A MARKOV CHAIN MODEL FOR CANDU FEEDER PIPE DEGRADATION

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Abstract

There is need for risk based approach to manage feeder pipe degradation to ensure safe operation by minimizing the nuclear safety risk. The current lack of understanding of some fundamental degradation mechanisms will result in uncertainty in predicting the rupture frequency. There are still concerns caused by uncertainties in the inspection techniques and engineering evaluations which should be addressed in the current procedures. A probabilistic approach is therefore useful in quantifying the risk and also it provides a tool for risk based decision making. This paper discusses the application of Markov chain model for feeder pipes in order to predict and manage the risks associated with the existing and future aging-related feeder degradation mechanisms. The major challenge in the approach is the lack of service data in characterizing the transition probabilities of the Markov model. The paper also discusses various approaches in estimating plant specific degradation rates.

1. Background

CANDU feeder pipes connect the inlet and outlet headers of the primary heat transport system to the reactor core and are designed to Class 1 piping requirements of the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB. The feeders are made of SA106 Grade B carbon steel with nominal pipe size ranging from 1.5 to 3.5 inches and nominal wall thickness from about 5.08 to 8.08 mm. The presence of incipient cracks, blunt flaws or material losses may increase the likelihood of leakage and rupture. The CANDU feeders are inspected in accordance with CSA N285.4. If wall thinning or a flaw (a crack or a blunt flaw) is detected in a feeder and does not satisfy the acceptance criteria of CSA N285.4, a fitness-for-service assessment may be performed in lieu of repair/replacement of the feeder. The Fitness for Service Guidelines [1] (FFSG) provide acceptance criteria, evaluation procedures, and guidance for the fitness-for-service assessment of wall thinning (general and local), blunt flaws, and cracking in feeders. If degradation is detected in one or more feeders, the FFSG requires an operational assessment and a condition assessment of postulated degradation of the same type in the entire feeder population in addition to a fitness-for service assessment of the detected degradation. The operational assessment evaluates the projected condition of the feeders at the end of the evaluation period based on current inspection results and predicted rates of wall thinning, flaw formation, and flaw growth rates, while the condition assessment compares the current inspection results to the predicted condition of the feeders by the operational assessment for the previous evaluation period. The FFSG only allows for deterministic assessments of detected degradation, but the operational and conditional assessments may be probabilistic or deterministic. However, the current revision of the FFSG does not specify acceptance criteria or procedures for probabilistic assessments. Furthermore, the FFSG stipulates that the extent of inspection, including sampling size, must provide adequate information for reliable statistical characterization of wall thinning and flaws, it does not specify inspection requirements or provide guidance for integrating in-service inspections with the aforementioned assessments.

Markov Chain modeling starts with representing a system (a feeder here) as a set of discrete and mutually exclusive states. At any instant in time, the system is permitted to change its current state in accordance with a certain probability law, considering the competing processes and maintenance activities that are appropriate for that system state. In this application of the Markov model, the system states refer to various degrees of a degraded feeder, for example, an intact state, a state with flaws, a leak, or rupture. The main strength of the Markov approach is its capability of explicitly modeling the interactions between degradation process and maintenance activities such as inspections, repair and replacement. The first step in Markov model is to identify the states of the degradation mechanism based on service data or experimental observations.

2. Current state of Knowledge on Feeder Degradation

Due to the unique design of CANDU feeders and operating conditions performance data does not exist from outside CANDU industry [2]. Specifically, feeder cracking is mostly observed at one CANDU plant and the plants with similar design/manufacturing have not experienced any cracking to date. The use of service data is therefore not appropriate for plants where cracking is not observed. Probabilistic safety assessment is performed for that specific CANDU plant where cracking is observed by the use of empirical model for cracking [3]. But this model could not be applicable to other CANDU plants where cracking is not observed.

The current knowledge of feeder cracking mechanism is that high cold work, high residual stress, oxidizing conditions, high temperature, and low temperature creep are drivers of cracking. Qualitative ranking of the relative risks of various feeder types and locations based on stress relieving, bend radius, and welds have been proposed [4]. Furthermore, uncertainty of crack growth rates which comes from NDE detection capability for use in probabilistic models is provided [5].

The wall thinning is believed to be influenced by various factors including coolant temperature, velocity, and feeder geometries that contribute to flow disturbances. It is generally recognised that wall thinning is relatively slow and predictable process and is argued that it is manageable with current programs. Blunt flaws are another degradation mechanism of concern where FAC is being considered as a factor. This degradation is described as a highly-localized thinning which was discovered in the vicinity of the welds. Well established structural integrity models exist for blunt flaw assessments. However, there is no established procedure for managing cracking degradation mechanism. There are still concerns cased by uncertainties in the inspection techniques and engineering evaluations which should be addressed in the current procedures [6]. Markov chain model developed by EPRI based on service data has been demonstrated to be a useful tool to study the impact of alternative strategies for in-service inspection and leak detection as well as changes in risk due to changes in the leak detection and in-service inspection programs [9]. A similar approach developed by EPRI is proposed by modelling the degradation mechanism. A Road Map document [10] was prepared by NSS staffs aiming at developing a similar Markov model for feeder pipes in particular, in order to predict and manage the risks associated with the existing and future aging-related feeder degradation mechanisms. The Road Map was developed based on the Business Case [11] in which alternative approaches suitable for existing plants were reviewed and the Markov Chain approach was selected for further investigation. The Road Map requires that the proposed Markov model should be able to accommodate the three degradation mechanisms that occurred in CANDU feeders and also be adaptive to future degradation mechanisms.

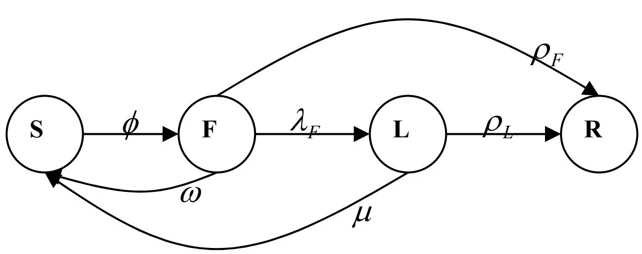
A Markov model for feeder cracking is currently addressed here which could be applicable to CANDU plants.

3. Proposed Markov Chain Model

The intent of the current model was to use information specific to feeder cracking and the flexibility to incorporate additional information with knowledge gained on feeder cracking.

Due to the strength of Markov model in considering the degradation dynamics and inspection modelling together with uncertainty analysis in input parameters makes it suitable for the purpose intended. The time dependent rupture frequency result from the Markov model will be used for evaluating the change in risk over the design life or extended life of the plant.

Due to limited or no service data or experimental data to identify the degradation states, the state representation of Markov model is a challenge. The state representation for the proposed Markov chain model is based on the extent of cracking degradation which is shown in Figure below. The degradation states are defined rather arbitrary by engineering judgment at this stage since we don't have service data or experimental data to statistically characterize the states. The states can be refined further with additional knowledge gain or with support from structural integrity assessments. A similar approach of defining the states based on the extent of degradation is applied for evaluation of piping reliability due to erosion-corrosion [7] and also for fatigue damage in welded structures [8]. The transition rates ($\varphi, \lambda_F, \rho_L$) are estimated as the inverse of the average time spent in each state. The flaw occurrence rate (φ) takes into account the crack initiation time and the time to reach detectable crack depth. The average time spent in each state is governed by the crack growth rate in that particular state. Such representation is considered to take advantage of the observed crack depths in addition to censored data where cracks are not observed.



States (defined by flaw depths)
S – Success, < 0.1t (detection threshold)
F – Detectable Flaw, >0.1t and < 0.3t (min wall thickness)
L – Detectable Leak, > 0.3t and < 0.8t (leak criteria)
R – Rupture, >0.8t

State Transition Rates
φ - Flaw occurrence rate (defined by waiting time to reach 0.1t flaw depth)
λ_F – Leak failure rate (defined by waiting time to reach flaw depth of 0.3t from 0.1t)
ρ_L – Rupture failure rate given leak (defined by waiting time to reach flaw depth of 0.8t from 0.3t)
ρ_F – Rupture failure rate given flaw (defined by pipe frequency from pressure transients)
ω - Repair rate from ISI exams
μ – Repair rate via leak detection

Figure 1: Proposed four state Markov model for feeder pipe degradation

Relative factors on transition rates could be used based on the qualitative ranking of the relative risks of various feeder types as prior information from a Bayesian framework. Such approach makes the model applicable to other CANDU plants with no observed cracking. Bayesian analysis is conducted to account for uncertainties from service experience and engineering judgment on Markov model parameters. In the case where information on parameters is insufficient, the generic service experience in the industry and input from structural integrity assessments will be used.

The basic structure of the four-state Markov model is similar to the model used by EPRI [9] and the same solutions are applicable whereas the state representations and parameter estimation are conducted differently in this approach. A similar Markov model could be applied to wall thinning due to flow accelerated corrosion (FAC) and blunt flaws.

The time dependent rupture frequency for the whole plant can be derived as

$$h_{Plant}(t) = \sum_{j=1}^{N} n_j h_j(t)$$

Where $h_j(t)$ is the time dependent rupture frequency of each feeder pipe in homogenous sub-population j with respect to factors susceptible to cracking, and $h_{Plant}(t)$ is the time dependent rupture frequency for whole plant with N sub-populations.

A pilot study will be conducted using the developed Markov model for a particular plant to conduct sensitivity studies on the model parameters.

4. Conclusion

The Markov model has been demonstrated to be a useful tool to study the impact of alternate strategies for in-service inspection and leak detection. Together with appropriate estimation of its input parameters, the model is capable of making reasonable predictions of time dependent piping system reliability as well as changes in risk due to changes in the leak detection and in-service inspection programs. An attempt to develop a semi-empirical probabilistic approach for feeder cracking is proposed here with the use of Markov chain model. Since there is limited data available to characterize the model at this stage, it will be currently used for sensitivity study where the applicability of the model will be further explored.

5. References

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