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USE OF MARKOV PIPING RELIABILITY MODELS TO EVALUATE TIME DEPENDENT FREQUENCIES OF LOSS OF COOLANT ACCIDENTS

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ABSTRACT

Markov model theory has been applied to develop a method to evaluate the influence of alternate strategies for in-service inspection and leak detection on the frequency of leaks and ruptures in nuclear power plant piping systems [1-4]. This approach to quantification of pipe rupture frequency was originally based on a Bayes' uncertainty analysis approach to derive piping system failure rates from a combination of service experience data and some simple reliability models [5-7]. More recently the Markov model approach has been used in conjunction with probabilistic fracture mechanics methods in the study of flow accelerated corrosion [8]. One interesting property of the Markov model is its capability to evaluate time dependent rupture frequencies via the model hazard rate. In this paper this time dependent modeling capability is used to investigate the age related and time dependent frequencies of loss of coolant accident (LOCA) initiating event frequencies. A case is presented that plant age dependent LOCA frequencies should be used in lieu of other metrics commonly used in probabilistic risk assessments and in risk informed inservice inspection evaluations. Such more commonly used metrics include the assumed constant failure rate method and the lifetime average rupture probability. Both of these methods are shown to provide optimistic estimates of LOCA frequencies for plants in the latter part of their design lifetimes, which most operating plants are approaching.

INTRODUCTION

A common practice in performance of Probabilistic Risk Assessments (PRAs) is to apply the assumption that initiating event frequencies for such events as LOCA due to pipe rupture are constant in time. This leads to a static treatment, which yields a prediction that the frequency of such initiating events is the same at the end of plant life as it is at the beginning. In fact, in PRAs that are performed to help justify license renewal and life extension, it is a standard assumption that the LOCA frequencies are the same during the extended lifetime period as they are during the original 40 year life.

While such submittals address the aging issue from a deterministic perspective, the probabilistic analysis have not been held accountable to justify why the LOCA frequencies should be plant age independent. The authors are unaware of any justification for such an assumption. In this paper, a justification is developed for treating LOCA initiating event frequencies as age dependent quantities.

NOMENCLATURE

ϕ	Flaw occurrence rate
λ	Weld failure rate (failure = active leakage)
ρ_F	Rupture failure rate given flaw
ρ_L	Rupture failure rate given leak
ω	Repair rate via ISI exams
μ	Repair rate via leak detection
F	Detectable flaw
L	Detectable leak
R	Rupture
S	Success, no detectable flaw
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
IGSCC	Intergranular Stress Corrosion Cracking
ISI	In-service Inspection
LCO	Limiting Condition for Operation
LOCA	Loss of Coolant Accident
NDE	Non-destructive Examination
PFM	Probabilistic Fracture Mechanics
POD	Probability of Detection
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RISI	Risk Informed ISI

MARKOV MODELS OF PIPING RELIABILITY

The most frequently used Markov model that has the capability to model all the known pipe failure mechanisms that are amenable to in-service inspection is illustrated in Figure 1. These failure mechanisms include damage mechanisms that act on pipe base metal (e.g. flow accelerated corrosion), those that act on welds (e.g. thermal fatigue), and combinations of mechanisms involving wall thinning and crack propagation. There is a more general version of the model described in Reference [4] which has not been extensively used which also includes damage unrelated mechanisms such as those associated with severe loading such as water hammer and overpressure, and failures due to various combinations of these failure mechanisms. Hence, in its most general form the model is capable of treating any known pipe failure mechanism that has been evidenced by the service experience.

The Markov model of Figure 1 can be used to address aging in the sense that ruptures are assumed to occur at a higher rate from state F compared with state S, and even higher from state L simulating the physical progression of a degradation mechanism through time in a discrete way. Similarly, leaks can be assumed to occur at a higher rate in state F when flaws are present in comparison with the leak occurrence rate from state S when no detectable flaws are present. Another aspect of the model that treats aging is the fact that leaks and ruptures cannot occur until damage has progressed to point that there are detectable flaws, and that may take significant periods of time from a starting point in which the pipe element is in an as good as new state represented by State S.

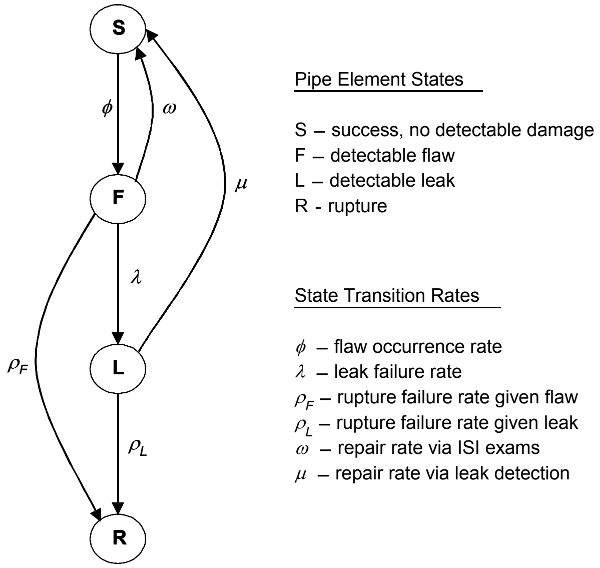

Figure 1 Four State Markov Model

The possibility that leaks and ruptures can occur from either the F or L state state reflects a property of certain pipe failure mechanisms that have occurred in pipe service experience. All pipe failure mechanisms that have been observed in the field [5,6] can be placed in one of the following categories:

1. A pipe failure caused by one or more pipe degradation mechanisms such as IGSCC. These usually produce a detectable flaw prior to the occurrence of a leak or rupture.
2. A pipe failure caused by normal or transient loading conditions on the pipe such as water hammer or vibrational fatigue that could occur even if the pipe component is in state S but perhaps at a higher rate when the pipe is degraded or already leaking.
3. A pipe failure due to the combination of one or more degradation mechanisms and loading conditions from any initial state.

Each of these failure mechanisms can result in a leak type failure mode, which is detected and repaired, a leak failure mode which remains undetected and later progresses to a rupture, or an immediate rupture failure mode without first exhibiting a leak.

DIFFERENTIAL EQUATIONS

The differential equations for the Markov model in Figure 1 can be written in vector form as:

$$\frac{d\mathbf{X}}{\mathrm{dt}} = \mathbf{AX} \tag{1}$$

where:

$$\mathbf{X}\{t\} = \begin{bmatrix} S\{t\} \\ F\{t\} \\ L\{t\} \\ R\{t\} \end{bmatrix} \tag{2}$$

$$\mathbf{A} = \begin{bmatrix} -\phi & \omega & \mu & 0 \\ \phi & -(\lambda_F + \rho_F + \omega) & 0 & 0 \\ 0 & \lambda_F & -(\rho_L + \mu) & 0 \\ 0 & \rho_F & \rho_L & 0 \end{bmatrix} \tag{3}$$

Note that since these four pipe states are mutually exclusive and a complete set:

$$S\{t\} + F\{t\} + L\{t\} + R\{t\} = 1 \tag{4}$$

for any time t. When the solutions to the above equations are solved, the time dependent probabilities of the piping component occupying each state can be determined. Under the assumption that all the transition rates are constant, the Markov model equations consist of a set of coupled linear differential equations with constant coefficients. These equations can be solved analytically or numerically to obtain the time dependent state probabilities. An example is given in Figure 2 for a weld in a PWR reactor coolant system subjected to thermal fatigue. The closed form solution of this model and the assumptions behind Figure 2 are given in Reference [4].

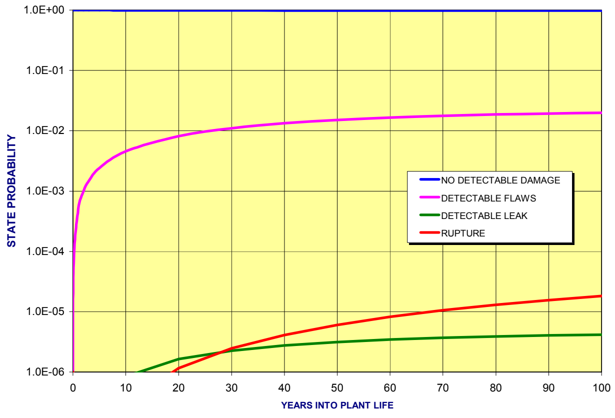

Figure 2. Example of Time Dependent State Probabilities

HAZARD RATE

In a PRA model, pipe ruptures are normally represented as initiating events. The frequency of these initiating events are normally assumed to be constant over time in PRAs, i.e. independent of plant age. With the Markov model, it is not necessary to make this assumption as the question of whether the failure frequency is constant or not is evident in the solution for a particular model. In general, the failure frequencies obtained from Markov models are time dependent. The appropriate reliability metric of the Markov model that quantifies the time dependent pipe rupture frequency is the system failure rate or hazard rate, as defined in the following.

To determine the system failure rate or hazard rate, one way is to first determine the system reliability function for the model and then to derive the hazard rate as a function of the reliability function according to the definition of the hazard rate as explained below. Since we are primarily concerned with pipe ruptures and seek to estimate pipe rupture frequencies, we may declare any state except for rupture a "success" state, such that only the rupture state is the "failure state." Using this concept, the reliability function for the Markov model, r{t}, is given by:

$$r\{t\} = 1 - R\{t\} = S\{t\} + F\{t\} + L\{t\} \tag{5}$$

From this, we can define the hazard rate for pipe ruptures, h{t}, as that given by Reference [1]:

$$h\{t\} = -\frac{1}{r\{t\}}\frac{dr\{t\}}{dt} = \frac{1}{\left(1 - R\{t\}\right)}\frac{dR\{t\}}{dt} \tag{6}$$

The hazard rate, h{t}, is the time dependent frequency of pipe ruptures. The time dependent form of this rate is dictated by the boundary conditions of the model and an asymptotic rate which is a function of the parameters (transition rates) of the model. As will be shown in the next section the time dependent hazard rate starts at 0 at t=0 (at the beginning of plant life) and gradually increases towards an asymptotic hazard rate, over a system time constant that is determined by the values of the transition rate parameters of the model. In practice, the growth of the time dependent hazard rate for pipe ruptures is too slow for the asymptotic rate to be realized within a plant lifetime.

The time dependent hazard rate is not to be confused with the annual average lifetime rupture probability, which is the quantity often used in RISI evaluations using the PFM method. Please note that even though the hazard rate reaches a steady state value, eventually the probability of occupying the rupture state for this and any other reliability model approaches 1. This is not true for availability models which may include a repair transition for the final rupture or failure state. However, for this application of the Markov model, such time frames are on the order of tens of millions of years and are of no practical interest for a nuclear power plant piping system with a lifetime of 40-60 years.

As shown in Figure 3 developed for the same PWR weld as for Figure 2 [4], which illustrates a typical plot of the hazard rate for a weld in a PWR reactor coolant system subject to the thermal fatigue damage mechanism, 60 years is insufficient to converge on the steady state hazard rate.

ESTIMATION OF MARKOV MODEL PARAMETERS

The repair rates μ and ω are estimated with the help of two simple models described as follows. For the flaw repair rate ω, the model of Equation (7) is used:

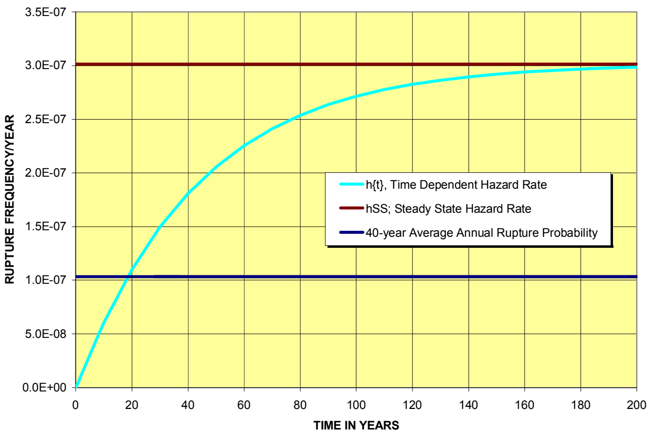

Figure 3 Example Time Dependent Rupture Frequency

$$\omega = \frac{P_I P_{FD}}{(T_{FI} + T_R)} \tag{7}$$

where:

P_I = probability that a piping element with a flaw will be inspected per inspection interval. In the case where inspection locations are inspected at random, this parameter is related to the fraction of the pipe segment that is inspected during each interval and the capability of the inspection strategy to pinpoint the location of possible flaws in the pipe. When locations for the inspection are fixed, this term is either 0 or 1 depending whether it is inspected or not.

P_{FD} = probability that a flaw will be detected given this segment is inspected. This parameter is related to the reliability of non destructive examination (NDE) inspection and is a conditional probability given that the location being inspected has a flaw that meets the criteria for repair according to the ASME code. This term is often referred to as the "probability of detection" or POD.

T_{FI} = mean time between inspections for flaws, (inspection interval)

T_R = mean time to repair once detected. There is an assumption in this model that any significant flaw that is detected will be repaired.

Similarly, estimates of the repair rate for leaks can be estimated according to:

$$\mu = \frac{P_{LD}}{(T_{LI} + T_R)} \tag{8}$$

where:

P_{LD} = probability that the leak in the segment will be detected per inspection,

T_{LI} = mean time between inspections for leaks

T_R = as defined above but for full power applications, this time should be the minimum of the actual repair time and the time associated with any technical specification limiting condition for operation (LCO) if the leak rate exceeds technical specification requirements.

Opportunities for leak detection are highly dependent on the system in which the leak occurs as well as the specific location and size of the leak. For example, in the reactor coolant system (RCS), leaks of a significant magnitude would create an immediate alarm in the control room from containment radiation sensors. In these cases, the time to inspection and repair is limited by technical specifications on RCS leakage. Other leaks may not cause an alarm but would be subject to possible detection during operator walk down visual inspections every shift or other opportunity for leak detection. There are some leaks that may only be detected upon periodic leak testing which may occur less often as required to meet ASME rules for different classes of pipe per ASME Section XI and other requirements for leak testing.

An important observation about this leak repair term μ in comparison to the flaw repair term ω is that for most leaks the detection possibilities are not normally limited to some predetermined population of welds that are inspected. However leak testing often provides an opportunity to inspect all locations system wide. Hence, given a leak of significant magnitude anywhere in the system, the probability of leak detection tends to be high. By contrast, most of the locations that could produce a non-leaking flaw are never inspected according to ASME rules, in which case the repair rate term, ω, is zero. Also, the time between successive inspections for leaks tends to be much shorter than for volumetric examination of welds with virtually instantaneous detection in cases when the leak would trigger an alarm in the control room. Hence, the Markov model provides the capability to take into account for the "leak-before-break" principle. The extent to which this principle contributes to reducing the probability of a rupture is only a function of the relative values of the Markov model transition rates as will be demonstrated in the examples that follow.

One of the objectives of this method was to develop pipe rupture frequency estimation techniques that not only provide a reasonable basis for evaluating different inspection strategies, but also a feasible method of estimating model parameters. The reliability engineering and PFM literature are full of theories on how to model failures but none of these theories are useful unless the input parameters for each of the models can be estimated and the models and data validated. The strategies available to estimate each of the Markov model parameters are discussed in detail in References [1] through [4]. Service experience with pipe flaws, leaks and ruptures are available to support the modeling of all the failure processes in the model. PFM, fatigue crack growth, and other physical models of specific damage mechanisms can also be used in conjunction with an assumption that the associated transition rate is proportional to the inverse of the characteristic time constant of the process (mean time to failure approach).

This approach to estimating the Markov model parameters was recently applied in Reference [8]. The models in Equations (7) and (8) provide a method for estimation of the inspection and repair rates of the model. When aided by the qualitative evaluation of piping systems with respect to the evaluation of pipe failure potential, a technically sound basis for quantifying the parameters of the model is provided. Examples which demonstrate this point are provided in Reference [4] and in the examples below.

The rates of occurrence of flaws can, in principle, be estimated from data collected in pipe inspections such as those performed as part of an ASME Section XI program. The units of ϕ are in terms of flaws per modeled piping component (weld or segment of pipe with similar characteristics) per unit time. This requires that we estimate the effective number of pipe components and the component years of experience that were responsible for the historical flaws in the data sample. This information combined with the observed number of flaws in the sample provides a basis for estimating this flaw occurrence rate. An alternative approach is to make use of the insight that any failure (leak or rupture) produced by a degradation mechanism must have occurred as a result of at least one flaw. Hence, the flaw rate can be inferred in terms of estimates of how many flaws are created for each observed leak or rupture, i.e., in terms of multiples of the leak and rupture rates.

EVALUATION OF LOCA FREQUENCIES

Recently, the Markov model was used as one of several inputs to an NRC sponsored study to redefine the large berak LOCA [9]. In this study [10], the Markov model was applied to estimate the LOCA frequencies from a selected BWR recirculation pipe segment that was susceptible to IGSCC and design and construction defects. The model was used to investigate both the time dependence of the LOCA frequencies based on the hazard rate and the influence of alternative ISI and leak inspection strategies. Selected results from this study are shown in Figure 4 which includes an evaluation of alternative strategies for ISI and leak inspection for this LOCA sensitive pipe segment.

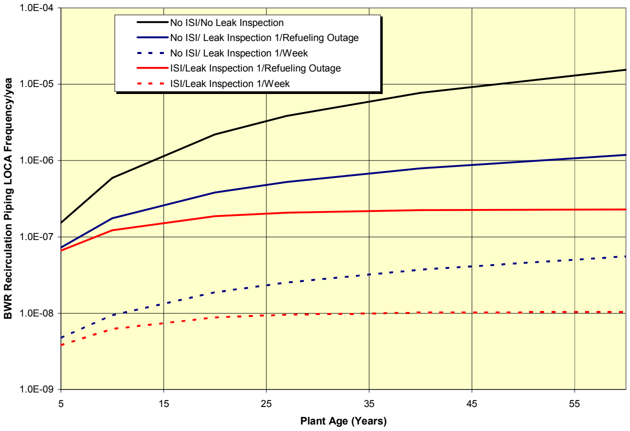

Figure 4. Time Dependent LOCA Frequency

As seen in this figure, LOCA frequencies are in fact time dependent for any of the evaluated inspection strategies. Moreover, in this example the LOCA frequencies are seen to be more sensitive to assumptions regarding leak detection than they are to whether any volumetric examinations under an ISI are performed. Another result from this example is the fact that a pipe system that is not subjected to any ISI or leak inspection strategy not only has a greater LOCA frequency but also progresses more slowly towards the steady state hazard rate beyond the 60 year plant age. By contrast, segments subjected to either ISI, leak detection or both have not only a lower LOCA frequency but also achieve the steady state hazard rate more quickly. The BWR example exhibits a stronger leak before break tendency indicated by a relatively low conditional probability of pipe rupture given failure. Hence, there are many opportunities to perform leak inspections, which means that steady state is achieved more quickly.

The results obtained from the Markov model, which predicts a time dependent LOCA frequency, should not be surprising as such a result is intuitively expected. In the most recent work in estimating pipe failure probabilities it is generally accepted that dominant failure mechanisms are damage mechanisms such as thermal fatigue, stress corrosion cracking, and other fatigue crack growth type of damage mechanisms. It is also generally understood that such damage mechanisms progress quite slowly over periods of several years or longer. It is also recognized that most pipe locations are never inspected whether subjected to a traditional ASME Section XI type of program or especially a risk informed ISI program unless the pipe is subjected to an augmented program.

For ASME Class 1 pipe, 25% of the welds are inspected while the remaining 75% are not inspected unless subjected to an expanded search after damage is discovered. For ASME Class 2 pipe, only 7.5% of the welds are ever inspected. When Class 1 and 2 pipe is subjected to a RISI program, these sampling percentages are even lower. It stands to reason then that the probability of a pipe rupture due to a fatigue crack growth type of damage mechanism should be expected to increase over time. It takes time for a crack to grow far enough that the possibility for achieving a critical flaw size will be able to materialize. Leak before break arguments can be used to justify a lower failure probability, but what ever that probability is should be expected to grow with time.

CONCLUSIONS

The common practice in PRA of assuming that LOCA initiating frequencies obey a constant failure rate process are not justified. Strong evidence has been shown in this paper that LOCA frequencies are plant age dependent, and that use of either a constant failure rate model or average lifetime failure probability will produce optimistic results for plants in the 2nd half of the plant lifetime. This problem is compounded when PRAs are performed to support license renewals in which it common to extend the plant license from 40 years to 60 years. The results in Figure 3 indicate that for the largest class of welds that are not subjected to ISI, rupture frequency increases approaching an order of magnitude or more can be expected at the end of 60 years relative to 20 years, depending on the leak inspection strategy.

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