A Methodology for Modeling Nuclear Power Plant Passive Component Aging in Probabilistic Risk Assessment under the Impact of Operating Conditions, Surveillance and Maintenance Activities

DISSERTATION

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Abstract

In the context of long operation of nuclear power plants (NPPs) (i.e., 60-80 years, and beyond), investigation of the aging of passive systems, structures and components (SSCs) is important to assess safety margins and to decide on reactor life extension as indicated within the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program.

In the traditional probabilistic risk assessment (PRA) methodology, evaluating the potential significance of aging of passive SSCs on plant risk is challenging. Although passive SSC failure rates can be added as initiating event frequencies or basic event failure rates in the traditional event-tree/fault-tree methodology, these failure rates are generally based on generic plant failure data which means that the true state of a specific plant is not reflected in a realistic manner on aging effects. Dynamic PRA methodologies have gained attention recently due to their capability to account for the plant state and thus address the 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). Physics-based models can capture the impact of complex aging processes (e.g., fatigue, stress corrosion cracking, flow-accelerated corrosion, etc.) on SSCs and can be utilized to estimate passive SSC failure rates using
realistic NPP data from reactor simulation, as well as considering effects of surveillance and maintenance activities.

The objectives of this dissertation are twofold: The development of a methodology for the incorporation of aging modeling of passive SSC into a reactor simulation environment to provide a framework for evaluation of their risk contribution in both the dynamic and traditional PRA; and the demonstration of the methodology through its application to pressurizer surge line pipe weld and steam generator tubes in commercial nuclear power plants.

In the proposed methodology, a multi-state physics based model is selected to represent the aging process. The model is modified via sojourn time approach to reflect the operational and maintenance history dependence of the transition rates. Thermal-hydraulic parameters of the model are calculated via the reactor simulation environment and uncertainties associated with both parameters and the models are assessed via a two-loop Monte Carlo approach (Latin hypercube sampling) to propagate input probability distributions through the physical model.

The effort documented in this thesis towards this overall objective consists of: i) defining a process for selecting critical passive components and related aging mechanisms, ii) aging model selection, iii) calculating the probability that aging would cause the component to fail, iv) uncertainty/sensitivity analyses, v) procedure development for modifying an existing PRA to accommodate consideration of passive
component failures, and, vi) including the calculated failure probability in the modified PRA. The proposed methodology is applied to pressurizer surge line pipe weld aging and steam generator tube degradation in pressurized water reactors.
Dedication

This document is dedicated to my family.
Acknowledgments

First and foremost I would like to thank my advisor Professor Tunc Aldemir for his guidance, continuous support and patience during my PhD work. His vast knowledge in the nuclear field, and specifically in risk assessment, has been a tremendous asset to me. I would also like to thank my co-advisor Professor Richard Denning for his advice. I have been very fortunate to have him share his knowledge and experience with me during my graduate work.

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Thank you to my parents, and my husband, Emre, for believing in me, and for supporting me all along throughout my years at The Ohio State University while I was far away from them. It meant the world to me.
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List of Acronyms

AEC– Atomic Energy Commission
CDF– Core Damage Frequency
DPRA – Dynamic Probabilistic Risk Assessment
EPRI– Electric Power Research Institute
FAC– Flow Accelerated Corrosion
HCTMC– Homogeneous Continuous-Time Markov Chain
ICTMC– Inhomogeneous Continuous-Time Markov Chain
LBE– Licensing Basis Event
LERF– Large Early Release Frequency
LHS– Latin Hypercube Sampling
LOCA– Loss of Coolant Accident
LTO– Long Term Operation
MC– Monte Carlo
MSM– Multi-state modeling
NRC– Nuclear Regulatory Commission
PDF– Probability Distribution Function
POD– Probability of Detection
PRA– Probabilistic Risk Assessment
PWR– Pressurized Water Reactor
PWSCC– Primary water stress-corrosion cracking
RISMC– Risk-Informed Safety Margin Characterization
SA– Sensitivity Analysis
UA– Uncertainty Analysis
VRT– Variance Reduction Technique
Chapter 1: Introduction

1.1 Problem Description

A nuclear power plant (NPP) has components that can be classed as passive and non-replaceable (e.g. reactor pressure vessel (RPV), containment). These are deemed ‘life determining’ since, it is virtually impossible to replace them or it is prohibitively expensive to do so. On the other hand active and replaceable components in NPPs are conceptually and practically replaceable in nature, albeit at a cost.

All NPPs in the U.S. have performed at least a Level 1 probabilistic risk assessment (PRA) for assessing core damage frequency (CDF) and a limited Level 2 analysis that is focused on assessing the frequency of large early release (LERF). Mostly, risk measures (CDF or LERF) have been estimated with focus on possible failure of active components. The reason why passive component failures have been either given less consideration or totally neglected is because they are historically more reliable than active components. Although this argument may be reasonable when SSCs are new when passive SSCs get older, reconsideration of this assumption is needed.

Aging is a concern for many types of passive SSCs in current operating power plants. Age related degradation of materials in the operating environment can lead to reduced performance, and in some cases, sudden failure. In case of long operation, aging-caused failures can differ from the originally expected ones. Reference [1] indicates that
typically failures resulting from degradation mechanism and loading conditions (i.e., intergranular stress corrosion cracking, flow-accelerated corrosion (FAC), etc.) are not anticipated in the original design. For instance, fatigue has been considered in the components design since the early 1970s. However, stress corrosion cracking (SCC) was not included, since it was believed the American Society of Mechanical Engineers (ASME) Class 1 piping material was not susceptible. Several failures [2] [3] [4] have shown the SCC can be of concern. Therefore, it is critical to estimate the likelihood of passive SSC aging-induced failures in the presence of active degradation mechanisms, service conditions, transient load conditions, location and existing surveillance and maintenance activities. Furthermore, because of limited options for rejuvenation, passive SSCs may be expected to play an increasing role in long-term risk [5]. Therefore, in the establishment of safety margins intended to ensure long-term safety, the effects and implications of passive SSC aging and degradation must be addressed.

While PRA tools have been developed to predict aging of active components [6] [7] [8] (also See Section 2.9), they do not adequately address important aging issues such as erosion of primary piping, which could have a significant impact on the conclusions drawn from PRA studies and applications where plants are operated at beyond the originally intended service period.

The proposed work aims to develop a general methodology to incorporate physics based aging models into PRA for evaluating the impact of rupture frequencies and reliability of the passive systems in the nuclear power plants on the estimated risk associated with their operation. The aging model representation is based on the theory of
semi-Markov processes. This methodology is applicable for the incorporation of aging effects of passive SSCs into PRA for reactor operation, power uprate considerations, and life extensions.

1.2 Objective

The objective of this work is to develop an overall methodology to include aging of passive SSCs in PRA and assess their risk-impacts on risk measures (CDF for Level 1, LERF for Level 2). The proposed work differs from the past efforts by considering the impact of the NPP operating conditions on the failure mechanisms, as well as the surveillance and maintenance activities, in a dynamic fashion. The methodology is illustrated by application to passive SSCs relevant to selected accident scenarios.

The overall methodology aims to:

- address multiple aging mechanisms (e.g., thermal fatigue, radiation embrittlement, SCC, FAC) 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 the component aging progress,
- assess aging affects in a dynamic simulation environment,
• provide ability to make PRAs more plant specific with the ability to support improvements in surveillance, maintenance and replacement strategies,
• provide ability to consider epistemic and aleatory uncertainties within the same phenomenological and stochastic framework,
• provide more realistic insights for decisions about plant operation and maintenance because of inclusion of aging effects of passive SSCs into PRA (traditional or dynamic).

Inclusion of aging effects of passive SSCs into PRA will result in more realistic insights for decisions about plant operation and maintenance. The results of the PRA can be used to evaluate the effectiveness of maintenance and surveillance in controlling aging and to direct resources to those SSCs that are most important to NPP risk.

1.3 Scope

This work develops an overall methodology to include aging of passive SSCs in PRA and assess their risk-impacts on risk measures (CDF for Level 1, LERF for Level 2). The proposed work differs from the past efforts by considering the impact of the NPP operating conditions on the failure mechanisms, as well as the surveillance and maintenance activities, in a dynamic fashion.

A multi-state physics-based model is selected to represent the aging process. The model is accommodated via the sojourn time approach to reflect the operational and maintenance history dependence of the transition rates. Thermal-hydraulic parameters of the model are calculated via a reactor analysis code and uncertainties associated with
both parameters and the models are assessed. The methodology is to be applied to SSCs relevant to selected accident scenarios.

1.4 Dissertation Overview

The thesis is divided into six chapters including the present chapter. Chapter 2 of the work provides background and historical context for the problem analyzed. This includes the brief overview of PRA, uncertainty and sensitivity analysis techniques, screening methods and a comparison of various aging models and finally a survey of the previous research.

Chapter 3 introduces the overall methodology. The reactor simulation environment is presented with the model assumptions and physics models of the selected degradation mechanisms are to be used in Chapter 4.

Chapter 4 reviews the physics-based multi-state aging model selected for this study and also provides two implementations of the model. Selected component geometries are described and the Markov sojourn time model is introduced and implemented to compare analysis results with the two other methods. The first method is a state-space enrichment method, which is a benchmark for our analysis and the other one is Monte Carlo (MC) simulation. The Markov process model is used to obtain both time-dependent and steady state solutions, develops and introduces. A graphic user interface (GUI) for the aging model is described, which enables the entry of input data and appropriately treats epistemic and aleatory uncertainties.
Chapter 5 illustrates how failure probability results of selected components obtained by sojourn time approach can be incorporated into PRA. Three different approaches are described. The first two approaches related to the manual modification of PRA input associated with the introduction of rupture frequencies from the physics based model, which can be used as new initiating events in a traditional PRA model or semi-Markov models can be turned into a dynamic event tree within a DPRA. The third approach is related with the mechanistic incorporation via coupling of the aging progression model with the RELAP-7/RAVEN environment, which is illustrative of a more mechanized approach.

Chapter 6 concludes with a summary of research contributions and recommendations for future studies.
Chapter 2: Background

This chapter starts by introducing a brief background on the long term operation (Section 2.1) and safety assessment for NPPs using PRA (Section 2.2), discusses uncertainty and sensitivity analysis (Section 2.3), provides overview of important aging mechanisms (Section 2.4) discusses age-based screening methodology of passive SSCs (Section 2.5), and state-of the art passive component representation in PRAs (Section 2.6), focuses on accident scenarios of interest (Section 2.7) to define the scope of the proposed research.

In Section 2.8, a literature survey of related aging models of the selected passive SSCs is given. The purpose of this survey is to provide a more rigorous framework for the comparison of different approaches.

Finally, Section 2.9 provides a summary of prior work on how aging of passive components is incorporated into PRA.

2.1 Overview of Long Term Operation

As of the end of 2015, there are 441 nuclear power plants operating around the world. Of these plants, 68 have been in service for over 40 years [9]. When these plants reach the end of their operating license, they will undergo a periodic safety review and an aging assessment of their essential structures, systems and components to validate or
renew their license to operate beyond the originally intended service period by conducting an integrated plant assessment.

The U.S. Nuclear Regulatory Commission (NRC) issues initial licenses for commercial power reactors to operate for up to 40 years, based on the US Atomic Energy Act of 1954, and allows these licenses to be renewed for an additional 20 years with each renewal application. Initial selection of 40 year license term is due to economic and antitrust reasons not because of the technical limitations [10]. There is no limit on the number of license renewals as long as the plant can continue to be run safely and comply with environmental requirements.

Long term operation (LTO) of an NPP may be defined as operation beyond an established time frame set forth by license or regulations, which has been justified by safety assessment with consideration given to life limiting processes such as radiation damage to SSC.

The U.S. practices the license renewal application (LRA) concept to obtain the authorization to LTO. Although the license renewal scope includes both active and passive SSCs, the screening process for license renewal eliminates active or frequently replaced SSCs from further aging evaluation, since these components are already adequately covered by the maintenance rule (10 CFR 50.65) for aging management or do not require aging management since they are replaced prior to LTO [11].
2.2 Probabilistic Risk Assessment

This section provides a history of regulatory limits imposed by the NRC and other regulatory bodies, and their interpretation. It also includes a discussion about proposed future regulatory guidelines and possible restrictions the limits may impose.

PRA is used to estimate risk by determining what can go wrong, how likely it is, and what are the consequences. Thus, PRA provides insights into the strengths and weaknesses of the design and operation of a nuclear power plant.

PRA can be divided into three levels. Level 1 PRA is tasked with predicting the frequency of core damage. Level 2 PRA, in addition, includes the analysis of accident progression, containment failure, and most importantly, the release of radionuclides to the environment. Level 3 PRA additionally incorporates calculation of human health effects. Traditional PRAs are static in nature and do not account for time-dependent phenomena. SAPHIRE [12], CAFTA [13] and RISKMAN [14] are the most common traditional PRA tools. DPRA [15] offers a methodology for accounting for time-based system evolution along with its stochastic behavior to account for possible dependencies among failure events. 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.

Dynamic PRA also 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 [13]. ADAPT [16],
MCDET [17] and ADS/IDAC [18] are dynamic PRA tools which have been used for analyzing complex realistic scenarios.

2.3 Uncertainty Analysis

Since often large uncertainties are associated with the data used for PRA, uncertainty quantification has been traditionally done using MC sampling. In the work described in Section 4.1.5, a two-loop MC approach was used to propagate input probability distributions through the physical model: an inner loop for aleatory uncertainties and an outer loop for epistemic uncertainties [19]. Then a series of model output forms can be developed, to provide more insight to a decision maker. The robustness of the model output forms can be assessed under variations in the categorization (epistemic versus aleatory) of input uncertainties.

Epistemic uncertainty arises from incompleteness of knowledge; sources of this uncertainty include measurement uncertainty, small sample sizes, detection limits and data censoring, and ignorance about the details of physical mechanisms and processes involved.

Aleatory uncertainty arises from inherent variability, natural stochasticity, environmental or structural variations across space or through time, and manufacturing heterogeneity among components.

In order to accelerate convergence of a sampling scheme relative to MC, stratified sampling schemes are used. Latin hypercube sampling (LHS) is often the preferred method of stratification when there is little knowledge about the input variables. This is
because LHS does not depend on analyst opinion or any ranking of input importance [20].

2.4 Selected Aging Mechanisms

In traditional PRA, the analyst needs to limit the scope of the risk analysis and focus on those mechanisms that are most likely to lead to failure, are sufficiently known to be able to make reliable predictions of degradation, and for which failures have risk significance because of the practical limits. NUREG/CR-6923, “Expert Panel Report on Proactive Materials Degradation assessment” describes an approach to selecting passive safety features and degradation mechanisms for mechanistic analysis [1]. Other references where aging of particular type of components and related aging degraded mechanisms are described and discussed in detail in [1] and [21].

The aging mechanisms active in the primary pressure boundary components and main feedwater and steam piping may be divided into four categories: (a) embrittlement mechanisms causing loss of material fracture toughness - radiation embrittlement and thermal aging, (b) fatigue mechanisms, (c) stress corrosion cracking mechanisms, and, (d) corrosion and wear mechanisms [1].

Figure 2.1 shows the comparison of the distributions of the structures and passive components degradation occurrences by major aging mechanisms among the three data series: LER 1999-2008, NUREG/CR-6679, and LER 1985-1997, respectively. As can be seen from the figure, SCC is by far the most significant aging mechanism for all data
series. Therefore SCC was selected as the aging mechanism to implement the proposed methodology (see Chapter 3) as applied to different scenarios (see Section 2.7).

![Figure 2.1: Distribution Comparison of Structures and Passive Components Degradation Occurrences over Aging Mechanism [23]](image)

SCC [22] is a form of environmentally assisted cracking and occurs when a component is under stress in a corrosive environment. The observed crack propagation is the result of the combined and synergistic interaction of mechanical stress and corrosion reactions.

Surface defects may pre-exist or could be nucleated under the influence of fluctuating mechanical or thermal stresses. Surface cracks, if nucleated under fatigue
loading, are generally a result of the propagation of Persistent Slip Bonds (PSBs) to the surface forming extrusions and intrusions in adjacent locations. These surface locations, which tend to be crack initiation points, have higher Gibb's free energy, as compared to other surface spots. Chemical corrosive reactions are therefore enhanced at intrusion/extrusion planes.

Crack propagation is favored once the stress intensity factor exceeds a critical value that is mainly determined by the surface energy on the plane of crack propagation, and the energy dissipated in the plastic zone ahead of the crack. The high chemical corrosion rate at the crack tip is driven by the fast diffusion rate of embrittling impurities toward the crack tip. The surface energy is thereby reduced and the critical stress intensity factor decreases.

Stress-corrosion cracking is a common problem for pressurized water reactor (PWR) steam generator tubes, primary piping welds, and control rod drive mechanisms [23]. The failure induced by primary water stress-corrosion cracking (PWSCC) has already been reported in many nuclear power plants [2] [3].

PWSCC can occur if the temperature is high enough (usually >300 °C) and the water chemistry is typical of operating PWR plants. Tensile stresses caused by a combination of service loads and weld residual stresses are a main driver of PWSCC.

Water chemistry (electrochemical potential, pH, and impurities) is another factor. Especially for the case of the Alloy 82 and 182 weld metal materials, the PWSCC crack growth rate is known to have a significant sensitivity to the electrochemical potential, which for PWSCC is controlled by the dissolved hydrogen concentration in the primary
water. Finally, in theory, various impurity species could have significant effects on PWSCC including the rate of crack propagation. However, impurities are maintained at very low levels in the primary water system, and thus in practice are generally considered not having a significant effect on PWSCC. It is noted that primary water chemistry excursions, for example involving significant resin intrusions, could result in significant effects on SCC in the primary system if sufficiently severe.

2.5 Selection of Passive Components

Taking into account the fact that in each NPP there are thousands of components, the components to be assessed for aging evaluation and management need to be very carefully selected. There are two methods that have been proposed for the screening analysis of passive components to determine the SSCs to be included in PRA. The first one is screening based on aging mechanisms and the second one is based on PRA results. Screening could be performed using by either of these two methods or a combination of the two [24]. This process is graphically illustrated in Figure 2.2.

In order to limit the scope of the overall PRA analysis, usually a preliminary risk screening would be performed [25]. The typical approach taken for prioritization of this type is the use of risk importance measures that involve modifying the reliability of a component, either to zero or one and observing the relative impact on plant risk. The other approach is to modify initiating event frequency due to passive SSCs failure. The importance of different initiators can be determined by setting each initiator frequency to zero and determining the effect on the core damage frequency. Having identified the most
potentially important initiating events, then components associated with those initiating events can be identified by the analyst. For those components, degradation mechanisms would then be identified that have high likelihood of occurrence and high state of knowledge about degradation mechanisms.

Measures of this type include risk reduction worth, risk achievement worth and Fussell-Vesely measure [24]. The risk increase measures are then ranked. Based on this ranking, a decision can then be made regarding the passive SSC to be included in PRA. Also in PRA, where we are talking about components important to safety, a selection should be performed to take into account components and aging effects with clear impact to plant risk level. This could help to assure analysis efficiency and reasonable usage of resources.

![Diagram of components important to safety](image)

Figure 2.2. Selection of components important to safety for further activities [24]
A screening methodology [26] is being developed that in the future could ultimately be used to determine which components and degradation mechanisms would be included in the analysis of a particular plant configuration in a New Generation System Code (NGSC) safety analysis [27]. An input to the methodology will be the stresses the components undergo during normal and transient conditions as determined by the data generated by NGSC. A preliminary application of such a methodology will be used to determine which components, mechanisms and scenarios to examine as examples in the current research project. Risk significance (specifically risk achievement worth) will be a key attribute of the selection methodology. In this dissertation, the scope of components, mechanisms and accident scenarios of interest are defined in Section 2.6 and 2.7. A list of possible degradation mechanisms has been compiled based on NUREG/CR-6936 [28].

Figure 2.3 shows the distributions of the degradation occurrences by components for three series of data. The bar chart displays the number of occurrences in the same order by component as reported in NUREG/CR-6679. Considering both LER 1999-2008 and NUREG/CR-6679 data, exchangers, piping system, and RPVs are the first three categories with the greatest number degradation occurrences. The piping system degradation occurrence records for LER 1985-1997 were determined to be very large and did not include all of the occurrences in the SSCs database that is reason why LER 1985-1997 indicates low number of occurrences for the piping system [29].
2.6 Passive Component Reliability in Current PRAs

The structures and passive components, such as filter, piping system, tank, exchanger, are those that fall within the scope of the NRC License Renewal Rule—10 CFR Part 54. Piping system which includes piping, fittings, small bore piping and tubing, sleeves, pipe supports (excluding hydraulic and mechanical assembly of snubbers), as well as buried piping are the focus for the implementation of the proposed methodology.

In PRA models, passive component failures seldom receive explicit treatment since according to WASH-1400 [30] piping failures are rare events relative to active component failures. Therefore, a prevailing mind set among PRA analysts has been that
contributions to plant risk by passive component failures are negligible. For example, Reference [31] indicates that consideration of passive component failures was excluded from individual plant evaluation (IPE) reports. However, when [23] the study team was challenged to address the impact of a failure of a manual isolation valve in a common suction line for emergency core cooling system, it was found that passive failure of the valve contributed to the final IPE results. The traditional piping failures addressed by PRA are the loss of coolant accident initiating events, such as the "double-ended guillotine break" (DEGB) and "fish mouth" failures resulting in a range of break sizes.

These events can lead to failure of core cooling, can produce internal floods, can damage other equipment as the result of pipe whip, and are also the focus of plant fragility evaluation for seismic events. Reference [32] gives a comprehensive review of available literature of LOCA in PRA. This report also contains a detailed review of many programs and dozens of specific PRA studies for different reactor types.

Models used to estimate pipe break frequencies for the initiating event are summarized in [32] and other references: a recent Electric Power Research Institute (EPRI) report on internal flooding initiating event frequencies [33], a study on high energy line pipe break (HELB) initiating event frequencies for Kewaunee [34], and the evaluation for piping systems for Columbia Generating Station [35]. The EPRI approach is similar to that used in recent NRC studies regarding LOCA initiating event frequencies [36] [37].

In a relatively recent study [1] it is noted that, since most of the passive components of interest are not included in a traditional PRA, one needs to extrapolate
from the components/systems that are included related to the passive components under consideration. It is proposed that, after selection of the PRA model, the model is modified to include important passive (or other) components not currently in the model and then to incorporate physical aspects of the aging mechanisms into the PRA model using basic events contained in fault or event trees.

To summarize passive SSC representation in different level of PRAs:

- **In PRA Level 1 (internal events)** the treatment typically consists of initiating event frequency estimation using published data (e.g., WASH-1400). In the case of interfacing system LOCA (ISLOCA), the assessments have largely focused on valve failure probability estimation.

- In **PRA Level 1 (external events)**, seismic evaluations address SSC fragilities. Fragility evaluations involve estimating the seismic input parameter value at which a given SSC fails. Estimation of this value (called the ground motion capacity) is accomplished using information on plant design bases, response calculated at the design analysis stage, and as-built dimensions and material properties. Flooding evaluations have sometimes focused on pipe or valve ruptures potentially causing flooding of vital plant areas.

- **PRA Level 2 (containment analysis)** includes identification of containment failure modes. A containment event tree is developed for each sequence of interest. If the containment is predicted to fail, the analysis predicts the time at which it will fail, where it will fail, and the internal energy associated with a released plume of radioactive material. Failure mode definition is based on reviews of existing
structural analysis developed at the design case, and sometimes supplemented with confirmatory structural analyses. Assessments of RPV failure probability are normally included in PRA Level 2.

Specifically, piping failures in PRA are accounted for in the following manner [32]:

1. Large LOCAs such as double-ended pipe breaks in reactor coolant system (RCS). Implicit assessment via initiating event frequency.

2. ISLOCA (or V-sequence) such as, failure of motor-operated valves (MOVs) and/or check valves, and rupture of low-pressure piping outside containment. Explicit analysis of piping component failure probabilities [38] [39].

3. Main steam line break (MSLB). Transient that begins with a steam line rupture. Rupture locations inside and outside containment considered. Initiating event frequency typically calculated from WASH-1400 data.

4. System analysis. Those instances where a piping rupture constitutes a single failure of emergency core cooling system (ECCS) identified and quantified using WASH-1400 data.

5. Steam generator tube rupture (SGTR). Initiating event frequency estimated from available operating experience.

6. Reactor vessel integrity; either as initiating event or induced by pressurized thermal shock (PTS). Implicit assessment using published failure probabilities.
2.7 Selected Accident Scenarios

The two accident scenarios selected for investigation in this dissertation involve failures of SSC due to degradation mechanisms for which there has been extensive operational experience:

2.7.1 Loss of Coolant Accident (LOCA) Scenario

In PRA applications, the consequences of pipe rupture are strongly influenced by the magnitude of the break size. Class 1 piping system breaks up to about 2” in diameter are classified as “Small LOCAs” and those above 6” are regarded as “Large LOCAs”. Small, medium and large LOCAs have different success criteria to prevent core damage. In a PRA analysis of internal flooding a small leak up to 100 gpm can be effectively mitigated by room drains and sumps, where larger breaks must be differentiated in size to characterize the time available for operator actions.

The LOCA scenario examined in this study involves the rupture of Alloy 82/182 dissimilar metal weld in a PWR primary coolant system. Nickel alloy welds are found in several key locations in ASME Class 1 piping structures, such as the interface in PWR between the reactor pressure vessel and coolant piping and the pressurizer surge line pipe weld. This component class is relevant to LOCA accident sequences which are generally significant risk-contributors (particularly small LOCAs) in PWRs. Dissimilar metal weld materials generally have high susceptibility to SCC which provides focus for the physics modeling [5].
Large break LOCAs (LBLOCA) mainly include a full or partial rupture of the main circulation line, typically with break areas higher than 25% of the cross-section of the main circulation line [34]. Ruptures of the major pipes connected to the primary circuit, such as the pressurizer surge line or the accumulator discharge lines, can also be considered as LB-LOCAs [40].

It was considered that aging may have the greatest effect on intermediate diameter (6 to 14-inch diameter) piping systems due to the large number of components within this size range and the fact that this piping generally receives less attention than larger diameter piping and is harder to replace than the more degradation-prone smaller diameter piping [16].

Methodology that is relevant to estimating LOCA frequencies is described in detail in [3] and has been recently applied in EPRI sponsored projects to develop piping system failure rates for use in internal flooding and high energy line break PRAs, as documented in [33] and [34]. The original EPRI study that was responsible for developing the Markov model and Bayes’ method for estimating pipe failure rates and rupture frequencies was documented in [41], and an early version of the pipe failure rate data base for both conditional and unconditional pipe failure rates was published in EPRI TR-111880 [42].

The expert elicitation that was performed and documented in [37] provided estimates of the frequencies for loss of coolant accidents based on a set of LOCA categories selected to span the break sizes and leak rates that are normally modeled in PWR and BWR PRAs.
2.7.2 Steam Line Break (SLB)/Main Steam Line Isolation Valve (MSLIV) Failure/Steam Generator Tube Rupture (SGTR) Scenario

In this case [16], a steam line breaks outside the containment and downstream of a MSIV serves as the initiating event. Following a steam line break, the accident continues with a failure of a MSIV to close and the rupture of a flawed SG tube in the steam generator upstream of the MSIV. FAC of piping in the power conversion system and stress corrosion cracking were selected as the acting degradation mechanisms.

2.8 Aging Models of Passive Components

Operational experience has shown that several aging mechanisms can lead to degradation of passive SSCs. Aging issues, introduced in Section 2.4, are complex, multi-parameter phenomena, and the susceptibility of a given site or SSCs cannot be determined by considering only a few parameters.

Conventional reliability models are parametric and rely on the statistical analysis of service data [8]. Reliability models within the context of the work described in this dissertation need to be physics-based and driven by the physical boundary conditions by the reactor simulator (see Section 3.1) to allow full integration of these models into a multi-physics environment (see Figure 3.1) and subsequently into the PRA. Section 2.8.1 focuses on pipe rupture models that have been utilized in the literature and then discusses two physics-based aging models: Multi-state models and Markov models.
2.8.1 *Pipe Rupture Models*

Since data regarding pipe ruptures in the nuclear plant are rare, different modeling approaches have been developed in the literature to estimate the rupture frequency, which serves as a useful input of the frequency of an initiating event or basic event in PRA.

In general, these approaches can be classified into four main groups: experience-based approaches, model-based approaches, knowledge-based approaches, and data-driven approaches [43]. This section does not attempt to review these approaches in detail as they are not the main focus of this dissertation. Amongst these approaches, model-based approaches and data-driven approaches are two typical approaches that can use degradation data for reliability assessment.

Experience-based approaches are the most straightforward approach as they require less detailed information than other approaches. These approaches are based on the distribution of event records of a population of identical items. Many traditional reliability approaches such as Exponential, Weibull, and Log-Normal distributions have been used to model asset reliability. The most popular approach amongst them is the Weibull distribution due to its ability to conduct different types of behavior including infant mortality and wear-out in the bathtub-tube curve [44]. In practical applications, experienced-based approaches can be implemented when historical repair and failure data are available.

Model-based approaches usually use mathematical dynamic models for a component being monitored. These approaches fall into the categories of physics-based models and statistical models. Statistical models are developed from collected
input/output data and as such might not account for conditions that have not been recorded and thus not included into the models. A widely used example of statistical models is the linearly increasing failure rate model (which is an approximate model) proposed in [6]. Bayes estimators for component lifetimes and component failure rates are presented in [41]. Disadvantages of directly assuming a form for the failure rate (linear or not), rather than starting from the formulation of physical models for the degradation mechanisms, is that the underlying physical phenomena and parameters are not identified in the analysis and extrapolation outside range of data the models are based on is debatable. Subsequently, large uncertainties can be introduced into the failure rate estimates and mask the physics of the problem that can affect aging risk management significantly.

In the literature, several other approaches have been applied to estimating pipe failure rates and rupture frequencies in both categories, from probabilistic fracture mechanics (PFM) to expert judgment. Probabilistic fracture mechanics [45], Markov [46] and multi-state process models [47] are the most common ones. In the PFM, quantification is based on MC simulation. PRO-LOCA [48] and PRAISE [49] computer codes are generally used to perform PFM calculations but this approach is limited by computational speed and the effectiveness of variance reduction techniques. Report [50] gives result of the PFM analysis for the selected passive components.

Multi-state process models and Markov models are described below regarding their capabilities and limitations.
2.8.2 Multi-state Models

Reliability analysis not only focuses on whether the component can perform its function or not but also on how well the component can perform its function. Degradation analysis can trace the whole performance path of the component and answer both of these questions.

Multi-state modeling (MSM) [47] is often applied in degradation process modeling, because it offers the possibility of describing the degradation state through a number of consecutive levels from working perfectly to complete failure. That is, the continuous degradation path of the component is separated into countable states. The main challenge with MSMs regarding aging degradation of SSCs is the description of the operation and maintenance dependence of state transition rates (see Section 4) since these rates are treated as constant.

2.8.3 Markov Models

Markov models are a subset of MSM. As with the rest of MSM techniques, the principal advantage of the Markov approach is that surveillance and maintenance strategies can be taken into account, such as leak detection and repair if failure is detected.

There are two important assumptions regarding Markov models: Markov property and stationary property. The Markov property assumes that the history of the process does not influence the transition probabilities, which is also called “memoryless” property. Stationary property assumes that the transition probabilities do not change over
time. To conclude, finite states with “memoryless” and stationary properties form the base of the model.

In the literature, Markov processes have been also applied quite frequently [24] [46] [51] [52] when it is suitable to model the stochastic progress through discrete states.

Markov models have been also used to model the dynamics of multi-state degradation process [51] [52]. In most cases, Markov modeling is used for systems that have constant transition rates such that the resulting stochastic process is a homogeneous continuous-time Markov chain (HCTMC) which implies that the state transition process is memoryless as well as time independent.

In the real world, external factor (e.g., environmental, metallurgical or operational conditions) effects on degradation, transition rates are time-dependent. Under these circumstances, the inhomogeneous continuous-time Markov chain (ICTMC) is more suited to modeling the degradation process.

Let \( \{X(t), t \geq 0\} \) be a Markov process on a finite state space \( S = \{0, 1, \ldots, N\} \). The primary quantity of interest in many applications of CTMC is the state probability vector \( p(t) = \{p_0(t), \ldots, p_m(t), \ldots, p_N(t)\} \) at any time instant \( t \) such that \( \sum_{n=0}^{N} p_n(t) = 1, \forall t \).

In the case of HCTMC, \( p(t) \) is calculated by solving the following system of differential equations

\[
\frac{dp_n(t)}{dt} = \sum_{m \neq n}^{N} p_m(t)\phi_{mn} - \sum_{m \neq n}^{N} p_n(t)\phi_{nm} \tag{2.1}
\]
where \( n \) is the state index ranging from 0 to \( N \), \( \phi_{nm} \) is transition rate which represents stochastic transition from state \( n \) to state \( m \). The transition rate \( \phi_{nm} \) is defined as:

\[
\phi_{nm} = \lim_{\Delta t \to 0} \frac{Pr(X(t + \Delta t) = m|X(t) = n)}{\Delta t}
\]  

(2.2)

Three common solution techniques for Equation 2.1 are using Laplace transforms, numerical integration or approximation of the equations as a discrete time process. Using Laplace transforms leads to a rigorous analytical expression and is quite desirable. However, it is typically only tractable for models with a small number of states. Numerical integration always works, however, obtaining the steady-state solution may be time consuming for repairable systems. Approximation of the equations as a discrete time process requires the time increment chosen to be very small with respect to the failure and repair rates. It has the advantage of being the simplest approach of the three.

In the case of ICTMC, the transition rate \( \phi_{nm} \) is dependent on time \( \phi_{nm}(t) \). Due to this time dependency, it is in general difficult to obtain the closed-form solutions to the ICTMC differential equations:

\[
\frac{dp_n(t)}{dt} = \sum_{m=0, m\neq n}^{N} p_m(t) \phi_{mn}(t) - \sum_{m=0, m\neq n}^{N} p_n(t) \phi_{nm}(t)
\]  

(2.3)
A number of numerical solution techniques for Equation 2.3 have been proposed. Four representative methods are: numerical solver of differential equations [53] (e.g. the Runge-Kutta method), uniformization [54], MC simulation [50], and state space enrichment [5]. If state changes follow a Markov process but it takes an arbitrarily distributed amount of time between changes, the process is called semi Markov. Residence duration dependent transition rates can be modeled as semi Markov processes as will be shown in Section 4.1.4.

2.9 Incorporating Aging Effects into PRA

This section provides a survey of the work conducted to address the aging of SSCs of NPPs in PRA.

The Taylor expansion approach presented in [55] [56] is a methodology developed to incorporate aging effects into a PRA to estimate the effect of aging on plant risk. This model relates the change in individual component unavailabilities (including maintenance) because of aging to the change in the overall plant risk through a Taylor-series expansion of the basic PRA model that calculates this risk from component unavailabilities [55]. However, as indicated in Section 2.8.6, aging in NPPs cannot be addressed by models that are based solely on the current traditional PRA structure and failure rates.

Reference [57] proposes a method to integrate aging of the passive components into PRA using the PRAISE code to perform a probabilistic structural analysis to calculate the probability that crack growth due to aging would cause the weld to fail. The
method is demonstrated by selecting a weld in the auxiliary feedwater system but this study concludes that probabilistic structural analyses costly to perform and it is not practical to do for every critical passive component in the PRA model.

In [1], a methodology is proposed which considers physics-based models that account for the operating conditions in the plant, however, effects of surveillance/inspection were not included. This methodology is implemented to calculate rupture probability of a main feedwater pipe (carbon steel piping on secondary cooling system of a PWR) and its impact under FAC using a load and capacity model [1]. Reference [58] describes processes and metrics for adapting an existing PRA to provide risk-informed insights on reactor aging management.
Chapter 3: Proposed Methodology

The envisioned interaction of the aging models with the plant dynamics within a PRA environment is schematically shown in Fig. 3.1. The paradigm, in essence, augments the methodology of [1] for compatibility with the NGSC environment. In the proposed methodology, the user first defines a time interval $T$, possibly chosen iteratively to represent the surveillance intervals or refueling outages, as well as degradation dynamics adequately.

In Fig. 3.1, plant state as at time $t=0$ is obtained from the surveillance data, plant configuration and state of process variables (Initial Conditions) that constitute the *Plant State*. These are fed into the *Plant Simulator*. *Plant State* and *Component Failure Rates/Probabilities* are also fed into the PRA code for the prediction of *Risk Metrics and Importances* at $t=T$.

The time dependent simulation of the state parameters that influence degradation mechanisms will be based on off-line RELAP5 analyses (or another transient safety analysis code depending on the nature of the scenarios selected) (See Section 3.1).

The *Plant Simulator* produces the thermal-hydraulic/neutronic data which are fed into the *Component Aging Progression Models* and assumed to stay constant within the time interval $T$ to predict failure rates/probabilities at $t=T$. 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 constant based on the results of off-line steady-state calculations performed with the Plant Simulator. Initial Conditions, Surveillance Data, maintenance and repair actions as they affect the Plant State are also updated at each time $t=kT$. If the observed Plant State is not consistent with the aging progression model predictions, Component Aging Progression Model is retuned (Retune Aging Model in Fig.3.1). The time is incremented by $T$, failure rates/probabilities are updated and the process is repeated until the target time horizon $KT$ is reached.

At the end of each time interval $kT \leq t \leq (k+1)T$, the plant state is re-evaluated as it impacts the determination of the Risk Metrics and Importances for that time interval.

As degradation processes continue over the time period $kT (k=0, 1, 2, \ldots)$ the potential will grow that an initiating event (aging-induced) of some kind would occur, such as a leak or rupture of a pipe at a weld. Based on the condition, the likelihood of an initiating event of this nature can be determined from the aging model and surveillance policy, 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 to decide if the surveillance program is adequate or if there is need to Update Surveillance Program. Similarly, the results of surveillance performed within a particular time interval could indicate the need to repair or replace a component or structure (Modify Plant in Fig. 3.1). Thus, components or structures can be returned to some initial state at which degradation mechanisms will again continue to degrade their performance.

The paradigm can be implemented manually or in a mechanized fashion depending on the capability of the Plant Simulator to simulate plant dynamics in a computationally efficient manner for the time horizon $kT$ (up to 80 years). Two differences in the manual and mechanized implementation of the paradigm are that: a) the time period $T$ in the manual implementation needs be chosen large (maybe a refueling period) whereas it can be can be arbitrarily small in mechanized implementation, and, b) the PRA code will be hard-coupled to the Plant Simulator to provide subsystem level failure data in mechanized implementation (e.g. probability of Emergency Core Coolant System failure).

Degradation mechanisms have very large associated uncertainties. It is not possible to predict that a degradation mechanism will lead to failure of a pipe during time interval $kT \leq t \leq (k+1)T$ but only some probability that it will occur in that interval. Similarly, there is some likelihood that surveillance will occur prior to failure that will indicate the need to repair or replace the pipe. Subsequently, as time progresses, there are a large number of alternative scenarios that are possible. If we were hypothetically to construct an event tree involving the behavior of all of the degradation mechanisms and potentially affected
structures and components, we would find that one could not establish a fixed order for these events. Thus, it is necessary to perform the PRA in a dynamic fashion [15], such as within the RELAP-7 framework. In the manual implementation, the complexity of a full uncertainty analysis is impractical. In mechanized implementation, however, the Plant Simulator/Component Aging Progression Model can be used to explore possible ways the system can evolve with the associated probabilities as it is currently done with dynamic PRA tools [15]. The results then can be used to augment Risk Metrics and Importances produced by a PRA code (e.g. SAPHIRE [12]), as well as determining the spread in Component Failure Rates/Probabilities for uncertainty quantification using the standard features of PRA codes. The benefits of the paradigm are the following:

- Mechanistic treatment of degradation mechanisms rather than reliance on historical plant service data
- Simultaneous consideration of multiple mechanisms within a dynamic environment that accounts for uncertainties
- Ability to make PRAs more plant specific with the ability to support improvements in surveillance, maintenance and replacement strategies
- Ability to model thermal cycle/fatigue cycle over the analysis time frame
- Ability to model progression of degradation over the analysis time frame
- Ability to include surveillance in the PRA with potential for component replacement or repair
- Ability to consider epistemic and aleatory uncertainties within the same phenomenological and stochastic framework.
Figure 3.1. The Proposed Methodology
In NUREG/CR-5632 [8], a methodology is proposed which considers physics-based models that account for the operating conditions in the plant, however, effects of surveillance/inspection were not included. In our methodology, surveillance/inspection effects are considered implicitly in the multi-state semi-Markov models via repair transition rates. Additionally (in an explicit treatment manner), at the end of each time step surveillance data and activities are updated according to component state.

This methodology is implemented to calculate rupture probability of main feedwater pipe (carbon steel piping on secondary cooling system of a PWR) and its impact in case of FAC using load and capacity model. The capacity model is selected as the purely deterministic KWU-KR model [59] and this model is directly linked to the SAPHIRE code and model parameters (e.g., temperature) are normally distributed in SAPHIRE via MC simulation with given mean and standard deviation value.

In the proposed methodology (see Figure 3.1), dynamic PRA tools such as ADAPT instead of SAPHIRE or with SAPHIRE could be coupled to generate DETs automatically by controlling the execution and stoppage of RELAP5 and by manipulating the input to the simulator at each stopping point.

Incorporation of passive component aging into dynamic PRA is not addressed in NUREG/CR-5632 and the proposed methodology is not suitable (aging analysis is not in conjunction with the evolving physical environment, modeled with a systems code such as RELAP5). In our approach physical environment (thermal-hydraulic) parameters are calculated via reactor simulation code, for instance, RELAP5 or RELAP-7. Therefore characterization of plant system behavior will be analyzed more realistically and this
linking between probabilistic and deterministic analysis also allows to incorporate aging models into dynamic PRA.

If the predicted Plant State (see Fig. 3.1) is found to be inconsistent with surveillance data, then the aging progression model can be re-tuned by fitting the model parameters to the observed data. Also, a physical model of the change in damage index over time, given the stressor values informed by thermal-hydraulic/neutronic data, in conjunction with a probabilistic prognostic algorithm can predict component performance (e.g., remaining useful life, the probability of failure, etc.) beyond the time at which surveillance is performed to determine if the Plant State predicted by the state transition model is not only consistent with current data but also estimated future performance of the plant given the level of observed degradation. Moreover, the results of surveillance performed within a particular time interval could indicate the need to repair or replace a component or structure based on time-to-failure and remaining-useful-life estimates obtained. Reactor Simulation and Component Aging Model modules in Fig.3.1 are described in detail in Section 3.1. and 3.2 respectively.

3.1 Reactor Simulation Environment RELAP5/MOD3.4

In reference [26], it is assumed that constant conditions prevail throughout the life of the NPP for a number of parameters even though some of them, such as operating temperature or pressure, could vary with time. Treating these quantities as constants for each fuel cycle reduces computational effort. Although the probabilistic treatments and characterizations of fatigue and stress corrosion cracking are well documented in the
literature, only a limited number of these publications document plant-specific and component-specific evaluations based on actual design or operating data.

For the research presented in this dissertation, the temperature dependent data is generated by RELAP5/Mod3.4 [60] simulation of a simplified model of a 3600 MWth 4-loop PWR under normal operating conditions obtained with a 100 s run. The nodalization diagrams for the PWR are given in the Fig. 3.2 and 3.3. Three loops are modeled together and the fourth loop is modeled separately, nodalization of the primary loops is shown in Fig. 3.2.

Figure 3.2. Nodalization diagram for the loops
Methodology was implemented to the pressurizer surge line pipe weld (See Section 4.1) and also to the SG tubes (Section 4.2). In the reactor simulation environment, pressurizer (see Figure 3.3) is represented by a time dependent volume with a pressure boundary (Node 158) and a pressure relief valve (Node 157). The cylindrical body of the pressurizer is modeled using a pipe (Node 150). A single junction (Node 151) connects the pressurizer to the pipe modeling the surge line (Node 152). Surge line connects to the hot leg via Node 102 (See Figure 3.2).

Figure 3.3. Nodalization diagram for SG and pressurizer
SG on the triple loop side is modeled as shown in Fig. 3.3 which is a U-tube SG hot water enters from (Node 105) and it connects to cold leg (Node 110) in Fig. 3.2.

3.2 Physics Models of PWSCC

In this section, selected crack initiation and the growth models for the PWSCC in pressurizer surge line pipe and also in steam generator tubes will be introduced. These models will be used to derive physics based transition rates in Chapter 4.

3.2.1 Crack Initiation Model

The first step in SCC formation is nucleation. A SCC is considered nucleated when the crack growth rate can be described by crack growth rate models. A number of alternative models have been used to characterize initiation [31-36], the Weibull model being the most widely adopted as also indicated in Section 2.8. In the Weibull model, the cumulative probability of crack initiation by time \( t \), \( P(t) \), is given by

\[
P(t) = 1 - e^{\left[-\left(\frac{t}{\eta}\right)^b\right]} \quad \text{(3.1)}
\]

In Equation 3.1, \( \eta \) is a Weibull scale parameter, which depends on both stress and temperature. The parameter \( b \) is the Weibull shape parameter. The scale parameter can be determined from [44]

\[
\eta = A\sigma^n e^{(Q/RT)} \quad \text{(3.2)}
\]

where

- \( A \) : fitting parameter that may include material and environmental dependences
- \( \sigma \) : explicit stress factor (MPa)
- \( n \) : stress exponent factor
- \( Q \) : crack initiation activation energy (kJ/mole)
Operating temperature (°K)
Universal gas constant (8.314 x 10^-3 kJ/mole-°K)

3.2.2 Crack Growth Models

Two different crack growth models will be introduced in this part for: a) pressurizer surge line pipe (alloy 182), and b) SGTs (alloy 600). The constituents of the alloys are given in Table 3.1.

Table 3.1. Main chemical composition (weight %) of nickel alloys [61] [62]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Ni %</th>
<th>Cr %</th>
<th>Fe %</th>
<th>Mn %</th>
<th>Nb %</th>
<th>Ti %</th>
</tr>
</thead>
<tbody>
<tr>
<td>182</td>
<td>67.0</td>
<td>15.0</td>
<td>8.0</td>
<td>7.0</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td>600</td>
<td>75.0</td>
<td>15.6</td>
<td>8.8</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Crack growth rates for alloy 182 have been generated Ringhals AB [39], Electricité de France [40], and the Electric Power Research Institute [41, 42]. All the models have a similar form that includes a stress and Arrhenius temperature dependence. EPRI report MRP-115 [62] is the most recent report with the most comprehensive data set and is therefore the best choice for our current purposes. The maximum credible crack growth rate $\dot{a}_M$, as a function of temperature $T$ is found from

$$\dot{a}_M = \alpha f_{\text{alloy}} f_{\text{orient}} K^\beta e^{-\left(\frac{Q_G}{R}(T^{-1}-T_{\text{ref}}^{-1})\right)} \quad (3.3)$$

with the other model parameters, their definitions and values summarized in Table 3.2. The full temperature range tested is 400 K to 650 K.

The $f_{\text{weld}}$ and $f_{\text{ww}}$ factors are intended to capture the uncertainty in the crack growth rate due to the effect of material condition (composition, microstructure, etc.). For the
deterministic MRP-115 equation, the 75th percentile value for $f_{weld}$ was chosen as a conservative mean in order to account for the concern that welds that are more susceptible than average to crack initiation (and hence are more likely to be cracked in a plant) tend to have higher crack growth rates than average.

Table 3.2. Model Input Parameters of MRP-115 [62]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{ref}$</td>
<td>reference temperature used to normalize data</td>
<td>400 K and the model is valid for 400 $K \leq T \leq 650$ K</td>
</tr>
<tr>
<td>$\beta$</td>
<td>stress intensity exponent</td>
<td>1.6</td>
</tr>
<tr>
<td>$K$</td>
<td>crack tip stress intensity factor</td>
<td>MPa√m</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>fitting constant for crack growth amplitude – lognormal distribution</td>
<td>$1.5 \times 10^{-12}$</td>
</tr>
<tr>
<td>$Q_G$</td>
<td>thermal activation energy for crack growth</td>
<td>220 kJ/mol (220-230 kJ/mol)</td>
</tr>
<tr>
<td>$R$</td>
<td>universal gas constant</td>
<td>$8.314 \times 10^{-3}$ kJ/mole-K</td>
</tr>
<tr>
<td>$f_{alloy}$</td>
<td>crack growth rate factor to account for effect of alloy composition</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_{orient}$</td>
<td>crack growth rate factor to account for crack orientation relative to the dendrite direction</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Stress intensity factor $K$ has been obtained by the Pacific Northwest National Laboratory (PNNL) for specific crack geometries and stress distributions. Since such application specific data are not currently available for our study, $K$ was chosen as 35 MPa√m which is close to the to the maximum considered in [5] and also yields a crack growth of rate $\dot{a}=2.99E-10$ m/s from Eq.(3.3) that is consistent with Fig. 3.4 taken from [63].

42
In 2009, EPRI published the MRP-263 [29] study. This study also included a detailed statistical assessment of the available PWSCC crack growth rate data indicating the effect of hydrogen concentration for Alloy 82 and 182 weld metal materials.

In accordance with standard practice for evaluation of SCC, a power-law dependence on stress intensity factor based upon the relationship originally developed by [64] was assumed by EPRI. Tabulation of crack growth rates for both Alloy 600 and Alloy 182 allowed an evaluation showing that SCC growth rates in Alloy 182 weld metal were factors of 3–5 faster than rates in Alloy 600 [65].
Previously, a crack growth equation based on primary water induced cracking of roll transitions of steam generator tubes—typically known as the modified Scott equation—has been used to predict crack growth of other Alloy 600 primary circuit components [66]. For the present work, the EPRI MRP-55 [67] model is selected as crack growth model for the Alloy 600 to be consistent with Case 1 in which similar empirical EPRI model is selected for the component of interest. which has been tested in the 563 K to 636 K temperature range:

\[
\dot{a}_M = \alpha \exp \left( \frac{Q_G}{R} \left( \frac{1}{T} - \frac{1}{T_{ref}} \right) \right) (K - K_{th})^\beta
\]  

(3.4)

The model parameters of Eq.3.4, their definitions and values are summarized in Table 3.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>fitting constant for crack growth amplitude</td>
<td>$2.67 \times 10^{-12}$</td>
</tr>
<tr>
<td>$Q_G$</td>
<td>thermal activation energy for crack growth</td>
<td>130 kJ/mole</td>
</tr>
<tr>
<td>$R$</td>
<td>universal gas constant</td>
<td>$8.314 \times 10^{-3}$ kJ/mole-K</td>
</tr>
<tr>
<td>$T_{ref}$</td>
<td>reference temperature used to normalize data</td>
<td>598.12 K</td>
</tr>
<tr>
<td>$\beta$</td>
<td>stress intensity exponent</td>
<td>1.16</td>
</tr>
<tr>
<td>$K_{th}$</td>
<td>threshold crack tip stress intensity factor</td>
<td>9 MPa√m</td>
</tr>
</tbody>
</table>

The key parameters of Eq. 3.4 need to be discussed in more detail. As can be seen from Eqs. 3.3 and 3.4, the PWSCC damage rate increases as an exponential function of stress. A threshold stress, i.e. a stress below which PWSCC does not initiate has not been determined experimentally for Alloy 600. However, use of the strain rate damage model,
which is based on slow strain rate test data, leads to an estimated threshold stress $\kappa_{th}$ of about 241 MPa at the operating temperature of about 315°C (600°F) [66]. All the PWSCC failures reported in the field, including hot leg penetrations cracking, resulted from high residual tensile stresses. High residual stresses are generally introduced during fabrication or installation of the Alloy 600 components. Cold work increases the residual stresses on the inside surface and thereby reduces the resistance to PWSCC.

Generation and extension of the PWSCC depends on the distribution shape and magnitude of residual stress in the welds [4] [68]. Therefore, the accurate prediction of welding residual stress can enhance the reliability of structural integrity evaluation of nuclear reactor plants. Stress intensity factor $K$ has been obtained by PNNL for specific crack geometries and stress distributions [63]. In most cases, the prediction is calculated by a numerical analysis approach such as the finite-element method [69] [70] [71].

PWSCC is a thermally activated process that can be described by an Arrhenius relationship of the form damage rate proportional to $e^{-Q_G/RT}$. PWSCC initiation is sensitive to temperature. For example, in any affected steam generator, the PWSCC has been first reported in the tubes on the hot-leg side, not on the cold-leg side. Similarly, PWSCC has been first reported in Alloy 600 penetrations in the hot leg and not in the cold leg. For activation energy, $Q_G$, equal to 209kJ/mole, a temperature reduction of 10°C (from 320 to 310°C (608–590°F)) will reduce the PWSCC initiation time by a factor of two.

Field experience and research results show that the PWSCC resistance of Alloy 600 is highest when the grain boundaries are covered with continuous or semi-continuous
carbides [65]. The PWSCC resistance is lower when the grain boundaries are covered with widely spaced, discrete carbides. The PWSCC initiation time increases by a factor of five as the grain boundary carbide coverage increases from 0 to 100% [41]. The reasons for this beneficial effect of the intergranular carbides are not yet fully understood.

Tests over the range of pH values from 6.9 to 7.4 at high temperatures show that the primary coolant chemistry has a secondary effect on PWSCC initiation in Alloy 600 material [4.73]. Some preliminary results show that PWSCC initiation is sometimes accelerated when the lithium content is high. For example, PWSCC initiation time was reduced (PWSCC susceptibility increased) by about a factor of two when the lithium concentration was increased from 2.2 ppm to 3.5 ppm at a constant boron concentration of 1200 ppm.
Chapter 4: Model Implementation: Evaluation of Pipe Failure Rates

This chapter expands on the physics models (Section 4.1.3 and 4.2.3) and shows implementation of the overall methodology for two case studies described in Chapter 3 by introducing operational data and time dependent transition and repair rates. Section 4.1 details physics based semi-Markov models for the pressurizer surge line pipe weld (Case 1), as well as uncertainty and sensitivity analysis results. A detailed analysis of the SGTR (Case 2) using the semi-Markov approach with multi-state physics model is described and compared with other studies, as well as with industry experience in Section 4.2. Lastly, the graphical-user interface (GUI) is introduced for the users to implement semi-Markov approach for selected mechanisms with uncertainty analysis (Section 4.3). Remarks relating to the probability of achieving the correct conclusion during an analysis are presented at the end of each subsection.

4.1 Case 1: Pressurizer Surge Line Pipe Weld

Reference [72] has demonstrated that about half of the total number of failures in pipe components in ASME Class 1 systems is due to welds. This assumption was confirmed by the statistics in Organization for Economic Cooperation and Development (OPDE) database for the relevant pipe category. From the total of 327 events in OPDE for PWR plants and for ASME Class 1 systems, 167 events were found to be related to
welds and the rest to other pipe components like elbows, straight pipe elements, fittings, nozzles, etc.

Because of the LOCA-significant location, dissimilar weld materials, high susceptibility to SCC, and significant non-detection probability, the selected component for analysis in this research was a PWR pressurizer surge line nozzle alloy 182/82 dissimilar butt weld. There is a considerable amount of publicly available information exists on the SCC of an alloy 82/182 dissimilar metal weld [73] [63] [5] [74].

For the Case 1 analysis, operational experience about SCC in pressurizer surge line pipe weld is summarized and mitigation method is discussed in Section 4.1.1 than component properties and geometry is described (Section 4.1.2), selected aging model (Section 4.1.3) and proposed solution method, sojourn time approach, is introduced (Section 4.1.4). MC simulation algorithm and analysis results are given in Section 4.1.5. Operating condition effects on state probabilities are discussed to clarify importance of thermal-hydraulic coupling with the aging model. At last, Section 4.1.7, sensitivity and uncertainty analysis is conducted.

### 4.1.1 Industry Experience and Mitigation Method

According to operational experience of NPPs, two PWS CC occurrences of flaws in surge line pipe have been observed [75]. First, in October 2006, several indications of circumferential flaws were reported in the pressurizer nozzles at Wolf Creek. The indications were located in the nickel-based Alloy 82/182 DM weld material, which is known to be susceptible to PWS CC. Second, PWS CC occurred in V. C. Summer reactor
vessel hot leg nozzle, Alloy 82/182 weld. It should be noted that this susceptible material is found at the Waterford 3 pressurizer surge nozzle and the hot leg to surge line nozzle locations [76]. However, structural weld overlay (SWOL) was implemented to mitigate the PWSCC concern. SWOL is a technique that is used to reinforce the Alloy 82/182 welds in PWR plants susceptible to PWSCC. The reinforcement material (Alloy 52M) forms a structural barrier to PWSCC and produces a compressive residual stress condition at the inner portion of the pipe/weld/fitting that mitigates future crack initiation and/or propagation due to PWSCC [76].

4.1.2 Component Description

Figure 4.1.a shows the bottom head area of a typical Westinghouse pressurizer and Fig. 4.1.b is picture of pressurizer surge line nozzle. A cutaway view through a typical surge nozzle, Alloy 182 weld joining the stainless steel safe end to the low alloy steel nozzle can be seen in Fig. 4.1.c.

The surge line joining material is Alloy 82/182 bimetallic weld. Common degradations of Alloy 82/182 are thermal fatigue and PWSCC. Loading conditions include pressure, thermal, residual stress, and dead weight nominal loads.
Operating conditions are taken for the pressurizer surge line pipe as 15.40978 MPa operating pressure and 618.15 K operating temperature from reactor simulation environment (See Section 3.1). The modeled pipe geometry properties are the following [50]:

- Inside Diameter = 282 mm
- Wall Thickness = 35.7 mm
• Circumference = 47 mm
• Outside Diameter = 317.7 mm

4.1.3 Physics-based Multi-State Aging Model

From the modeling standpoint, certain assumptions were made due to the limited scope of the case study. Manufacturing defects and fatigue initiation and growth and axial crack formations are ignored. A multi-state model was adopted that incorporates the physics of SCC micro-crack initiation and crack growth for various crack morphologies, to the point of leak or rupture [5]. Figure 4.2 shows the state transition diagram for the model. State evolutions are described through equations (4.2)-(4.6).

\[
\frac{dX(t)}{dt} = A(t)X(t) \quad (4.1)
\]
where

\[
X(t) = \begin{bmatrix}
S(t) \\
M(t) \\
C(t) \\
D(t) \\
L(t) \\
R(t)
\end{bmatrix}
\]

and

\[
A(t) = \begin{bmatrix}
-\phi_1(t) & \omega_1 & \omega_3 & \omega_2 & \omega_4 & 0 \\
\phi_1(t) & -\omega_1 - \phi_2(t) - \phi_3(t) & 0 & 0 & 0 & 0 \\
0 & \phi_3(t) & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -\phi_4(t) & 0 & 0 \\
0 & 0 & 0 & \phi_6 & 0 & \phi_5 \\
0 & 0 & \phi_6 & \phi_5 & 0 & 0
\end{bmatrix}
\]

with the components of \(X(t)\) defined as in Fig.4.2. The transition rates \(\phi_5, \phi_6\) and \(\omega_i\) \((i=1,2,3,4)\) are constant. Simplified version of the transition rates \(\phi_i(t)\) for \((i=1,\ldots,4)\) in \(A(t)\) are presented in [5].

The transition rate \(\phi_1\) from initial state S to micro-crack state M is defined as

\[
\phi_1(t) = \left(\frac{b}{\eta}\right) \left(\frac{t}{\eta}\right)^{b-1}
\]

Equation 4.3, \(\eta\) is a Weibull scale parameter, which has been observed to have both a stress and temperature dependence; \(b\) is a Weibull shape parameter (See Section 3.2).
The transition rate \( \phi_2 \), describing the transitions from micro-crack state M to radial-crack state D

\[
\phi_2(t) = \begin{cases} 
0 & \text{if } u \leq \frac{a_D}{\dot{a}_M} \\
\frac{a_D P_D}{\dot{a}_M u^2 \left(1 - P_D \left(1 - \frac{a_D}{u \dot{a}_M}\right)\right)} & \text{if } u > \frac{a_D}{\dot{a}_M}
\end{cases}
\]  
(4.4)

Similar definition is derived for the transition rate \( \phi_3(t) \) from micro-crack state M to circumferential-crack state C.

\[
\phi_2(t) = \begin{cases} 
0 & \text{if } u \leq \frac{a_c}{\dot{a}_M} \\
\frac{a_c P_C}{\dot{a}_M u^2 \left(1 - P_C \left(1 - \frac{a_c}{u \dot{a}_M}\right)\right)} & \text{if } u > \frac{a_c}{\dot{a}_M}
\end{cases}
\]  
(4.5)

The transition rate \( \phi_4 \) between state D and state L is defined by the growth in crack size up to a threshold of leakage:

\[
\phi_4(t) = \begin{cases} 
\frac{1}{w} & \text{if } w > \frac{(a_L - a_D)/\dot{a}_M}{w} \\
0 & \text{otherwise}
\end{cases}
\]  
(4.6)

where \( w \) is the time since the radial crack formation.

In Eqs.(4.3) - (4.6), \( u \) is a time after crack initiation and \( w \) is time after macro-crack formation and the other parameters are the following:

\( a_D \) : Crack length threshold for radial macro-crack
\( P_D : \) Probability that micro-crack evolves as radial crack

\( P_C : \) Probability that micro-crack evolves as circumferential crack

\( \dot{a}_M : \) Maximum credible crack growth rate

\( \alpha_C : \) Crack length threshold for circumferential macro-crack

\( \alpha_L : \) Crack length threshold for leak

\( \omega_1 : \) Repair transition rate from micro-crack

\( \omega_2 : \) Repair transition rate from radial macro-crack

\( \omega_3 : \) Repair transition rate from circumferential macro-crack

\( \omega_4 : \) Repair transition rate from leak

\( \phi_5 : \) Leak to rupture transition rate

\( \phi_6 : \) Macro-crack to rupture transition rate

The repair rates refer to in-cycle inspection within the context of Fig.3.1.

One of the challenging issues with the representation of the state transition diagram of Figure 4.2 through Eqs. (4.1)-(4.6) while maintaining consistency with the physics of the degradation process is the representation of the transition rates given in Eqs.(4.4)-(4.6). The reason is that while, for example, physically State D in Fig.4.2 will not be achieved before State M is achieved, State D will start being populated at time \( t=0 \) during the solution of Eqs.(4.1)-(4.6) because of the Markov chain characteristics.

The impact of thermal-hydraulic data on the transition rates is mainly through \( \tau \) and \( \dot{a}_M \) in Eqs (4.3)-(4.5).

As can be seen from Eqs.(4.3)-(4.6), some transition rates of this model are functions of system residence time, system operational history in terms of pressure and
temperature, therefore the model does not have Markov property. In [5], the state-transition model is converted to a Markov model by introducing auxiliary state variables which also substantially increases the model size. In an earlier study reported in [77] related to this research and described in Section 4.1.4, the multi-state model was represented as a semi-Markov process using the concept of sojourn time (i.e. expected residence time in a given state) which reduces the model size and furthermore allows optimization of surveillance times in case of history dependent maintenance actions. Reference [77] uses the temperature/pressure independent transition rates of [5] in order to compare the semi-Markov approach to the approach used in [5] (see Section 4.1.4). Section 4.1.5 compares semi-Markov results to those obtained by MC simulation.

4.1.4 Sojourn Time Approach

The variables $u$, $w$ in the Eqs. (4.4) – (4.6) represent the time since the last transition in $X(t)$ and hence are different that the time $t$ which represents time at which the stochastic process was started. Due to this operational history dependence, the model represented in Figure 4.2 is not Markovian. For this reason, these equations were solved in [5] with state enrichment method which converts it into a Markovian process by partitioning the time interval of interest into 160 segments and augmenting the state space of Fig.4.2 by auxiliary variables which represent the probabilities of the States $S$, $M$, $C$, $D$, $L$ and $R$ being in each segment as a function of time. The resulting model has $6 \times 160 = 960$ states. While this approach is closer to physical reality, each of these 960 states will get populated starting from time $t=0$ during the solution of the resulting 960 differential equations as well. Thus, consistency with the physics of the process still remains a
problem. Furthermore, the arbitrary discretization of the time horizon of interest brings a subjective element to the solution process and number of equations to be solved grows very rapidly with increasing number of components to be modeled, as well as the temporal refinement of the solutions.

A new solution approach to the problem was developed to meet these challenges through the use of the concept of sojourn time. The sojourn time, in essence, is the expected time that the system resides in a given state and for this problem is defined through

\[
\tau_{n,k} = \int_{0}^{T_k} dt \frac{dx_n(t)}{dt}
\]

where \( \tau_{n,k} \) is the sojourn time in State \( n \) until time \( t = T_k \) and \( x_n(t)dt \) is the probability of being in State \( n \) within the time interval \( dt \) around \( t \). The approach to the solution of the problem, while taking into account possible repair, was formulated as the following:

Consider the semi-Markov process with sojourn time dependent transition rates

\[
\frac{dx_n(t)}{dt} = -x_n(t) \sum_{m=1, m \neq n}^{N} \phi_{mn}(\tau_n) + \sum_{m=1, m \neq n}^{N} \phi_{nm}(\tau_m) x_m(t) (n = 1, \ldots, N).
\]

where \( \tau_m \) is the total sojourn time of the system in State \( m (m = 1, \ldots, N) \), \( x_n(t) \) is the probability that the system is in State \( n \) until time \( t \), and \( \phi_{mn}(\tau_n) \) is the transition rate from State \( n \) to State \( m \) as a function of sojourn time. The solution involves the following steps:
1. Partition the time interval of into intervals of length $T_k - T_{k-1} = \Delta T_{k-1} \ (k = 1, \ldots, K)$ with $T_0 = 0$

2. For the interval $\Delta T_0$, solve Eq.(4.10) with $\tau_m = 0 \ (m = 1, \ldots, N)$

3. Let $k=1$

4. For the interval $\Delta T_k$ let

$$\tau_{n,k} = \int_{T_{k-1}}^{T_k} dt \ (t - T_{k-1}) \frac{dx_n(t)}{dt} + \tau_{n,k-1} \quad (4.9)$$

5. Calculate $\phi_{mnk} = \phi_{mn}(\tau_{n,k}) \ \forall n, m = 1, \ldots, N$ from Eqs.(4.3)-(4.6), solve Eq.(4.10) with these transition rates and using $x_n(T_{k-1}) \ (n = 1, \ldots, N)$ as initial conditions. If repair has taken place for State $n$ at the end of $\Delta T_k$, restore $\phi_{mn}(\tau_{n,k})$ for all $m=1,\ldots,N$ to their initial values of $\phi_{mn}(0)$.

6. Let $k=k+1$ and go to Step 4.

In the algorithmic implementation of Step, Eq. (4.7) is converted into the differential equation

$$\frac{d\tau_{n,k}(t)}{dt} = (t - T_{k-1}) \left[ -x_n(t) \sum_{m=1 \atop m \neq n}^{N} \phi_{mn}(\tau_n) + \sum_{m=1 \atop m \neq n}^{N} \phi_{nm}(\tau_m) x_m(t) \right] \quad (4.10)$$
for format consistency with Eq.(4.8). For the comparison of this approach to the one used in [5], the semi-Markovian model was implemented using the data in Table 4.1 by MATLAB.

### Table 4.1 Transition Rate Parameters [5]

<table>
<thead>
<tr>
<th>Model Input Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b - Weibull shape parameter for crack initiation model</td>
<td>2.0</td>
</tr>
<tr>
<td>$\eta$ - Weibull scale parameter for crack initiation model</td>
<td>4 years</td>
</tr>
<tr>
<td>$a_D$ - Crack length threshold for radial macro-crack</td>
<td>10 mm</td>
</tr>
<tr>
<td>$P_D$ - Probability that micro-crack evolves as radial crack</td>
<td>0.009</td>
</tr>
<tr>
<td>$a_M$ - Maximum credible crack growth rate</td>
<td>9.46 mm/yr</td>
</tr>
<tr>
<td>$a_C$ - Crack length threshold for circumferential macro-crack</td>
<td>10 mm</td>
</tr>
<tr>
<td>$P_C$ - Probability that micro-crack evolves as circumferential crack</td>
<td>0.001</td>
</tr>
<tr>
<td>$a_L$ - Crack length threshold for leak</td>
<td>20 mm</td>
</tr>
<tr>
<td>$\omega_1$ - Repair transition rate from micro-crack</td>
<td>$1 \times 10^{-3}$/yr</td>
</tr>
<tr>
<td>$\omega_2$ - Repair transition rate from radial macro-crack</td>
<td>$2 \times 10^{-2}$/yr</td>
</tr>
<tr>
<td>$\omega_3$ - Repair transition rate from circumferential macro-crack</td>
<td>$2 \times 10^{-2}$/yr</td>
</tr>
<tr>
<td>$\omega_4$ - Repair transition rate from leak</td>
<td>$8 \times 10^{-1}$/yr</td>
</tr>
<tr>
<td>$\phi_5$ - Leak to rupture transition rate</td>
<td>$2 \times 10^{-2}$/yr</td>
</tr>
<tr>
<td>$\phi_6$ - Macro-crack to rupture transition rate</td>
<td>$1 \times 10^{-5}$/yr</td>
</tr>
</tbody>
</table>

The comparison is shown in Fig.4.3 below which indicates that the agreement is good. The differences can be partly explained in terms of the semi-discrete nature of the solution technique of [5] (i.e. transitions occur in 6 month intervals) versus the continuous time representation of the semi-Markov model. For example, the semi-Markov model predicts a lower leak probability because it accounts for repair continuously whereas [5] accounts for the repair in 6-month intervals. Similarly, while the probability of circumferential and radial crack state probabilities are of similar order for both [5] and the semi-Markov model, the differences between the two state probabilities are much closer to each other for $t=80$ years in the semi-Markov model.
results as expected since they both originate from the same micro-crack state with similar transition rates (see Fig. 4.2). Also note that the initial state decreases more rapidly in the semi-Markov model because aging takes place on a continuous basis rather than in 6-month intervals as it does in [5].

![Figure 4.3. Comparison of the semi-Markov model to the approach reported in [2]](image)

In practice, the growth of the time dependent hazard rate is too slow to reach the asymptotic value within a plant lifetime. That is why Fig. 4.3 shows a monotonically increasing rupture probability over 80 years (and monotonically decreasing probabilities for the other states).

4.1.5 **MC Simulation**

The MC simulation of the multi-state physics based model, the history dependent transition rates given by Eqs. (4.3)-(4.6) are not sampled directly. Instead, the process
holding time at State \( i \) (i.e., \( u \) or \( w \)) is sampled assuming uniform distribution within specified bounds and then the transition from State \( i \) to State \( j \) is determined. This procedure is repeated until the accumulated holding time reaches the predefined time horizon. The external influencing factors on crack initiation and crack growth such as pressure, temperature are taken from Plant Simulator in Fig. 1 (e.g. RELAP5 or RELAP-7) for each MC run.

The algorithm for the simulation of the process of component degradation on the time horizon \([0, t_{\text{max}} = 80 \text{ years}]\) is given by the following pseudo-code:

**initialize** the system is in state \( i = S \) (initial state: no flaw)

set the time \( t = 0 \) (initial time)

input the total number of replications \( N_{\text{max}} \)

set \( t^* = 0 \)

set \( n = 1 \)

**while** \( n < N_{\text{max}} \)

**while** \( t < t_{\text{max}} \),

take external influencing factors \((T, P)\) data from RELAP5 run

sample a departure time \( t \) from the distribution function

sample a random number \( \xi \) from the uniform distribution in [0, 1]

**for** each outgoing transition \((j = 0, 1, \ldots, M, j \neq i)\),

calculate the transition probability \( \phi_{ij}(t, T, P) \)

If \( \sum_{k=0}^{j-1} \phi_{ik}(t) < \xi < \sum_{k=0}^{j} \phi_{ik}(t) \)

**then** activate the transition to state \( j \)

**end if**

**end for.**

set \( t^* = t \)

**remove** the system from place \( i \) to place \( j \)

**end while**

set \( n = n + 1 \)

**end while**

The numerical comparisons on the state probability values at year 80 are summarized in Table 4.2. MC results validate results of the proposed semi-Markov process models.
Table 4.2 Comparison of Sojourn Approach, MC Simulation and State-Space Enrichment Approach at year 80

<table>
<thead>
<tr>
<th>State Probabilities</th>
<th>Sojourn-Approach</th>
<th>MC Simulation (1,000 runs)</th>
<th>MC Simulation (10,000 runs)</th>
<th>State-Space Enrichment (step size 6 months)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>0.0001</td>
<td>0.00012</td>
<td>0.00012</td>
<td>0.0034</td>
</tr>
<tr>
<td>Micro Crack</td>
<td>0.9957</td>
<td>0.9958</td>
<td>0.9958</td>
<td>0.9961</td>
</tr>
<tr>
<td>Circumferential Crack</td>
<td>1.09E-4</td>
<td>2.93E-4</td>
<td>2.86E-4</td>
<td>2.33E-04</td>
</tr>
<tr>
<td>Radial Crack</td>
<td>1.382E-4</td>
<td>7.20E-4</td>
<td>1.72E-4</td>
<td>6.97E-05</td>
</tr>
<tr>
<td>Leak</td>
<td>2.19E-06</td>
<td>2.00E-6</td>
<td>2.53E-6</td>
<td>1.06e-05</td>
</tr>
<tr>
<td>Rupture</td>
<td>7.732E-05</td>
<td>7.11E-5</td>
<td>7.96E-5</td>
<td>1.73e-04</td>
</tr>
</tbody>
</table>

Among all methods, sojourn time has the fastest method and MC simulation is generally slower than the state-space enrichment method (depends on selected time interval), with the difference between their state probability estimations increasing as the transition rates increase. However, it should be noted that the memory requirement of the state-space enrichment is much higher than other two methods. It can be seen that when MC runs increased, simulation results getting closer to sojourn time approach results except for the circumferential crack. Since after system entering the micro crack state, it evolves according to experience based probabilities assigned to the radial, $P_D$, (0.001) or circumferential, $P_C$, (0.009) crack states (See Table 4.1) the system goes to circumferential case less. Weighted sampling approach or more realizations could be used to reduce these discrepancies.
4.1.6 Operating Condition Affects

As indicated in Section 1.2, an objective of this research is to account for the plant specific physical conditions on the aging of SSC. Equations (4.3)-(4.6) show that such an accounting is critical in view of the physical parameter dependency of the transition rates. Updating thermal-hydraulic data for every fuel cycle will help to follow cracks more mechanistically and improve the effectiveness of surveillance and maintenance program. For instance, crack growth rate in degrading pipes is likely to be faster in hotter regions of the piping system.

In order to observe the impact of such effects, a sensitivity study was conducted with the multi-state transition model parameters reported in [2] for Eqs. (3.1)-(3.3) versus those given in Table 4.3. The temperature dependent data in Table 4.3 were generated by RELAP5/Mod3.4 simulation (see Section 3.1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$- operating temperature at crack location</td>
<td>610 K</td>
</tr>
<tr>
<td></td>
<td>(400 K$\leq T \leq$650 K)</td>
</tr>
<tr>
<td>$\sigma$- explicit stress factor</td>
<td>106 MPa</td>
</tr>
<tr>
<td>$A$- fitting parameter</td>
<td>2.524 $\times 10^5$</td>
</tr>
<tr>
<td>$\alpha$- fitting constant for crack growth amplitude – lognormal distribution</td>
<td>1.5 x $10^{-12}$</td>
</tr>
<tr>
<td>$Q$-crack initiation activation energy</td>
<td>130 kJ/mol</td>
</tr>
<tr>
<td>$Q_G$-thermal activation energy for crack growth</td>
<td>220 kJ/mol (220-230 kJ/mol)</td>
</tr>
</tbody>
</table>
Figure 4.4. Comparison of the state transition model results: (a) semi-Markov approach using [2] data, (b) semi-Markov approach using RELAP5 temperature/pressure data

Figure 4.4 shows the results. The rupture probability in Figure 4.4(b) is lower than in Figure 4.4(a) since the micro crack initiation rate obtained with Table 4.3 data is
smaller. Figure 23(a) assumes $\tau=4$ years whereas $\tau$ determined from Table 4.3 data is 150.6 years, leading to a much smaller $\phi_1$ (see Eq.(4.3)) and hence much slower micro crack initiation (see Figure 4.2). Also, using Table 4.3 data the crack growth rate $\dot{a}_M$ is calculated as 6.94 $mm/yr$ instead of 9.46$mm/yr$ assumed in Table 4.3.

Therefore $\phi_2, \phi_3$ stay closer to zero for longer period (see Eqs. 4.4 and 4.5, respectively) and hence initial transitions to both the circumferential and radial macro crack states are being delayed.

4.1.7 Sensitivity of Transition Rates to Uncertainties

A literature survey indicates that weld residual stress $\sigma$ in Eq.(3.2) is one of the major drivers to SCC. In that respect the uncertainty in $\sigma$ must be represented for accurate predictions of subcritical crack growth [29]. Also, the results reported in Section 4.1.6 indicate that temperature $T$ is an important factor affecting both the scale parameter $\tau$ in Eq.(4.3) and crack growth rate $\dot{a}_M$ in Eq.(3). Possible uncertainties in $\sigma$ and $T$ were quantified using the normal distributions given in Tables 4.4 and 4.5 for xLPR data [29].
Table 4.4 PWSCC initiation Eq. (4.3) parameters and values used in different studies

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
<th>xLPR [27]</th>
<th>Unwin[28]</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$</td>
<td>Operating temperature at crack location</td>
<td>K</td>
<td>Type</td>
<td>Normal</td>
<td>617</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>617.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. Deviation</td>
<td>0.0882</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deterministic</td>
<td>618</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>Weibull shape parameter</td>
<td>None</td>
<td></td>
<td>3</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distribution Type</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>3.915</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mode</td>
<td>4.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>4.785</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Applied tensile stress factor</td>
<td>MPa</td>
<td></td>
<td>Normal</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>300.3</td>
<td>300.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. Deviation</td>
<td>110</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deterministic</td>
<td>150</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>Stress exponent factor</td>
<td>None</td>
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<td>-4</td>
<td></td>
<td>-7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distribution Type</td>
<td>Triangular</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>-7.7</td>
<td></td>
<td></td>
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<td></td>
<td>Mode</td>
<td>-7</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>-6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A$</td>
<td>Fitting parameter</td>
<td>None</td>
<td></td>
<td>0.04</td>
<td></td>
<td>2.524E5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.524E5</td>
<td>2.524E5</td>
</tr>
<tr>
<td>$Q_1$</td>
<td>Crack initiation activation energy</td>
<td>kJ/mole</td>
<td></td>
<td>182.9</td>
<td></td>
<td>130</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distribution Type</td>
<td>Triangular</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>116.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mode</td>
<td>129.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>142.67</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 4.4, it can be seen that the scatter in crack-initiation times with a triangular distribution is simulated to characterize the uncertainty in the shape parameter of the Weibull function.
Table 4.5 Definition of the Inputs of MRP-115 Model (3.2) and Values used in Different Studies

<table>
<thead>
<tr>
<th>Sym-bol</th>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
<th>Unwin[30]</th>
<th>Base Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>Stress intensity exponent</td>
<td>None</td>
<td>1.6</td>
<td>Distribution Type</td>
<td>Triangular 1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Minimum</td>
<td>1.44</td>
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<td></td>
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<td></td>
<td>Mode</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Maximum</td>
<td>1.76</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Fitting constant for crack growth amplitude</td>
<td>(m/s) (MPa-m$^{0.5}$)$^{1/6}$</td>
<td>$9.82 \times 10^{-13}$</td>
<td>Distribution Type</td>
<td>Normal 1.5 x $10^{-12}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Threshold</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>$8 \times 10^{-13}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Std. Deviation</td>
<td>-</td>
</tr>
<tr>
<td>$Q_G$</td>
<td>Thermal activation energy for crack growth</td>
<td>kJ/mole</td>
<td>Distribution Type</td>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. Deviation</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deterministic</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>$f_{alloy}$</td>
<td>Common factor applied to all specimens fabricated from the same weld to account for weld heat processing and for weld fabrication</td>
<td>None</td>
<td>Distribution Type</td>
<td>Lognormal 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>0.9989</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. Deviation</td>
<td>1.835</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deterministic</td>
<td>1.075</td>
<td></td>
</tr>
<tr>
<td>$f_{orient}$</td>
<td>“within weld” factor accounts for specimens fabricated from the same weld</td>
<td>None</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The uncertainty in $\sigma$ and $T$ were propagated through the model using LHS. The LHS sampling is performed independently for each parameter $\sigma$ and $T$ for ranges $150 \leq \sigma \leq 551$ MPa [28] and $400 \leq T \leq 610$ K [31], respectively. Each range was partitioned into 100 intervals. Values from each interval were sampled randomly without replacement. The LHS matrix generated consists of 100 rows (realizations) and of 2
columns corresponding to the number of varied parameters. Figure 4.5 provides an
illustration of the process but with only 5 realizations. Each pair of parameter values
(each row of the LHS matrix in Fig. 6.3) are used to generate 100 solutions for the model.

\[
T \sim \text{Normal}(344.9, 0.0882)
\]

\[
\sigma \sim \text{Normal}(300.3, 110)
\]

Figure 4.5. Schematic Illustration of the Uncertainty Analysis Performed with LHS for
Sampling Size 5 and for Two Parameters: Temperature (T) and Residual Weld Stress (\(\sigma\))

Figure 4.6 graphically represents the structure of Agingso_LHS.m which is a
MATLAB code written to implement the LHS method. Listing of Agingso_LHS.m as
well as the other modules in Fig.4.6, are given in Appendix A.
Figure 4.7 shows the results for the leak state probability \( L \) and rupture state probability of \( R \) as a function of time \( t \) over 80 years. The results show that there is initially a 4-5 order of magnitude spread in both \( L(t) \) and \( R(t) \) which becomes smaller for \( L(t) \) for large \( t \) since the contribution to \( L(t) \) is only from radial macro cracks but the contribution to \( R(t) \) is from both radial and circumferential macro cracks. Also note that \( R(t) \) reaches steady state values with increasing time due to repair represented by \( \omega_1, \omega_2 \) and \( \omega_3 \) in Eq.(4.2). The large spread in \( L(t) \) and \( R(t) \) is mainly due to the large standard deviation in \( \sigma \).
Figure 4.7. Rupture and Leak State Probabilities during 80 years in case of 100 realizations of LHS for $T \sim \text{Normal}(344.9, 0.0882)$, $\sigma \sim \text{Normal}(300.3, 110)$

Figure 4.8 shows that the spread reduces significantly when the standard deviation in $\sigma$ is reduced from 110 MPa to 30 MPa.
Figure 4.8. Rupture and Leak State Probabilities during 80 years in case of 100 realizations of LHS for $T \sim \text{Normal} (344.9, 0.0882), \sigma \sim \text{Normal} (300.3, 30)$

This fact is further substantiated by Fig. 4.9 and 4.10 which show $L(t)$ and $R(t)$ with only $\sigma$ or $T$ varied. As expected, the spread is much larger when $T$ is fixed and $\sigma$ is varying (Fig.4.9) than the case where $\sigma$ is fixed and $T$ is varying (Fig.4.10). Note that Fig. 4.10 shows a greater spread for $L(t)$ after 10 years since temperature is an explicit input both for crack initiation and crack growth rate (see Eqs.(3.1) and (3.3)) whereas stress only affects crack growth rate (see Eq.(3.3)).
Figure 4.9. Rupture and Leak State Probabilities during 80 years in case of 100 realizations of LHS for $T=618\,\text{K}$, $\sigma \sim \text{Normal}(300.3, 110)$
Regarding the confidence levels on the distributions obtained for \( L(t) \) and \( R(t) \), as a function of time, the estimation was accomplished by computing the 95\textsuperscript{th} and 5\textsuperscript{th} percentiles of the distribution on the probability of leak \( L(t) \) and rupture \( R(t) \) at each time point. Figure 4.11 shows the distribution of the raw data (gray), as well as the 95\textsuperscript{th} percentile (red) and 5\textsuperscript{th} percentile (blue) confidence levels for \( L(t) \) and \( R(t) \) with \( T \sim \text{Normal}(617.9, 0.0882) \) [30] and \( \sigma \sim \text{Normal}(300.3, 110) \) [29]. The 95\textsuperscript{th} percentile increases from 0 to a stable 0.01 around 10 years, which means that at least 5\% of the
results indicate 0.01 probability of rupture beyond 10 years. The magnitude and uncertainty on $L(t)$ decreases with time as expected, since the leak is either repaired or leads to rupture.

Figure 4.11. Leak (L) and Rupture (R) State Probabilities during 80 years in case of 100 realizations of LHS for $T \sim \text{Normal} (344.9, 0.0882)$, $\sigma \sim \text{Normal} (300.3, 110)$. The red line indicates 95th and blue line indicates 5th percentile.
Figures 4.12 and 4.13 examine trends in the relative importance of $T$ vs. $\sigma$ for rupture at various time points and indicate that there is a very complex relationship among stress, temperature and rupture probability $R$. 

Figure 4.12. Rupture State Probabilities, Stress and Temperature Realizations at $t=10$, 40 and 80 years in case of 100 realizations of LHS for $T \sim \text{Normal} (617.9, 0.0882), \sigma \sim \text{Normal} (300.3, 110)$
Figure 4.13. Rupture State Probabilities, Stress and Temperature Realizations at $t=40$ and 60 years in case of 100 realizations of LHS for $T \sim \text{Normal} (617.9, 0.0882)$, $\sigma \sim \text{Normal} (300.3, 110)$

Since it is very difficult to determine the trends from Figs. 4.12 and 4.13, it was decided to develop a response surface from the data points. Figure 4.14 shows the impact of weld residual stress and temperature variations on the rupture probability at $t=40$ years in case of 100 realizations. In Fig. 4.14, the response surface clearly shows the consistency of the results and the greater sensitivity to the uncertainty in stress than to the uncertainty in temperature. The fitting was done by using the method of least squares and Eq. (4.11). Coefficients of Eq. (4.11) are listed in Table 4.5 and statistics goodness-of-fit data are summarized in Table 4.6.
\[ f(T, \sigma) = p_{00} + p_{10}T + p_{01}\sigma + p_{20}T^2 + p_{11}T\sigma + p_{02}\sigma^2 \]  \quad (4.11)

Table 4.6 Fitting equation coefficients with 95% confidence bounds

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>95% confidence bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p_{00} = -24.39)</td>
<td>-363.2, 314.5</td>
</tr>
<tr>
<td>(p_{10} = -7.953 \times 10^{-5})</td>
<td>-0.003004, 0.002845</td>
</tr>
<tr>
<td>(p_{01} = 0.07899)</td>
<td>-1.017, 1.175</td>
</tr>
<tr>
<td>(p_{20} = 3.302 \times 10^{-7})</td>
<td>3.228 \times 10^{-7}, 3.375 \times 10^{-7}\</td>
</tr>
<tr>
<td>(p_{11} = -7.747 \times 10^{-8})</td>
<td>-4.81 \times 10^{-6}, 4.655 \times 10^{-6}\</td>
</tr>
<tr>
<td>(p_{02} = -6.394 \times 10^{-5})</td>
<td>-9.51 \times 10^{-5}, 8.231 \times 10^{-4}\</td>
</tr>
</tbody>
</table>

Table 4.7 Statistic goodness-of-fit data

<table>
<thead>
<tr>
<th>Goodness of fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSE: (2.457 \times 10^{-7})</td>
</tr>
<tr>
<td>R-square: 0.9995</td>
</tr>
<tr>
<td>Adjusted R-square: 0.9995</td>
</tr>
<tr>
<td>RMSE: (5.113 \times 10^{-5})</td>
</tr>
</tbody>
</table>

An issue that has been often brought up in uncertainty analyses is whether there is need to distinguish between epistemic and aleatory uncertainties. Whether in theory there is a fundamental separable difference between these two types of uncertainty has been hotly debated. To the decision-maker, however, there is a difference in how the results are displayed and interpreted depending on how they are classified.
Figure 4.14. Rupture probability change as a function of temperature \((T)\) and weld stress \((\sigma)\) at 40 years.

When both aleatory and epistemic uncertainties are present in the model, it has been suggested by some that adequate treatment of both types of uncertainties would
require a two-step simulation. As illustrated in the xLPR report [29] one way to do that is to have the inner loop and outer loop address the aleatory uncertainties and the epistemic uncertainties, respectively. In the outer loop, parameter values are sampled from epistemic uncertainty distributions and passed on to the inner loop. For each sample in the outer loop, LHS draws from aleatory uncertainty distributions are performed in the inner loop over the time-frame of interest accounting for the aleatory uncertainty. From these results an average rupture probability can be calculated. From the outer loop analysis, it is therefore possible to obtain a distribution of the average rupture probabilities. This distribution provides measures of the uncertainty in rupture probability that could be reduced by further experimentation or model development. As LHS is also used to generate epistemic uncertainty, the simple arithmetic mean of the rupture probability over epistemic uncertainty yields the expected value \( \langle R \rangle \) of the rupture probability. i.e.,

\[
\langle R \rangle = \frac{1}{N} \sum_{n=1}^{N} \left( \frac{1}{M} \sum_{m=1}^{M} R_{mn} \right)
\]

(4.12)

where \( M \) is the number of aleatory draws, \( N \) is the number of epistemic draws and \( R_{mn} \) are the rupture probabilities calculated from the state transition model for each draw combination. In general, it is expected that the overall average value will be the same regardless of whether the sampling is performed in a single-step or a two-step process. However, to test whether the overall average is affected by the sampling approach, a comparison was made of the two-step LHS versus single step LHS. Uncertainty in \( T \) and \( \sigma \) were characterized using normal PDFs: \( T \sim \text{Normal} (617.9, 0.0882) \), \( \sigma \sim \text{Normal} (300.3, \ldots) \).
In the two-step LHS, the uncertainty for $T$ and $\sigma$ were characterized as epistemic and aleatory, respectively, instead of both as epistemic.

Equation (4.12) was implemented with $N=100$ and $M=100$ resulting in a total of 10,000 realizations. The single-step LHS realization was also performed for 10,000 draws to obtain $\langle R \rangle$ in Eq.(4.12). Figure 4.15 shows the comparison of single step and two-step LHS sampling processes and Fig. 4.16 shows $\langle R \rangle$ as a function of time for the single-step and two-step LHS. The temperature draws $T_N$ in Fig. 1 are for every 2 years. As can be seen in Fig. 6.13, difference between two methods is extremely small (on the order of $10^{-5}$) as expected.

![Single-Step LHS](image1)

![Two-Step LHS](image2)

Figure 4.15. Illustration of single step and two-step LHS comparisons

Using a multi-state physics based model to describe the PWSCC, uncertainties in the input data for crack initiation and crack growth are represented by probability distributions. LHS is used to generate observations from the distributions governing $T$ and $\sigma$ with a two-step approach that distinguishes between aleatory and epistemic uncertainties.
Comparison of the results to a single-step quantification process indicates that the differences between one-step and two-step approach are negligible with regard to the mean rupture probability (on the order of $10^{-5}$). However, the separation into sources of aleatory and epistemic uncertainty could enable the decision-maker to determine the potential value of activities to reduce the epistemic uncertainty, such as by the performance of research. Indeed, for this example, nearly all of the uncertainty shown in Fig. 4.11 arises from the “epistemic” uncertainty associated with the weld residual stress $\sigma$. 

Figure 4.16. Comparison of single-step and two-step LHS results
4.2 Case 2: Steam Generator Tube Degradation

Alloy 600 components such as steam generator tubes, pressurizer instrument penetrations and heater sleeves, control rod drive mechanisms (CRDM) nozzles, and hot leg penetrations have experienced PWSCC. In PWRs, SG tube reliability is critical since SG tubes constitute more than half of the primary system pressure boundary and these tubes are life-limiting components of SGs. The integrity of tubing has been a significant aging problem resulting from several degradation mechanisms.

Over the years, research for preserving steam generator tube integrity has shifted from the study of primarily wastage (wall-thinning) and denting up (until 1980s) to the study of SCC mechanism (into the mid-1990s). Currently, the most commonly experienced form of failure is intergranular attack/SCC [2].

This section presents an implementation of the semi-Markov approach for life assessment of SG tubes, which provides a mechanistic approach for quantifying the probability of SGTR for PRAs. SG tube properties and assumptions in the aging model implementations are described in Section 4.2.1, surveillance and detection probability consideration in the aging model is discussed in Section 4.2.2. PWSCC is selected as the degradation mechanism for illustration. The degradation models are given in Section 3.2 and applications described in this section. In Section 4.2.3, SG tube degradation state probabilities are calculated in case of PWSCC via multi-state aging model with the sojourn time approach.
4.2.1 Component Description and Model Assumptions

Mill-annealed Alloy 600 tubing material is selected for the SGTR analysis since it is most susceptible to PWSCC. Also, only axially oriented cracks were simulated, considering that most of the PWSCC cracks in the roll transition region are axial [78]. Failure of a tube is defined as the removal of the tube from service by plugging or sleeving. Common degradation mechanisms (outer diameter stress corrosion cracking (ODSCC) and intergranular attack (IGA)) in different tube locations are shown in Fig. 4.17.

Figure 4.17. Schematic of SG tube degradation mechanisms [79]
The input parameters assumed in this study for SG geometry are the following:

- Number of tubes = 3330
- Wall Thickness = 1.27 mm
- Tube Outside Diameter = 22.22 mm

Additionally, in the crack growth model tubes are assumed to have only one dominant crack and crack coalescence is neglected. Radial penetration of a crack through the SG tube wall has not been considered in this study and also sleeving as maintenance action is neglected.

4.2.2 Probability of Detection (POD)

The investigation of the MSLB induced rupture of degraded SG tubes in this study has indicated the importance of a realistic characterization of failure to detect critical flaws in the development of a condition-based risk assessment [66]. One aspect of detection failure is associated with the probability of failure to detect a flaw as a function of flaw size given that surveillance has occurred. Another aspect relates to the statistical probability that flaws will fail to be detected because they are missed because of the random aspect of the sampling scheme.

Based on the degradation methodology developed by Lewandowski [15], the Scott equation [64] is used to model crack growth rates in SG tubes (as also described in Section 3.2). To better reflect varying growth rates found in actual SG tubes, cracks initiated in each cycle are divided into 20 cohorts that represent 20 crack growth amplitudes. The crack growth amplitudes are estimated using a statistical fit of previous
plant data and are used as multipliers in Scott’s equations. From the results of this analysis, it is possible to determine which cohorts are vulnerable and the number of tubes vulnerable during each operating cycle.

Using this model, the results of the analysis can be applied to surveillance programs at NPPs to determine the likelihood of identifying vulnerable tubes. The original sampling algorithm used by an example nuclear power plant was based on Regulatory Guide 1.83 [16] and its subsequent revisions. This sampling algorithm randomly assigns SG tubes to specific cohorts, where cracks are introduced and grow according to the Lewandowski model. At the end of each operating cycle, a single steam generator is inspected and 3% of the total SG tubes are inspected in this SG, where tubes are selected on a semi-random basis, depending on results from previous inspection.

Steam generator tubes are then classified into one of three groups: tubes that are not degraded or defective, tubes that are degraded, and tubes that are defective. Tubes that are not degraded or defective have detectable wall penetrations less than 20% of through wall thickness, and no action is required when these tubes are found. Degraded tubes exhibit detectable wall penetrations between 20-40% through wall thickness. If a degraded tube is detected, it is required to be re-evaluated during the next inspection. Defective tubes are tubes that exhibit greater than 40% through wall thickness. Defective tubes exceed the plugging limit and will thus be plugged upon being detected. Three through wall (TW) crack depth conditions important for SG surveillance:

- Degraded (>20% & <40% TW),
- Defective (>40% & <100% TW),
- 100% TW (tube wall thickness is 1.27 mm).
Degraded tubes sampled again during the next refueling outage.

The results of each inspection are classified into three categories, each with a corresponding action that is required. The most severe of these categories occurs when more than 10% of the total tubes inspected are degraded tubes, or more than 1% of the inspected tubes are defective. If it is the first inspection, then all tubes in that SG are inspected, and additional tubes from the other SGs are also randomly tested. If the results of this additional inspection produce the same category of results, then all tubes in all SGs are inspected. POD curve for Eddy Current reliability results from the SG mock-up analysis round robin used in the Lewandowski model is adopted in the present study to modify plugging probability depends on crack depth evaluated in each time interval (See Section 4.2.3).

![Figure 4.18. POD curve from [80]](image)

Figure 4.18. POD curve from [80]
4.2.3 Physics-based Multi-State Aging Model

The aging model under current consideration in this study is a state transition model for crack initiation and growth adapted from [5] and consisting of four first order differential equations with system history dependent transition rates. Fig. 4.19 shows the state transition diagram. State evolutions are described through

\[
\frac{dS}{dt} = -\phi_1 S \tag{4.12}
\]
\[
\frac{dM}{dt} = \phi_1 S - \phi_2 M - \phi_3 M \tag{4.13}
\]
\[
\frac{dR}{dt} = \phi_2 M \tag{4.14}
\]
\[
\frac{dP}{dt} = \phi_3 M \tag{4.15}
\]

where \(S(t), M(t), R(t), P(t)\) denote the probability of being in the states shown in Fig.4.17 until time \(t\). \(R(t)\) and \(P(t)\) are absorbing states and all transition rates are time dependent.

Figure 4.19. State Transition Model for SGTR Process in case of PWSCC

The transition rates \(\phi_1, \phi_2\) and \(\phi_3\) are modified versions of the transition rates \(\phi_i(t)\) \((i=1,2,3)\) presented in [5], i.e.
\[ \phi_1(t) = \left( \frac{b}{\eta} \right) \left( \frac{t}{\eta} \right)^{b-1} \] (4.16)

\[ \phi_2(t) = \begin{cases} 
0 & \text{if } u \leq \frac{a_A}{\alpha M} \\
\frac{a_A P_R}{u a_A P_R + u^2 \alpha M P_P} & \text{if } u > \frac{a_A}{\alpha M} \text{ and } u \leq \frac{a_P}{\alpha M} \\
\frac{a_A P_R}{u a_A P_R + u a_P P_P} & \text{if } u > \frac{a_A}{\alpha M} \text{ and } u > \frac{a_P}{\alpha M} 
\end{cases} \] (4.17)

\[ \phi_3(t) = \begin{cases} 
0 & \text{if } u \leq \frac{a_P}{\alpha M} \\
\frac{a_P P_P}{u a_A P_R + u^2 \alpha M P_P} & \text{if } u > \frac{a_P}{\alpha M} \text{ and } u \leq \frac{a_R}{\alpha M} \\
\frac{a_P P_P}{u a_A P_R + u a_P P_P} & \text{if } u > \frac{a_P}{\alpha M} \text{ and } u > \frac{a_R}{\alpha M} 
\end{cases} \] (4.18)

The parameter \( \eta \) in Eq. (4.16) is a Weibull scale parameter (4.35 years) and \( b \) is a shape parameter (2.374) [81]. The parameter \( \dot{a}_M \) is the maximum crack growth rate (m/s (or in/yr)) and is estimated using

In Eqs. (4.17) - (4.18), \( u \) is a time after axial-crack formation, \( a_A \) is a threshold axial-crack length (0.1 mm), and \( a_P \) is the threshold length for plugging.

In this study, \( a_P \) is 40 percent of the tube wall thickness since traditional plugging criteria is based on a minimum wall thickness requirement. Typically, the tube wall thickness may be allowed to degrade up to 40 percent of the initial wall thickness before the tube is plugged [82] (State \( P \) in Fig. 4.19).

The parameter \( P_P \) is the probability for crack detection and plugging if the crack length is bigger than \( a_P \). It is assumed that the surveillance program for crack detection is
effective with an initial detection rate of 98 percent ($P_P$) [21]. $P_R$ is the probability that the crack is not detected or detected but not repaired because the crack length is less than $a_P$ and the crack continues to grow towards rupture.

The transition rates $\phi_2(t)$ and $\phi_3(t)$ depend on the residence time $u$ of the hardware in State $M$ (see Fig. 4.19). The concept of sojourn times is used to account for the state residence time (see Section 4.1.4 and also [83]), i.e.

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

for $(T_{k-1} \leq t \leq T_k; k = 1, \cdots, K)$ \hspace{1cm} (4.19)

where $\tau_{n,k}(t)$ is sojourn time of state $n$ and for $kth$ time interval, $x_n(t)$ is the probability of given in State $n$ until time $t$, and $\phi_{nm}(\tau_{m,k-1})$ is the transition rate from State $n$ to State $m$ in $T_{k-2} \leq t \leq T_{k-1}$ as a function of sojourn time.

Time span for the study was selected as 60 years and time interval for each cycle is assumed as 1 year. The results are shown in Fig. 4.20. The steady state SGTR frequency is of the order $10^{-3}$/year. As of 1996, the frequency of ruptures attributable to corrosion related mechanisms at Westinghouse and Combustion Engineering plants with Alloy 600 tubing has been shown to be $5.4 \times 10^{-3}$/year [82]. The difference of our result from the observed data can be partly explained in terms of model assumptions, such as
effects of local temperature, pressure, neglecting circumferential cracks and crack coalescence, and input uncertainties [65] [81].

![Figure 4.20. Semi-Markov approach results for the preliminary state transition model.](image)

The results of this study are retrospective. Most plants have replaced their steam generator tubes with Alloy 690 tubing, which is expected to be much more resistant to SCC.

4.3 Introduction of the Aging GUI

A graphical user interface (GUI) for standalone implementations of the semi Markov aging model (Section 4.1.4), as well as interfacing with a quasi-steady state condition PRA while the plant is at power during a fuel cycle has been developed in MATLAB. An example input screen with corresponding results is shown in Fig.4.21. On left hand side
of the main window there are two frames. *Model Parameters* frame lists the controls for loading and managing input data for crack initiation and crack growth models. *Sampling Parameters* lists the number of realizations for epistemic and aleatory uncertainty via a two-loop uncertainty analysis using LHS. On the left bottom, there are *Result* and *Help* buttons. *Help* button provides information on the model and mechanism details and how the user can modify this model. For instance to build a 4-state semi-Markov model instead of a 6-state model to simulate stress corrosion cracking for a steam generator tube rupture scenario described in Section 4.2.

*Result* button operates as a run command and calls all required functions to produce the sojourn time approach results (state probabilities vs time) and results of the two-loop uncertainty analysis on the right hand side of the window. The uncertainty analysis results are shown with mean value for leakage probability $L(t)$ (red line) and rupture probability $R(t)$ (blue line) as function of time, as well as the spread in $L(t)$ and $R(t)$ (gray bands around the mean values).
For the incorporation of maintenance activities into the paradigm initial conditions, surveillance data, maintenance and repair actions as they affect the Plant State are also updated at each time \( t=k \) in Fig. 3.1. If the observed Plant State is not consistent with the aging progression model predictions, Component Aging Progression Model is retuned. As also stated in Section 2, 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 to decide if the surveillance program is adequate or if there is need to update the surveillance program. Finally, event sequences involving repair/replacement actions need to be integrated into the PRA in a manner that does not lead to non-coherence (see Chapter 5).
This chapter illustrates the mechanics of incorporating aging analysis into the PRA. Three aspects of this incorporation discussed in detail. First aspect relates to using age-based reliability of passive SSCs as initiating events of interest to the existing PRA model (Section 5.1). Second aspect is the incorporation of the model results into a dynamic event tree (DET) to reflect system dynamics consistently with the existing PRA (Section 5.2). Third one is coupling of aging model, introduced in Section 5.3, into the RELAP-7/RAVEN simulation environment to have a more mechanized implementation of the methodology.

5.1 Incorporation into Traditional PRA

Consideration of aging effects could be reflected in a traditional PRA model as the following:

- **New Initiating Events (Approach 1)**. The failures of passive components are taken into account in addressing initiating event frequencies. The possibility exists to have “new” initiators become important that may have been previously excluded due to low likelihood. Examples could include pipe break or flooding scenarios that were thought to be unlikely.

- **New Basic Events (Approach 2)**: As a function of a physical aging model (e.g., corrosion, fatigue, stress corrosion cracking), component failure rates can be affected.
Also, the possibility of conditional aging-related failures needs to be investigated (e.g., aged component failure given an initiating event which results from the failure of another component subject to a different aging mechanism). The fault tree logic should be changed to represent new basic events (e.g., passive component failures) important to scope of the research.

Aging can also affect transients in the PRA model due to its effect on the SSC failure probabilities. Additionally, cutsets that were truncated from the original PRA because of their low probabilities may now need to be restored. As a last note, the accident sequence events will need to be reviewed to ensure that aging affects will not change the attributes of the accident sequence such as high pressure injection system availability changing due to aging which leads to feed and bleed system needing to be activated.

In order to import the aging model results into SAPHIRE, the results need to be described in the event tree (ET) or fault tree (FT) form which is the typical SAPHIRE database. An event sequence resulting from the aging model can be described as a series of AND events (cutsets) for which each combination of events are input to OR Gate to Top Event since one of the sequences is enough to cause system failure.

The work detailed in this section has been performed using SAPHIRE, Version 8.0.9 [12]. The code allows the user to enter initiating events, such as a LOCA, and then model the response of the plant (or other facility or system) to these events, calculating a core damage frequency using the ET/FT method.
5.1.1 *Analysis Results and Their Incorporation into PRA*

Aging issues such as erosion and corrosion of primary piping may play an important role in impact to LOCA frequencies as discussed in Section 2.7.1.

In the first approach, we have chosen an ET representation of the accident sequences. ET techniques allow the identification of all the different chains of accident sequences deriving from an initiating event. The initiating event is an event (e.g. equipment failure, transient) that can lead to the accident if no protective action is taken by safety systems. Each sequence of the ET represents a certain combination of events corresponding to the failure or to the success of safety systems. Therefore, ET provides a set of alternative consequences. An example of an event tree is shown in Fig. 5.1.

![Figure 5.1. Example of an Event Tree](image)

<table>
<thead>
<tr>
<th>Initiating Event</th>
<th>Safety System 1</th>
<th>Safety System 2</th>
<th>Safety System 3</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available</td>
<td>Available</td>
<td>Available</td>
<td>Available</td>
<td>Consequence A</td>
</tr>
<tr>
<td>Fails</td>
<td>Fails</td>
<td>Fails</td>
<td>Fails</td>
<td>Consequence B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Consequence C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Consequence D</td>
</tr>
</tbody>
</table>
The consequences in the case of Level 1 PRA of nuclear reactors are either core damage (CD) or no core damage (OK). These consequences are generally evaluated by thermal-hydraulic calculations carried out in a conservative way. For example, in determining “minimum safeguards” an analyst performs RELAP5 calculations using one emergency coolant pump, two coolant pumps and three coolant pumps to determine the number of pumps required to prevent core damage for a given size of LOCA. This choice of the event tree presentation might seem unsuitable to represent the aging process because it does not consider the dynamic aspects of the degradation progression including dynamic system interactions, thermal-hydraulic induced failure and operator actions in response to system dynamics. However, the overall reactor, including the safety systems and in particular the passive components, is modeled by the thermal-hydraulic code. Thus, the dynamic system interactions are taken into account by the thermal-hydraulic calculation itself, irrespective of whether component failure is the result of an aging mechanism.

So, for Approach 1, the event tree presentation seems an adequate and simple representation for the assessment of accident sequences, including the passive SSCs. The accident sequences are defined using an ET, taking into account the success or the failure of the components and of the physical process involved. Knowing the occurrence of each accident sequence frequency and considering that all the events are independent, the estimation of the core damage probability can be carried out by summing up the probabilities of each sequence leading to a core damage.
5.1.2 Case 1: Pressurizer Surge Line Pipe Weld Rupture

For Case 1, there is a monotonic increase in the probability of the Rupture state reaching an asymptote of about $10^{-6}$ as can be seen in Fig. 4.3.b (which is high, but again, our current quantification is intended primarily to demonstrate the feasibility of the methodology).

This frequency of rupture (FR) is used in both the reevaluation of the initiating event frequency and the system unavailability evaluation for the PRA. In the literature, the rupture frequency is generally calculated by using the Jeffrey’s method which accounts for different degradation mechanisms [36]. The Jeffrey’s method is based on the statistical assessment of a database of events that have occurred such as leaks and/or ruptures. The FR by the Jeffrey’s method is given as $FR = (n + 0.5) / T$, where $n$ is the number of ruptures and/or leaks and $T$ is the operation years.

The rupture rate, $R$, that is, associated with rupture For Case 1, defined as

$$ r = \frac{dR}{dt} (1 - R)^{-1}. $$

For $\tau = 4$ years [9], the rupture rate is approximately equal to the asymptotic value of $10^{-7}$/ weld yr occurs.

In Ref. [36], the frequency for medium pipe break LOCA was estimated to be $4 \times 10^{-5}$ (per plant per year), and for large pipe break LOCA was estimated to be $5 \times 10^{-6}$ (per plant per year). The frequency for the small pipe break LOCA was estimated to be $5 \times 10^{-4}$ (per plant per year) for both PWR and BWR plants. For PWR plants, the estimated frequency for STGR was about a factor of 10 greater, at $7 \times 10^{-3}$ (per plant per year).

According to [50], frequency of through-wall cracks in pressurizer surge nozzle weld was estimated to be $1.2 \times 10^{-6}$ failures per weld per year. Using a plant availability
of 80 percent, plant operation for 6 years would correspond to 4.8 years for the PFM calculations which predicts a cumulative probability of through-wall cracking about 0.50. In contrast, the operating data gives a cumulative probability of $6 \times (1.2 \times 10^{-6}) = 7.2 \times 10^{-6}$ per weld. To conclude, the semi-Markov analysis gives closer result, $10^{-7}$/ per weld year to operation experience comparison with the PFM calculations.

Figure 5.2. Fault Tree of the LOCAs in PRA

For LOCA categories, the frequencies were evaluated using data and information prior to 1987 due to their relatively low frequency and the corresponding sparseness of data. No pipe break LOCA events were found in the U.S. operating experience. For the
small pipe break LOCA frequency, the estimate from WASH-1400, Reactor Safety Study, was updated using U.S. reactor experience. For medium and large pipe break LOCAs, frequency estimates were calculated by using the frequency of leaks or through-wall cracks that have occurred which challenge the piping integrity. Further, conservative estimates were used for the probability of break given a leak (based on a technical review of information on fracture mechanics, data on high energy pipe failures and cracks, and assessment of pipe break frequencies estimated by others since WASH-1400). The pipe-break LOCA frequencies (per critical year) estimated from the experience are:

Being based on reported operational events, the theoretical estimates are relatively good for small leaks, which have little potential to contribute to core damage. However, large pipe ruptures estimates are subject to much larger uncertainties.

Pressurizer failure is typically an accident, which is comparable to a medium or large LOCA. In the case of a pressurizer failure, the surge line (typically 200 mm) limits the flow rate. Rupture of the pressurizer would actually cause a simultaneous leak from a cold leg and a hot leg and therefore complicates the accident mitigation [84]

Steam generator tube ruptures (SGTR) have been a major concern for the NRC because they have led to non-negligible release of noble gases and iodine to the environment, although the associated human health related effects have been minor. From a PRA viewpoint, SGTR events in combination with other system failures can have a significant contribution to risk because of the potential for severe core damage in combination with a route to bypass the containment. The steam generator tube rupture frequencies are normally separate from other passive system failures in PRAs because
they have occurred relatively frequently and there is thus a database for estimating their frequency.

A challenge with the semi-Markov approach developed in Section 4.1.4 is the difficulty of integrating the results of the analysis into an existing PRA. The purpose of this section is to address these challenges by performing a comparison of the results obtained for a particular scenario on a real system by using traditional PRA analysis and a parallel analysis performed using a particular dynamic PRA.

5.2 Constructing DETs from Markov Models

DET analysis proved to be a powerful tool in modeling plant response in a physically consistent manner given an input probabilistic model and provided additional insight into the potential accident progression. The Markov transition matrix generated by the process described in Section 4.1.3 can be thought of as a process model describing the stochastic dynamic behavior of the finite-state system. We can therefore search the state space starting from a set of initial states to explore all possible paths to failure (scenarios) with associated probabilities and generate the DETs by the algorithm shown in Figure 5.3. The DETs can be integrated into PRA via SAPHIRE as described below.
The work detailed in this section has been performed using SAPHIRE, Version 8.0.9 [12]. When describing the dynamic model as FT, it is important that any dynamic information is retained in the FT model using tags, such as time tags [85]. This in turn requires the dynamic information to be discretized. The time duration of the analysis is subdivided into selected time intervals as explained in (Section 3.1). Each event may then be tagged with the time step in which it occurs.

Once the dynamic model has been described as a FT, it must then be written as properly formatted text file, readable by SAPHIRE by using MAR-D feature. MAR-D provides the means for loading and unloading PRA data from the IRRAS relational database. MAR-D uses a simple ASCII data format. This format allows interchange of data between PRAs performed with different types of software; data of PRAs performed by different codes can be converted into the data format appropriate for 101
IRRAS, and vice-versa. This file may have any name desired provided the file extension is “.fTL”. More detail on the incorporation process can be found in [86] [87].

5.3 Incorporation into the RAVEN/RELAP-7 Environment

For the illustration of the incorporation of aging model results into a dynamic PRA, the physics based semi-Markov model was coupled with the RELAP-7/RAVEN environment, using RELAP-7 to predict the physical conditions and RAVEN for the control logic) (See Fig. 5.5) [88].

In this figure, the RELAP-7 model of the system is shown in the upper left corner. The box illustrates the location of the weld between the surge line to the pressurizer and the hot leg. RELAP-7 is capable of modeling the long term temperature and pressure at
this location, including the cycling that occurs as the level in the pressurizer rises and falls during operation and during the shutdown and startup transients at refueling outages. It is also capable of analyzing the reactor coolant system behavior subsequent to rupture at the weld location. These data feed into the dynamic Markov analysis describing the state of stress corrosion cracking in the zone of the weld.

RAVEN (Reactor Analysis and Virtual control Environment) [89] 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 [90], as well as RELAP5-3D [60]. RAVEN/RELAP-7 combination is a candidate for a next generation system code (NGSC) environment.

The multi-state semi-Markov model will be an aging tool in the simulation environment in which input is a user-defined transition rate matrix and output is time dependent state probabilities.
If the analysis is addressing the aging of passive components for a specific degradation mechanism (such as FAC, SCC) the Markov model transition rates will be dependent on the state holding time as defined in [5]. Therefore the model becomes to semi-Markov model (inhomogeneous transition rates). To solve either Markov or semi-Markov model in the RELAP-7/RAVEN environment two different solution procedure will be available: i) a numerical solver of the ordinary differential equations (ODEs) (if model is semi-Markov then with sojourn time approach modification), and, ii) a MC solution (if the model is semi-Markov then sample also sojourn time). 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.

The methodology described above has been incorporated into the RELAP-7/RAVEN environment and the MATLAB program Agingso_LHS.m has been converted to C++ program for the incorporation process.

The MC procedure for the simulation environment is given in Section 4.1.5. The C++ version of Agingso_LHS.m is ready to couple with RELAP-7/RAVEN environment to implement overall methodology in a dynamic manner as described above illustrated in Fig. 5.6.

Figure 5.6. Aging Model and Coupling with the RAVEN/RELAP-7 Environment
Chapter 6: Conclusions and Recommendations for Future Work

Chapter 6 summarizes the research and results of the research described in this dissertation. Section 6.1 is an overview of the contribution of the research to the state-of-the-art. Section 6.2 discusses the limitations of the model. Section 6.3 suggests areas research that could be extended beyond those described in this dissertation.

6.1 Overall Methodology and Feasibility

Rather than rely on statistical service data to estimate for the failure rates associated with degradation, this dissertation investigates the development of physics of failure models for deriving these rates for selected components and degradation mechanisms. Since the incorporation of physics-based state transition models are found to violate Markov conditions (involving, for example, randomly distributed time-inhomogeneous transition rates), alternative methods for solving the transition model are explored and sojourn-time approach is applied.

The process, a semi-Markovian approach to address crack initiation and growth in system piping, is compatible with the anticipated NGSC structure. It can be also used to augment existing PRAs with regard to passive component failures using legacy codes. The benefits of the proposed approach are the following:
• Mechanistic treatment of degradation mechanisms rather than reliance on historical plant service data
• Simultaneous consideration of multiple mechanisms within a dynamic environment that accounts for uncertainties
• Ability to make PRAs more plant specific with the ability to support improvements in surveillance, maintenance and replacement strategies
• Ability to model thermal cycle/fatigue cycle over the analysis time frame
• Ability to model progression of degradation over the time frame
• Ability to include in the PRA surveillance with potential for component replacement or repair
• Ability to include in the PRA dynamic events stochastically, such as PTS, water hammer (due to condensation instability), earthquake loads, or accident loads
• Ability to consider epistemic and aleatory uncertainties within the same phenomenological and stochastic framework

Because of the LOCA-significant location, dissimilar weld materials, high susceptibility to stress corrosion cracking, and significant non-detection probability, the selected component for illustration was a PWR pressurizer surge line nozzle alloy 182/82 dissimilar butt weld. This component provided an excellent selection to investigate enhanced computational approaches to solve the Markov model ordinary differential equations (ODEs) as well as to explore the use of physics of failure models to enhance the capabilities of the current passive component reliability models used in PRAs. The
SGTR accident in case of PWSCC is also analyzed via sojourn time approach by using semi-Markov models. Both case analysis results show good comparison with the literature and the industry experience.

6.2 Technical Challenges /Limitations

The key technical challenges in implementing the new paradigm are the following:

- Inclusion of all potential passive components and their degradation mechanisms into a simulation environment would be prohibitive and impractical due to the vast number of candidate components (such as pipe segments, welds, and other containment barriers). In that respect, a screening methodology is needed to select components for inclusion. In Section 2.8, this challenge is addressed and a candidate screening methodology is briefly described but needs to be improved, such as by limiting passive SSCs and aging mechanisms to be considered for the accident scenarios of interest as described in Section 2.7.

- Component reliability models are generally parametric in nature, relying on plant service data as the basis for quantification. However, the physics-based modeling environments being developed for RELAP-7, and the incorporation of the concept of diminishing safety margin with component age, indicate the need to develop reliability models of component aging that are based on the underlying physics of material degradation. The epistemic uncertainties associated with these models need to be accounted for. Within the scope of the proposed work, this challenge is partly
addressed by considering the physics-based models [5] for the LOCA scenario (see Section 2.7).

- The possibility to repair the components before failure may lead to non-coherence in the traditional ET/FT approach and complicates reliability quantification. Both the sojourn time approach described in Section 4 and dynamic PRA methodologies are used to deal with this challenge.

- Incorporation of passive failure modes into system failure models may introduce spatial dependences not previously identified, such as a pipe failure that floods an area in which a redundant system resides. Statistical dependencies among failure events can also be introduced due to model uncertainties. While not specifically addressed within the scope of the proposed work, dynamic PRA methodologies (which are part of the paradigm shown in Fig.3.1) are capable to address this challenge by coupling the stochastic SSC behavior with the simulation environment for accident evolution.

Additionally, more realistic weld residual stress models and transient definitions are needed to reduce uncertainties in crack growth Eqs.(3.3) and (3.4).

For Case 1, considering only circumferential and radial cracks may over-predict the rupture probabilities. The addition of axial cracks may reduce the rupture probabilities due to their higher leakage probabilities which would lead to early detection and subsequent repair/mitigation.
6.3 Future Work

Only PWSCC was selected for the illustration of the methodology for incorporating aging effects into PRA. Extension to more complicated application cases, e.g. including multiple competing degradation processes of components and systems, and interdependencies among the external factors need be taken into account. Common cause effect of aging should be considered since aging may lead to a large scale degradation of physical barriers and redundant components resulting in an increased probability of common cause failures.

In PRA applications the consequences of the pipe rupture are strongly influenced by the degree of severity of the pipe rupture. An improved model would be to have multiple rupture states so the competing aspects of these states could be determined in a more integrated fashion.

Seismic PRAs use best estimate or design values for material properties of SSCs without consideration of any aging effects. In order to develop a realistic evaluation of the seismic safety of a plant, the potential effects of age-related degradation on SSCs should be considered for the fragility curves.
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Appendix
Appendix A: The Matlab Graphical User Interface and Related Functions

Model_LHS.m
Main file. It defines the LHS matrix by calling the LHS scheme (LHS_call.m). It also calls the parameter file (Parameter_settings_LHS.m) and the ODE solver (ode15s) with the ODE model (ODE_LHS.m). It creates the outputs and stores everything in a Matlab workspace

Parameter_settings_LHS.m
It defines parameter baseline values and labels, time span of the simulations, initial conditions for the ODE model and output labels

LHS_call.m
It implements LHS scheme from normal and uniform distribution, no correlation. A logarithmic sampling scheme is implemented for uniform pdfs if a threshold (representing xmax/xmin) is given as an input of LHS_call. If no threshold is specified, a linear scale is applied. A common (base 10) logarithm is used, but the natural logarithm is given (commented out). An histogram of the pdf can be displayed as an output (commented out).

function varargout = untitled(varargin)
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFcn', untitled_OpeningFcn,
    ...
'gui_OutputFcn', @untitled_OutputFcn,
...
'gui_LayoutFcn', [], ...
'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before untitled is made visible.
function untitled_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version
% of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to untitled (see VARARGIN)

% Choose default command line output for untitled
handles.output = hObject;

sojournTimeApproach (handles);
lhs5(handles);
lhs4(handles);

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes untitled wait for user response (see UIRESUME)
% uiwait(handles.figure1);
% --- Outputs from this function are returned to the command line.
function varargout = untitled_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
sojournTimeApproach(handles);
lhs5(handles);
lhs4(handles);

function lhs4(handles)
cla(handles.axes4)
cla(handles.axes4,'reset')
axes(handles.axes4)

% Sample size N
runm=str2double(get(handles.edit5,'String'));
runn=str2double(get(handles.edit6,'String'));
% user defined model parameters

bo = str2double(get(handles.edit2,'String')) ;% weibull shape parameter
to = str2double(get(handles.edit3,'String')) ; % weibull scale parameter
ad = str2double(get(handles.edit7,'String')) ;% crack length threshold for radial crack
ac = str2double(get(handles.edit8,'String')) ;% crack length threshold for circumferential crack
al = str2double(get(handles.edit9,'String')) ; % crack length threshold for leakage
Pd = str2double(get(handles.edit10,'String')) ; % radial crack probability per year
Pc = str2double(get(handles.edit11,'String')) ;
% circumferential crack probability per year
w1 = str2double(get(handles.edit12,'String')) ; % repair transition rate from micro-crack per yr
w2 = str2double(get(handles.edit13,'String')) ; % repair transition rate from radial macro-crack per yr
w3 = str2double(get(handles.edit14,'String')) ; % repair transition rate from circum. macro-crack per yr
w4 = str2double(get(handles.edit15,'String')) ; % repair transition rate from leak per yr
q5 = str2double(get(handles.edit16,'String')) ; % leak to rupture transition rate per yr
q6 = str2double(get(handles.edit17,'String')) ; % macro-crack to rupture transition rate per yr

% aleatory part
%
% LHS MATRIX

Parameter_settings_LHS;

T_LHS = LHS_Call(600, 617.9, 650, 0.0882 ,runm,'norm');
sigma_LHS = LHS_Call(150, 300.3, 551, 30, runn,'norm');

% LHS MATRIX and PARAMETER LABELS
LHSmatrix = [T_LHS];
LHSmatrix = [sigma_LHS];

t0 = 1e-30;
tf = 80;
x0=[1 0 0 0 0 0 0 0 0]';
t1=0; t2=0; t3=0;
b=x0';
for z=1:runn
    z
    t0=1e-30;
    tf=80;
    x0=[1 0 0 0 0 0 0 0 0]';
    t1=0; t2=0; t3=0;
b=x0';
    for y=1:runm %run solution x times choosing different values
        f=@ODE_LHS;
        LHSmatrix(y);
        LHSmattrix(z);
        t1=0; t2=0; t3=0;
        m1=[];
        t0=1e-30;
        tf=80;
        x0=[1 0 0 0 0 0 0 0 0]';
        t1=0; t2=0; t3=0;
b=x0';
        for tf=1e-20:0.1:2
            [t, x] = ode15s(@(t, x) f(t, x, LHSmatrix, LHSmattrix, y, z, runm, runn, t1, t2, t3, bo, to, ad, ac, al, Pd, Pc, w1, w2, w3, w4, q5, q6), [t0 tf], x0, []);
            xTemp = x(end, 1:9);
            m1 = [m1; xTemp];
            x0 = xTemp';
            t1 = abs(x0(7, 1));
            t2 = abs(x0(8, 1));
            t3 = abs(x0(9, 1));
            t0 = tf;
        end
        m=[];
        m=[m; b];
t0=1.99;
for tf=2:2:80
    [t, x] = ode15s(@(t, x) f(t, x, LHSmatrix, LHSmattrix, y, z, runn, runm, t1, t2, t3, bo, to, ad, ac, al, Pd, Pc, w1, w2, w3, w4, q5, q6), [t0 tf], x0, []);
xTemp = x(end, 1:9);
m = [m; xTemp];
x0 = xTemp';
t1 = abs(x0(7, 1));
t2 = abs(x0(8, 1));
t3 = abs(x0(9, 1));
t0 = tf;
end
p = m;

L1_lhs(:, y) = m1(:, 5);
R1_lhs(:, y) = m1(:, 6);
L_lhs(:, y) = p(:, 5);
R_lhs(:, y) = p(:, 6);

end
R_ep(:, z) = sum(R_lhs, 2)/runm;
R_ep1(:, z) = sum(R1_lhs, 2)/runm;

%%
i = (0:2:80); whos

semilogy(handles.axes4, i, p(:, 6), 'color', [0.8 0.8 0.8]),
xlabel('t (year)'), ylabel('R(t)');
axis(handles.axes4, [0 tf 1.0E-10 1]);
grid on
set(gca, 'YTick', [10^-6, 10^-5, 10^-4, 10^-3, 10^-2, 10^-1])
hold on
semilogy(handles.axes4, 1e-20:0.1:2, m1(1:21, 6), 'color', [0.8 0.8 0.8]);
axis([0 tf 1.0E-10 1]);
grid on
set(gca, 'YTick', [10^-6, 10^-5, 10^-4, 10^-3, 10^-2, 10^-1])

end
R_f = sum(R_ep, 2)/runn;
R_f1 = sum(R_ep1, 2)/runn;
i = (0:2:80); whos
semilogy(handles.axes4,i,p(:,6),'b'), xlabel('t(year)'),
ylabel('R(t)');
hold on

function lhs5(handles)
cla(handles.axes5)
cla(handles.axes5,'reset')
axes(handles.axes5)

% Sample size N
runm=str2double(get(handles.edit5,'String'));
runn=str2double(get(handles.edit6,'String'));

%------------user defined model parameters------------------
bo=str2double(get(handles.edit2,'String')) ;%weibull shape parameter
to=str2double(get(handles.edit3,'String')) ; %weibull scale parameter
ad=str2double(get(handles.edit7,'String')) ;%crack length threshold for radial crack
ac=str2double(get(handles.edit8,'String')) ;%crack length threshold for circumferential crack
al=str2double(get(handles.edit9,'String')) ;%crack length threshold for leakage
Pd=str2double(get(handles.edit10,'String')) ;%radial crack probability per year
Pc=str2double(get(handles.edit11,'String')) ;%circumferential crack probability per year
w1=str2double(get(handles.edit12,'String')) ;%repair transition rate from micro-crack per yr
w2=str2double(get(handles.edit13,'String')) ;%repair transition rate from radial macro-crack per yr
w3=str2double(get(handles.edit14,'String')) ;%repair transition rate from circum. macro-crack per yr
w4=str2double(get(handles.edit15,'String')) ;%repair transition rate from leak per yr
q5=str2double(get(handles.edit16,'String')) ;%leak to rupture transition rate per yr
q6=str2double(get(handles.edit17,'String')); %macro-crack to rupture transition rate per yr

%aleatory part%
%
%% LHS MATRIX %
Parameter_settings_LHS;

T_LHS=LHS_Call(600, 617.9, 650, 0.0882 ,runm,'norm');
sigma_LHS=LHS_Call(150,300.3,551,30,runn,'norm');

%% LHS MATRIX and PARAMETER LABELS
LHSmatrix=[T_LHS];
LHSmattrix=[sigma_LHS];

t0=1e-30;
tf=80;
x0=[1 0 0 0 0 0 0 0 0]';
t1=0;t2=0;t3=0;
b=x0';
for z=1:runn
    z
    t0=1e-30;
tf=80;
x0=[1 0 0 0 0 0 0 0 0]';
t1=0;t2=0;t3=0;
b=x0';
    for y=1:runm %Run solution x times choosing different values
        f=@ODE_LHS;
        LHSmatrix(y);
        LHSmattrix(z);
        t1=0;t2=0;t3=0;
        m1=[];
        %m1=[m1;b];
        t0=1e-30;
tf=80;
x0=[1 0 0 0 0 0 0 0 0]';
t1=0;t2=0;t3=0;
b=x0';
        for tf=1e-20:0.1:2
            [t,x]=ode15s(@(t,x)f(t,x,LHSmatrix,LHSmattrix,y,z,runm,runn

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, t1, t2, t3, bo, to, ad, ac, al, Pd, Pc, w1, w2, w3, w4, q5, q6, [t0 tf], x0, []);
    xTemp = x(end, 1:9);
    m1 = [m1; xTemp];
    x0 = xTemp';
    t1 = abs(x0(7, 1));
    t2 = abs(x0(8, 1));
    t3 = abs(x0(9, 1));
    t0 = tf;
end
m = [];
m = [m; b];
t0 = 1.99;
for tf = 2:2:80
    % time(tf) = tf;
    [t, x] = ode15s(@(t, x) f(t, x, LHSmatrix, LHSmatrix, y, z, runn, runm,
                      t1, t2, t3, bo, to, ad, ac, al, Pd, Pc, w1, w2, w3, w4, q5, q6), [t0 tf], x0, []);
    % [rows, cols] = size(x);
    xTemp = x(end, 1:9);
    m = [m; xTemp];
    x0 = xTemp';
    t1 = abs(x0(7, 1));
    t2 = abs(x0(8, 1));
    t3 = abs(x0(9, 1));
    t0 = tf;
end
p = m;
L1_lhs(:, y) = m1(:, 5);
R1_lhs(:, y) = m1(:, 6);
L_lhs(:, y) = p(:, 5);
R_lhs(:, y) = p(:, 6);
end
R_ep(:, z) = sum(R_lhs, 2)/runm;
R_ep1(:, z) = sum(R1_lhs, 2)/runm;

%%
i = (0:2:80); whos
semilogy(handles.axes5,i,p(:,5),'color', [0.8, 0.8, 0.8]),
xlabel('t(year)'), ylabel('L(t)');
axis([0 tf 1.0E-10 1]);
grid on
set(gca,'YTick',[10^-6,10^-5,10^-4,10^-3,10^-2,10^-1])
hold on
semilogy(handles.axes5,1e-20:0.1:2,m1(1:21,5),'color',[0.8,0.8,0.8]);
axis([0 tf 1.0E-10 1]);
hold on

end
R_f=sum(R_ep,2)/runn;
R_f1=sum(R_ep1,2)/runn;

%% Save the workspace
save Model_LHS.mat;
%%
i=(0:2:80); whos
semilogy(handles.axes5,i,p(:,5),'r'), xlabel('t(year)'),
ylabel('L(t)');
hold on

title('
fontsize{16}LHS Results');
hold on

function sojournTimeApproach( handles)

cla(handles.axes6)
cla(handles.axes6,'reset')

axes(handles.axes6);

format long
t0=1e-15;
tp=0;
x0=[1 tp tp tp tp tp tp tp tp tp];
b=x0';

%----------user defined model parameters---------------------
-----------
bo=str2double(get(handles.edit2,'String'));%weibull shape parameter
to=str2double(get(handles.edit3,'String'));%weibull scale parameter

ad=str2double(get(handles.edit7,'String'));%crack length threshold for radial crack
ac=str2double(get(handles.edit8,'String'));%crack length threshold for circumferential crack
al=str2double(get(handles.edit9,'String'));%crack length threshold for leakage
Pd=str2double(get(handles.edit10,'String'));%radial crack probability per year
Pc=str2double(get(handles.edit11,'String'));%circumferential crack probability per year
w1=str2double(get(handles.edit12,'String'));%repair transition rate from micro-crack per yr
w2=str2double(get(handles.edit13,'String'));%repair transition rate from radial macro-crack per yr
w3=str2double(get(handles.edit14,'String'));%repair transition rate from circum. macro-crack per yr
w4=str2double(get(handles.edit15,'String'));%repair transition rate from leak per yr
q5=str2double(get(handles.edit16,'String'));%leak to rupture transition rate per yr
q6=str2double(get(handles.edit17,'String'));%macro-crack to rupture transition rate per yr

%---sojourn time approach-------------------------------

for tf=1e-20:0.1:2
    time(tf)=tf;
    [t,x]=ode45(@agingso,[t0 tf],x0,[],t1,t2,t3,bo,to,ad,ac,al,Pd,Pc,w1,w2,w3,w4,q5,q6);
    %[rows,cols]=size(x);
    xTemp=x(end,1:9);
    m1=[m1;xTemp];
    x0=xTemp';
    t1=abs(x0(7,1));
    t2=abs(x0(8,1));
end

m1=[];
m1=[m1;b];
for tf=1e-20:0.1:2
    time(tf)=tf;
    [t,x]=ode45(@agingso,[t0 tf],x0,[],t1,t2,t3,bo,to,ad,ac,al,Pd,Pc,w1,w2,w3,w4,q5,q6);
    %[rows,cols]=size(x);
    xTemp=x(end,1:9);
    m1=[m1;xTemp];
    x0=xTemp';
    t1=abs(x0(7,1));
    t2=abs(x0(8,1));
t3 = abs(x0(9,1));
end
m=[];
m=[m;b];
t0=1.99
for tf=2:2:80
    [t,x]=ode45(@agingso,[t0 tf],x0,[],t1,t2,t3,bo,to,ad,ac,a1,Pd,Pc,w1,w2,w3,w4,q5,q6);
    xTemp= x(end,1:9);
    m = [m;xTemp];
    x0 = xTemp';
    t1=abs(x0(7,1));
    t2=abs(x0(8,1));
    t3=abs(x0(9,1));
    t0 = tf;
end
p=m;

i=(0:2:80);whos
semilogy(handles.axes6,i,p(:,3),'b',i,p(:,4),'r',i,p(:,5),'g',i,p(:,6),'--b'), xlabel('t(year)'), ylabel('State Probabilities(t)');
hold on
semilogy(handles.axes6,i,p(:,2),'color',[0.5 0 0.5]);
hold on
semilogy(handles.axes6, i,p(:,1),'color',[1 .5 0]);
hold on
semilogy(handles.axes6, 1e-20:0.1:2,m1(1:21,3),'b',1e-20:0.1:2,m1(1:21,4),'r',1e-20:0.1:2,m1(1:21,5),'g',1e-20:0.1:2,m1(1:21,6),'--b'), xlabel('t(year)'), ylabel('State Probabilities(t)');
hold on
semilogy(handles.axes6,1e-20:0.1:2,m1(1:21,2),'color',[0.5 0 0.5]);
legend( 'Circumferential','Radial','Leak','Rupture','Micro-Crack','Initial','Location','southeast')

axis(handles.axes6,[0 tf 1.0E-10 1]);
grid on
set(gca,'YTick',[10^-6,10^-5,10^-4,10^-3,10^-2,10^-1])
function edit2_Callback(hObject, eventdata, handles)
    % hObject    handle to edit2 (see GCBO)
    % eventdata  reserved - to be defined in a future version
    % of MATLAB
    % handles    structure with handles and user data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit2 as text
    %         str2double(get(hObject,'String')) returns contents of edit2 as a double

    % --- Executes during object creation, after setting all properties.
    function edit2_CreateFcn(hObject, eventdata, handles)
        % hObject    handle to edit2 (see GCBO)
        % eventdata  reserved - to be defined in a future version
        % of MATLAB
        % handles    empty - handles not created until after all
        % CreateFcns called

        % Hint: edit controls usually have a white background on Windows.
        %       See ISPC and COMPUTER.
        if ispc && isequal(get(hObject,'BackgroundColor'),
            get(0,'defaultUicontrolBackgroundColor'))
            set(hObject,'BackgroundColor','white');
        end

    function edit3_Callback(hObject, eventdata, handles)
        % hObject    handle to edit3 (see GCBO)
        % eventdata  reserved - to be defined in a future version
        % of MATLAB
        % handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'String') returns contents of edit3 as text
%       str2double(get(hObject,'String')) returns contents of edit3 as a double

% --- Executes during object creation, after setting all properties.
function edit3_CreateFcn(hObject, eventdata, handles)
  hObject    handle to edit3 (see GCBO)
  eventdata  reserved - to be defined in a future version of MATLAB
  handles    empty - handles not created until after all CreateFcns called

  % Hint: edit controls usually have a white background on Windows.
  %       See ISPC and COMPUTER.
  if ispc && isequal(get(hObject,'BackgroundColor'),
                   get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
  end

function edit4_Callback(hObject, eventdata, handles)
  hObject    handle to edit4 (see GCBO)
  eventdata  reserved - to be defined in a future version of MATLAB
  handles    structure with handles and user data (see GUIDATA)

  % Hints: get(hObject,'String') returns contents of edit4 as text
  %       str2double(get(hObject,'String')) returns contents of edit4 as a double

  % --- Executes during object creation, after setting all properties.
  function edit4_CreateFcn(hObject, eventdata, handles)
  hObject    handle to edit4 (see GCBO)
function edit5_Callback(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit5 as text
%        str2double(get(hObject,'String')) returns contents of edit5 as a double

% --- Executes during object creation, after setting all properties.
function edit5_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit5 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
function edit6_Callback(hObject, eventdata, handles)
    % hObject    handle to edit6 (see GCBO)
    % eventdata  reserved - to be defined in a future version
    % of MATLAB
    % handles    structure with handles and user data (see
    % GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit6 as
text
    %        str2double(get(hObject,'String')) returns contents
    of edit6 as a double

    % --- Executes during object creation, after setting all
properties.
function edit6_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to edit6 (see GCBO)
    % eventdata  reserved - to be defined in a future version
    % of MATLAB
    % handles    empty - handles not created until after all
CreateFcns called

    % Hint: edit controls usually have a white background on
Windows.
    %        See ISPC and COMPUTER.
    if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end

    % --- Executes on button press in pushbutton2.
function pushbutton2_Callback(hObject, eventdata, handles)
    % hObject    handle to pushbutton2 (see GCBO)
    % eventdata  reserved - to be defined in a future version
    % of MATLAB
    % handles    structure with handles and user data (see
    % GUIDATA)
    h = msgbox(’This semi-Markov aging model simulates stress
corrosion cracking mechanism. 6 states exist: Initial,
    micro-crack, circumferential macro-crack, radial macro-
crack, leakage and rupture. This model can be applied to
all SCC and Markov model states can be modified.'','Help');

function edit7_Callback(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version
% of MATLAB
% handles    structure with handles and user data (see
% GUIDATA)

% Hints: get(hObject,'String') returns contents of edit7 as text
%       str2double(get(hObject,'String')) returns contents of edit7 as a double

% --- Executes during object creation, after setting all
% properties.
function edit7_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit7 (see GCBO)
% eventdata  reserved - to be defined in a future version
% of MATLAB
% handles    empty - handles not created until after all
% CreateFcns called

% Hint: edit controls usually have a white background on
%       Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit8_Callback(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version
% of MATLAB
% handles    structure with handles and user data (see
% GUIDATA)
% Hints: get(hObject,'String') returns contents of edit8 as text
%       str2double(get(hObject,'String')) returns contents of edit8 as a double

% --- Executes during object creation, after setting all properties.
function edit8_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit8 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit9_Callback(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit9 as text
%       str2double(get(hObject,'String')) returns contents of edit9 as a double

% --- Executes during object creation, after setting all properties.
function edit9_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit9 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all
CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
  set(hObject,'BackgroundColor','white');
end

function edit10_Callback(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version
% of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit10
% as text
%       str2double(get(hObject,'String')) returns contents
% of edit10 as a double

% --- Executes during object creation, after setting all
properties.
function edit10_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit10 (see GCBO)
% eventdata  reserved - to be defined in a future version
% of MATLAB
% handles    empty - handles not created until after all
CreateFcns called

% Hint: edit controls usually have a white background on
Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
  set(hObject,'BackgroundColor','white');
end
function edit11_Callback(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit11 as text
%        str2double(get(hObject,'String')) returns contents of edit11 as a double

% --- Executes during object creation, after setting all properties.
function edit11_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit11 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit12_Callback(hObject, eventdata, handles)
% hObject    handle to edit12 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit12 as text
%        str2double(get(hObject,'String')) returns contents of edit12 as a double
function edit12_CreateFcn(hObject, eventdata, handles)
    hObject    handle to edit12 (see GCBO)
    eventdata  reserved - to be defined in a future version of MATLAB
    handles    empty - handles not created until after all CreateFcns called

    if ispc && isequal(get(hObject,'BackgroundColor'),
                      get(0,'defaultUicontrolBackgroundColor'))
        set(hObject,'BackgroundColor','white');
    end

function edit13_Callback(hObject, eventdata, handles)
    hObject    handle to edit13 (see GCBO)
    eventdata  reserved - to be defined in a future version of MATLAB
    handles    structure with handles and user data (see GUIDATA)

    % Hints: get(hObject,'String') returns contents of edit13 as text
    %        str2double(get(hObject,'String')) returns contents of edit13 as a double

function edit13_CreateFcn(hObject, eventdata, handles)
    hObject    handle to edit13 (see GCBO)
    eventdata  reserved - to be defined in a future version of MATLAB
    handles    empty - handles not created until after all CreateFcns called
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit14_Callback(hObject, eventdata, handles)
% hObject    handle to edit14 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit14 as text
%        str2double(get(hObject,'String')) returns contents of edit14 as a double

% --- Executes during object creation, after setting all properties.
function edit14_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit14 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit15_Callback(hObject, eventdata, handles)
% hObject    handle to edit15 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit15 as text
%        str2double(get(hObject,'String')) returns contents of edit15 as a double

% --- Executes during object creation, after setting all properties.
function edit15_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit15 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit16_Callback(hObject, eventdata, handles)
% hObject    handle to edit16 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit16 as text
%        str2double(get(hObject,'String')) returns contents of edit16 as a double
% --- Executes during object creation, after setting all properties.
function edit16_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit16 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
    get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit17_Callback(hObject, eventdata, handles)
% hObject    handle to edit17 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit17 as text
%        str2double(get(hObject,'String')) returns contents of edit17 as a double

% --- Executes during object creation, after setting all properties.
function edit17_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit17 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
%
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function xdot=agingso(t,x,t1,t2,t3,bo,to,ad,ac,al,Pd,Pc,w1,w2,w3,w4,
q5,q6)
xdot=zeros(9,1);

%% Constant Model Parameters
adotmx=9.46; %max. credible crack growth rate

%% Time Dependent Transition Rates (piecewise functions)
q1=@(t1) (bo/to).*((t1/to)^(bo-1)); %t is time from last
repair
q2=@(t2) (t2<=ad/adotmx).*0+(t2>ad/adotmx &
t2>ac/adotmx).*((ad*Pd/t2^2*adotmx*Pc));
q3=@(t2) (t2<=ac/adotmx).*0+(t2>ad/adotmx &
t2>ac/adotmx).*((ac*Pc/t2^2*adotmx*Pc));
q4=@(t3) (t3>((al-ad)/adotmx)).*(1/t3)+(t3<=((al-
ad)/adotmx)).*0;

%% Differential Equations
xdot(1)=-q1(t).*x(1)+w1.*x(2)+w3.*x(3)+w2.*x(4)+w4.*x(5);
xdot(2)=q1(t).*x(1)-(w1+q2(t)+q3(t)).*x(2);
xdot(3)=q3(t).*x(2)-(w3+q6).*x(3);
xdot(4)=q2(t).*x(2)-(w2+q4(t)).*x(4);
xdot(5)=q4(t).*x(4)-(w4+q5).*x(5);
xdot(6)=q6.*x(3)+q5.*x(5);

%----------------sojourn time approach----------------------
%---------------------------------------------------------
xdot(7)=abs(t.*xdot(1)); % Initial State sojourn time
xdot(8)=abs(t.*xdot(2)); % Micro-Crack State sojourn time
xdot(9)=abs(t.*xdot(4)); % Radial-Macro Crack state sojourn time

function s=LHS_Call(xmin,xmean,xmax,xsd,nsample,distrib,threshold)
% s=latin_hs(xmean,xsd,nsample,nvar)
% LHS from normal distribution, no correlation
% method of Stein
% Technometrics 29:143-151

if nsample==1
    s=xmean;
    return
end
if nargin<7
    threshold=1e20;
end

[sample,nvar]=size(xmean);
if distrib == 'norm'  % you only need to specify xmean & xsd
    ran=rand(nsample,nvar);
    s=zeros(nsample,nvar);
    method of Stein
    for j=1: nvar
        idx=randperm(nsample);
        P=(idx'-ran(:,j))/nsample;      % probability of
        s(:,j) = xmean(j) + ltqnorm(P).* xsd(j); % this can
    end
end

if distrib == 'unif'  % you only need to specify xmin & xmax
    if xmin==0
        xmin=1e-300;
    end
    nvar=length(xmin);
    ran=rand(nsample,nvar);
    s=zeros(nsample,nvar);
    for j=1: nvar
        idx=randperm(nsample);
        P=(idx'-ran(:,j))/nsample;
        xmax(j);
        xmin(j);
        xmax(j)/xmin(j);
        if (xmax(j)<1 & xmin(j)<1) || (xmax(j)>1 &
            xmin(j)>1)
'SAME RANGE';
if (xmax(j)/xmin(j))<threshold %% It uses the 
log scale if the order of magnitude of [xmax-xmin] is 
bigger than threshold
    '<1e3: LINEAR SCALE';
    s(:,j) = xmin(j) + P.* (xmax(j)-xmin(j));
else
    '>=1e3: LOG SCALE';
    s(:,j) = log(xmin(j)) + 
P.*abs(abs(log(xmax(j)))-abs(log(xmin(j))));
    s(:,j) = exp(s(:,j));
end
else
    'e- to e+';
    if (xmax(j)/xmin(j))<threshold %% It uses the 
log scale if the order of magnitude of [xmax-xmin] is 
bigger than threshold
        '<1e3: LINEAR SCALE';
        s(:,j) = xmin(j) + P.* (xmax(j)-xmin(j));
    else
        '>=1e3: LOG SCALE';
        s(:,j) = log(xmin(j)) + 
P.*abs(log(xmax(j))-log(xmin(j))));
        s(:,j) = exp(s(:,j));
    end
    end
end
hist(s)   % plots the histogram of the pdf

function z = ltqnorm(p)
%LTQNORM Lower tail quantile for standard normal 
distribution.
%
%   Z = LTQNORM(P) returns the lower tail quantile for the 
standard normal 
%   distribution function. I.e., it returns the Z 
satisfying Pr{X < Z} = P,
%   where X has a standard normal distribution.
%
%   LTQNORM(P) is the same as SQRT(2) * ERFINV(2*P-1), but 
the former returns a
% more accurate value when P is close to zero.

% The algorithm uses a minimax approximation by rational functions and the
% result has a relative error less than 1.15e-9. A last refinement by
% Halley's rational method is applied to achieve full
% machine precision.

% Author:      Peter J. Acklam
% Time-stamp: 2003-04-23 08:26:51 +0200
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% Coefficients in rational approximations.
\[ a = \begin{bmatrix}  \-3.969683028665376e+01 & 2.20960984245205e+02 \\ -2.759285104469687e+02 & 1.383577518672690e+02 \\ -3.064497806614716e+02 & 2.506628277459239e+02 \end{bmatrix}; \]
\[ b = \begin{bmatrix}  \-5.447609879822406e+01 & 1.615858368580409e+02 \\ -1.556989798598866e+02 & 6.680131188771972e+01 \\ -1.328068155288572e+01 \end{bmatrix}; \]
\[ c = \begin{bmatrix}  \-7.784894002430293e-03 & -3.223964580411365e-01 \\ -2.400758277161838e+00 & -2.549732539343734e+00 \\ 4.37466141464968e+00  \end{bmatrix}; \]
\[ d = \begin{bmatrix}  \ 7.784695709041462e-03 & 3.224671290700398e-01 \\ 2.445134137142996e+00 & 3.754408661907416e+00 \end{bmatrix}; \]

% Define break-points.
plow  = 0.02425;
phigh = 1 - plow;

% Initialize output array.
z = zeros(size(p));

% Rational approximation for central region:
k = plow <= p & p <= phigh;
if any(k(:))
    q = p(k) - 0.5;
    r = q.*q;
    z(k) = ((((a(1)*r+a(2)).*r+a(3)).*r+a(4)).*r+a(5)).*r+a(6)).*q ./
    (((((b(1)*r+b(2)).*r+b(3)).*r+b(4)).*r+b(5)).*r+1);

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end

% Rational approximation for lower region:
k = 0 < p & p < plow;
if any(k(:))
    q = sqrt(-2*log(p(k)));
    z(k) = (((((c(1)*q+c(2)).*q+c(3)).*q+c(4)).*q+c(5)).*q+c(6)) ./
    (((d(1)*q+d(2)).*q+d(3)).*q+d(4)).*q+1);
end

% Rational approximation for upper region:
k = phigh < p & p < 1;
if any(k(:))
    q = sqrt(-2*log(1-p(k)));
    z(k) = -(((c(1)*q+c(2)).*q+c(3)).*q+c(4)).*q+c(5)).*q+c(6)) ./
    (((d(1)*q+d(2)).*q+d(3)).*q+d(4)).*q+1);
end

% Case when P = 0:
z(p == 0) = -Inf;

% Case when P = 1:
z(p == 1) = Inf;

% Cases when output will be NaN:
k = p < 0 | p > 1 | isnan(p);
if any(k(:))
z(k) = NaN;
end

% The relative error of the approximation has absolute
% value less than 1.15e-9. One iteration of Halley's rational
% method (third
% order) gives full machine precision.
k = 0 < p & p < 1;
if any(k(:))
e = 0.5*erfc(-z(k)/sqrt(2)) - p(k);  % error
u = e * sqrt(2*pi) .* exp(z(k).^2/2);  % f(z)/df(z)
%z(k) = z(k) - u;

Newton's method
z(k) = z(k) - u./( 1 + z(k).*u/2 );

Halley's method
end

function xdot=agingso(t,x,LHSmatrix,LHSmattrix,y,z,runn,runm,t1,t2,t3,bo,td,ad,ac,al,Pd,Pc,w1,w2,w3,w4,q5,q6) %q1,q2,q3,q4 now they are constant
%% PARAMETERS %
Parameter_settings_LHS;
T=LHSmatrix(y);
sigma=LHSmattrix(z);
%sigma=LHSmatrix(y,2);
%dummy_LHS=LHSmatrix(y,2);

xdot=zeros(9,1);
%% Physical Parameters Dependent Data

%ad=10^-2;%crack length threshold for radial crack
%ac=10^-2;%crack length threshold for circum. crack
%al=2*10^-2;
%Pd=0.009; %probability that micro crack evolves as a radial crack per yr
%Pc=0.001;
%w1=10^-3; %repair transition rate from micro-crack per yr
%w2=2*10^-2; %repair transition rate from radial macro-crack per yr
%w3=2*10^-2; %repair transition rate from circum. macro-crack per yr
%w4=8*10^-1; %repair transition rate from leak per yr
%q5=2*10^-2; %leak to rupture transition rate per yr
%q6=10^-5; %macro-crack to rupture transition rate per yr
A=2.524*10^5; %is the fitting parameter
n=-7; %for Alloy 182 and -6 for Alloy 82
Q=130; % activation energy for crack initiation [kJ/mole]
Qg=220; % activation energy for crack growth [kJ/mole]
R=8.314*10^-3; %universal gas constant [kJ/mole-K]
falloy=1; % for Alloy 182 and 1/2.6
forient=1; %except 0.5 for crack propagation (perpendicular to dendrite solidification)
alpha=1.5*10^-12; % crack growth amplitude
beta=1.6; % stress intensity factor exponent
Tref=400; % Kelvin
K=35; % MPa*m^0.5
% sigma=300;
to=A*(sigma^n)*exp(Q/(R*T)); % time constant in the Weibull model
adotmx=alpha*falloy*forient*(K^beta)*exp(-(Qg/R)*(T^-1-Tref^-1));

%% Time Dependent Transition Rates (piecewise functions)
q1=@(t1) (bo/to).*((t1/to)^(bo-1)); % t is time from last repair
q2=@(t2) (t2<=ad/adotmx).*0+(t2>ad/adotmx & t2>ac/adotmx).*((ad*Pd/(t2*ad*Pd+t2^2*adotmx*Pc)));
q3=@(t2) (t2<ac/adotmx).*0+(t2>ac/adotmx & t2>ac/adotmx).*((ac*Pc/(t2*ad*Pd+t2^2*adotmx*Pc)));
q4=@(t3) (t3>((al-ad)/adotmx)).*(1/t3)+(t3<=((al-ad)/adotmx)).*0;

%% Differential Equations
xdot(1)=-q1(t).*x(1)+w1.*x(2)+w3.*x(3)+w2.*x(4)+w4.*x(5);
xdot(2)=q1(t).*x(1)-(w1+q2(t)+q3(t)).*x(2);
xdot(3)=q3(t).*x(2)-(w3+q6).*x(3);
xdot(4)=q2(t).*x(2)-(w2+q4(t)).*x(4);
xdot(5)=q4(t).*x(4)-(w4+q5).*x(5);
xdot(6)=q6.*x(3)+q5.*x(5);

%----------------sojourn time approach-----------------------------
xdot(7)=abs(t.*xdot(1)); % Initial State sojourn time
xdot(8)=abs(t.*xdot(2)); % Micro-Crack State sojourn time
xdot(9)=abs(t.*xdot(4)); % Radial-Macro Crack state sojourn time

% q2(t) q3(t) q4(t)
% xdot(1)
% xdot(2)
% xdot(4)

% PARAMETER BASELINE VALUES
T=618;
sigma=150;
dummy=1;
% Parameter Labels
%PRCC_var={'T', 'sigma', 'dummy'};% %

% Variables Labels
x_var_label={'S(t)', 'M(t)', 'C(t)', 'D(t)', 'L(t)', 'R(t)'}