeated until the target time horizon *kT* is reached.

Currently, the *Component Aging Model* under consideration is multi-state physics based model (see Fig. 2) with state transitions described by

$$dS/dt = -\phi_1 S + \omega_1 M + \omega_2 D + \omega_3 C + \omega_4 L \tag{1}$$

$$dM/dt = \phi_1 S - \omega_1 M - \phi_2 M - \phi_3 M \tag{2}$$

$$dC/dt = \phi_3 M - \omega_3 C - \phi_6 C \tag{3}$$

$$dD/dt = \phi_2 M - \omega_2 D - \phi_4 D \tag{4}$$

$$dL/dt = \phi_4 D - \omega_4 L - \phi_5 L \tag{5}$$

$$dR/dt = \phi_6 C + \phi_5 L \tag{6}$$

and state probabilities defined as S, M, C, D, L and R, respectively, in Fig.(2). The transition rates ϕ_5, ϕ_6 and ω_i (i=1,2,3) are constant. Simplified version of the transition rates $\phi_i(t)$ (i=1,…,4) as presented in [7] are

$$\phi_1(t) = (b/\beta)(t/\beta)^{b-1} \tag{7}$$

$$\phi_2(t) = \tag{8}$$

$$= \begin{cases} 0 & \text{if } u \le \dfrac{a_D}{\dot{a}_M} \\ \dfrac{a_D P_D}{u\, a_D P_D + u^2\, \dot{a}_M P_c} & \text{if } u \le \dfrac{a_C}{\dot{a}_M} \\ \dfrac{a_D P_D}{u\, a_D P_D + u\, a_C\, P_c} & \text{if } u > \dfrac{a_D}{\dot{a}_M} \end{cases}$$

$$\phi_3(t) = \tag{9}$$

$$= \begin{cases} 0 & \text{if } u \le \dfrac{a_C}{\dot{a}_M} \\ \dfrac{a_C P_C}{u\, a_D P_D + u^2\, \dot{a}_M P_c} & \text{if } u > \dfrac{a_C}{\dot{a}_M} \\ \dfrac{a_C P_C}{u\, a_D P_D + u\, a_C\, P_c} & \text{if } u > \dfrac{a_D}{\dot{a}_M} \end{cases}$$

$$\phi_4(t) = \begin{cases} 1/w & \text{if } w > (a_L - a_D)/\dot{a}_M \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

In Eqs.(8) - (10), *u* is a time after crack initiation and *w* is time after macro-crack formation. The other parameters in Eqs.(8) - (10) are:

a_C: Crack length threshold for circumferential macro-crack
a_D: Crack length threshold for radial macro-crack
a_L: Crack length threshold for leak

P_C: Probability that micro-crack evolves as circumferential crack

P_D: Probability that micro-crack evolves as radial crack

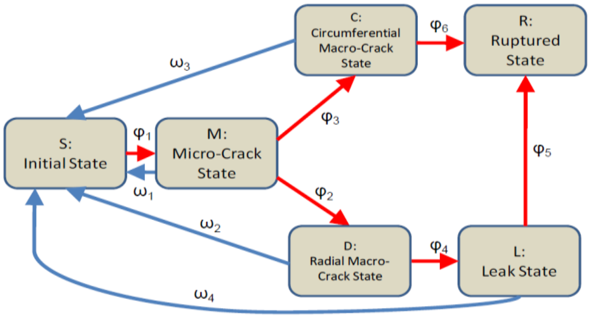

Fig.2. Multi-state physics based transition model [7]

A semi-Markov approach is used to represent the residence time and operational data dependent transition rates in Eqs.(7)-(10) leading to:

$$\frac{d\tau_{n,k}(t)}{dt} = (t - T_{k-1})\left[-x_n(t)\sum_{\substack{m=1\\ m\neq n}}^{N}\phi_{mn}(\tau_{n,k-1}) + \sum_{\substack{m=1\\ m\neq n}}^{N}\phi_{nm}(\tau_{m,k-1})\,x_m(t)\right] \qquad (11)$$

$$\text{for } (T_{k-1} \le t \le T_k;\ k=1,2,..K)$$

where $\tau_{n,k}(t)$ is sojourn time of state *n* and for *kth* time interval (see Fig.1) replacing *u* and *w* in Eqs.(8)-(10), $x_n(t)$ is the probability of being in State *n* at time *t*, and $\phi_{nm}(\tau_{m,k-1})$ is the transition rate from State *n* to State *m* as a function of sojourn time.

3. RAVEN/RELAP-7ENVIRONMENT COUPLING

Two numerical solution techniques will be available in the RAVEN/RELAP-7 environment to solve Eqs.(1) through (11): i) a numerical solver of the ordinary differential equations (ODEs), and, ii) a Monte Carlo (MC) solution scheme. A 4^{th} Runge-Kutta solver is used to solve the system of equations for a given set of operational data (e.g., temperature and pressure) from RELAP-7 code for each selected time interval. The calculated failure probability will be used in the control logic of RAVEN to activate required safety systems in RELAP-7 to mitigate component failure affects and also as a post processor parameter to modify initiating event/ basic event probabilities.

In the MC simulation of the semi-Markov model, state probabilities will not be sampled directly. Instead, state residence times will be sampled and then transition rates will be calculated. This procedure will repeat till targeted time horizon and the calculated failure probability reaches convergence. In the RAVEN code, calculated failure rate functions as a control logic parameter for the RELAP-7 code and as an initiating event/basic event for the PRA study (see Fig. 3).

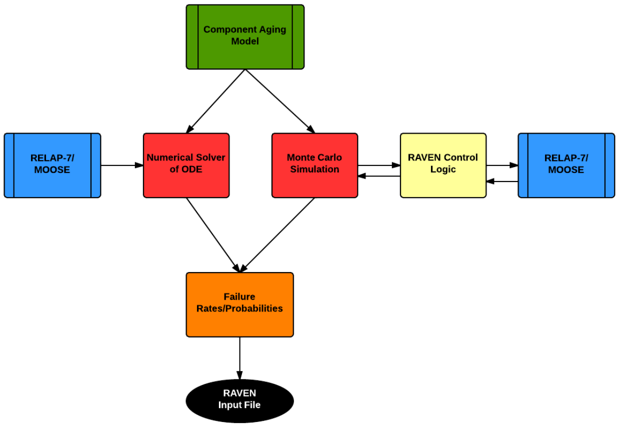

Fig.3. Aging model and coupling with the RAVEN/RELAP-7 environment

4. DISCUSSION

Earlier work [8, 9] indicates that implementation of a semi-Markov model for life assessment of SSCs provides a computationally feasible approach for quantifying the probability of rupture for PRAs in a realistic manner. The multi-physics simulation environment, RAVEN/ RELAP-7, is targeted to provide operational data in accounting for the underlying physics of material degradation an input data for the semi-Markov SSC degradation over 60 years.

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