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Evaluation of LOCA frequency using alternative methods

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Abstract

The report presents two different models for derivation of plant specific frequency, in case of Loss of Coolant Accident (LOCA), using specific data from Goesgen NPP, as well as data from the OPDE-database. The first model is using the EPRI methodology of pipe section, and the second model is using the Markov modelling for piping reliability assessment.

For both methods, the pipe boundaries are considered to be ASME Class 1 pipes, with diameters between 10 and 750 mm.

The information gathered provides valuable insights with respect to Goesgen pipe reliability and can be used for different applications, as for example the evaluation of LOCA or the frequency of internal floods. The information gathered also provides insights with respect to evaluation of the efficiency of the plant-specific ageing management program.

Acknowledgements

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1   INTRODUCTION

In probabilistic safety analysis (PSA) studies, the failures of passive components are mainly taken into account in addressing initiating event frequencies.

Even if the passive components are considered highly reliable, some unforeseen failure events are still possible, and this was proved by the operating experience (failures caused by thermal fatigue, stress corrosion cracking). Still, these are not numerous events, and the lack of failures of these components makes the collection of statistical data quite difficult. A piping reliability parameter data handbook would be very useful for risk-informed applications that involve the consideration of structural integrity of piping systems.

The following methods can be used to estimate the reliability of passive components:
- probabilistic fracture mechanics/ structural reliability models
- statistical estimation from experience data, using large databases
- expert judgments (decision based on e.g. deterministic structural models and operating experiences)

In the last period of time, many organizations have performed some major work in order to assess frequencies for pipe degradations and failures. Some examples are given below.

In the frame of OECD-NEA Piping Failure Data Exchange Project (OPDE), an international database on pipe degradation and failures in commercial NPP in OECD Member Countries has been developed.

The database supports the following activities:
- Trend analyses, including ageing trend analyses
- Statistical analyses to determine pipe failure rates and rupture frequencies for use in risk-informed activities (e.g., loss-of-coolant-accident frequency assessment, internal flooding initiating frequency assessment)
- Degradation mechanism analysis in risk-informed in-service-inspections (RI-ISI) applications
- Development of protection measures against systematic pipe failures

ODPE data base can be used as source of data parameters (input) to probabilistic fracture mechanics codes, and it can provide information on degradation susceptibilities and degradation rates, information useful in the verification and validation of probabilistic fracture mechanics (PFM) codes.

R-Book (Sweden) is a project that used the screened OPDE data and operating experience, in order to obtain rupture frequencies for various leakage threshold values for pipes according to initial defects, pipe size, type of piping components and materials.

GRS has updated and extended the details on the estimation of leak and break frequencies in piping systems for the PSA. The statistical method, based on the evaluation of the German operational experience for piping systems with different diameters, was updated by the inclusion of structure reliability models based on fracture mechanics calculation procedures.

In support of risk-informed revision of the design-basis break size requirements for NPP, US NRC had estimated the loss-of-coolant accident (LOCA) frequency estimates using an expert elicitation process. The objective was to develop separate BWR and PWR piping and non-piping passive system LOCA frequency estimates as a function of effective break size and operating time through the end of license extension. In this process, service history data and insights from probabilistic fracture mechanics (PFM) studies were consolidated with knowledge of plant design, operation, and material performance.

NUREG 6936 provided estimates of initiating events at U.S. nuclear power plants, based on operating experience as well as other engineering evaluations. The objectives of the study were:
- to provide revised frequencies for the initiating events,
- to compare these estimates with prior estimates used in PRA
- to review the plant trends data related to specific plant types (PWR plants versus BWR plants).

Loss-of-coolant accidents including pipe breaks were a major consideration in the study. The study used as sources of data the NRC Licensee Event Reports (LER) - events of interest were limited to those that resulted in reactor trips, events like occurrences of small leaks and observations of material degradation were not taken into account.

The estimated frequencies for LOCA events were less than the frequencies for other important initiating events such as loss of offsite power and loss of feedwater flow.

For medium and large breaks, the frequencies were based in part on the operating data for small breaks and in part on conservative estimates from available fracture mechanics evaluations for the ratios between frequencies for the different LOCA categories. The frequency for medium pipe break LOCA was estimated to be 4×10^{-5} (per plant per year), and for large pipe break LOCA was estimated to be 5×10^{-6} (per plant per year).

The frequency for the small pipe break LOCA was estimated to be 5×10^{-4} (per plant per year) for both PWR and BWR plants. For PWR plants, the estimated frequency for steam generator tube rupture was about a factor of 10 greater, at 7×10^{-3} (per plant per year).

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. [7]

Some general conclusions could be drawn from this study:
- the number of precursor events (cracks and leaks) is generally a good barometer of the LOCA susceptibility for the associated degradation mechanism
- welds are almost universally recognized as likely failure locations due to high residual stress, preferential attack of many mechanisms, and the increased defect likelihood
- the biggest frequency contributors for each LOCA size tend to be systems having the smallest pipes, or component, which can lead to that size LOCA - a complete break of a smaller pipe, or non-piping component, is generally more likely than an equivalent size opening in a larger pipe, or component, because of the increased severity of fabrication or service cracking
- the PWR LOCA frequencies are dominated by the non-piping contributions for LOCA Categories 1 and 2. The major piping contributors for PWR (and BWR) Category 1 and 2 LOCA are the instrument and drain lines.

The steam generator tube rupture frequencies are normally separate from other passive system failures in probabilistic risk assessment analyses because they have occurred relatively frequently.

The relative non-piping contributions are much higher for PWR plants because of plant design differences and the increased population of non-piping primary pressure boundary components.

Within the framework of the participation of NPP Goesgen to Ageing PSA network a systematic investigation of NPP Goesgen pipe reliability has been performed, in the following steps:
1. Collection of plant-specific information from plant-specific in-service inspections records (according to inspection protocols)
2. Development of a plant-specific database containing the information from NPP Goesgen pipe inspections
3. Analysis of generic information of the OPDE database with respect to characteristic pipe flaws and their applicability to NPP Goesgen conditions

The information gathered provides valuable insights with respect to Goesgen pipe reliability and can be used for different applications, as for example the evaluation of LOCA or the frequency of internal floods. The information gathered also provides insights with respect to evaluation of the efficiency of the plant-specific ageing management program.

The evaluation of LOCA-frequency for NPP Goesgen was performed using the information collected at Goesgen as well as data from the OPDE-database. Two different methods have been applied:
1. The EPRI-methodology [2]
2. A Markov model approaches [1]

For both methods, the pipe boundaries are considered to be ASME Class 1 pipes, with diameters between 10 and 750 mm.

2   WORKING CONSIDERATIONS

2.1   In-service inspection practice at NPP Goesgen

According to SVTI - Festlegung NE-14 – In Service Inspection Program, rev. 6, from 1.01.2005, for Class 1 pipe components is required that the following tests to be performed in KKG:

- for D≥ 100mm is required a 25% volumetric test (UT, X Ray) of welds;
- for 25<D<100 mm is required to perform a 10% surface testing (MT, PT) on ferritic materials and 5% volumetric testing on austenitic materials;

Obs.: Class 1 pipe materials are austenitic only in KKG, with the exception of the HKL-Reactor Coolant System pipes, which are ferritic with austenitic cladding materials.

- for D≤ 25mm it is not required any ND test, although the connections between main pipes and these tubes (up to the first valve) are also subject to volumetric and surface testing.

The time interval for performing all tests mentioned above is 10 years. The location of the welds does not change over one interval to another. This inspection practice is applied according to ASME Code XI regulations and is common to the majority of utilities, at least on PWR type.

From discussion with the specialists of ISI program of KKG it was learned that during volumetric or surface inspections performed from one time interval to another it may happen that an originally welding failure (root fusion failure, pores, intrusions, lack of fusion between base and weld materials) to evolve into a part-crack failure. This fact is confirmed by Ref. 6, pag. 4-7, where is specified that particularly lack of fusion types of failures can lead to crack propagation.

2.2   Structure of Pipe Failure Database in Goesgen NPP

Goesgen NPP pipe failure database structure is based primarily on the structure and concept of OPDE database, and use a relational structure of tables, queries, reports and forms on pipe degradation and failure.

To the basic table of OPDE database (3755 registrations, from 1970 to 2007) were added few more fields which accounts for the particularities of the data from Goesgen NPP. The data were extracted from the reports of Non Destructive tests performed in the plant systems over the period between 1977 and 2008. Further refinement was done to eliminate the pipe components not in the purpose of the study: snubbers, hangers, holders, supports, pump casings, valve bonnets. According to KKG internal classification of protocol findings (Dokument-Nr. VOR-M-0212), there are five codes of findings:

N – without finding,

B – no further measures to be taken,

R – the finding is compulsory to be registered because the limits of the ND specification were trespassed,

D – the finding must be discussed and reasons for performing certain actions must be given,

U – unacceptable finding, it is required to repair, to take compensatory actions and eventually to request regulatory permission to further operate.

From these codes, into the database were imported only R, D and U codes and from these codes it were further detailed only the records that do not contain 0 (i.e. R0, D0, U0) – a manual screening process was necessary.

The input into the Goesgen NPP Pipe failure database consists in 385 protocols, of which 163 were partially completed in respect to the information related to plant operating state, failure type, corrective action, system group, component affected, dimensions and material of pipe, process medium, crack dimension and other plant specific fields.

3 EVALUATION OF LOCA FREQUENCY FOR NPP GOESGEN USING THE EPRI METHODOLOGY

3.1 EPRI methodology

EPRI Technical Report 1013492, "PRA Compendium of Candidate Consensus Models", provided a structured methodology for estimation of the pipe failure rates to be used in LOCA frequency assessments, according to pipe location and size.

This method operates with a series of concepts, some, like pipe section, being inherited from WASH–1400 study, and some being new. The new concepts are briefly explained bellow:

- Pipe section - a segment between major discontinuities like valves, pumps, tees (instrumentation connections are not considered as such), with length between 10 to 100 feet and containing 4 to 8 welds, several elbows and flanges;

- Diameter size groups: i=3; 1 is the smallest;

- Equivalent break area – describes the severity of failure for each of the 3 pipe size categories described by diameter size groups. For example, R1 is the equivalent break area of size diameter 1 and is assigned to a failure in all 3 diameter size categories. For size 1 diameters, R1 corresponds to a complete rupture. R2 is the equivalent break area of size 2 diameter and corresponds to a failure in pipe size diameters 2 and 3. For pipe size 2 diameters, R2 represents a complete rupture;

- Conditional probability – represents the probability that a break in size group j will have the equivalent break area of size group i, i≤j.

The concept of pipe section is considered to be more powerful than the concept of the physical length of a pipe system, because it contains more than one weld, and it was demonstrated [4] that about half of the total number of failures in pipe components in ASME Class 1 systems are due to welds. On the other hand, the length by itself is a weak measure as it cannot incorporate the important pipe components which are more prone to failure. The section contains basically all the elements which are susceptible to failure: welds, elbows, straight pipe, etc. From this perspective, the pipe section can be treated as normalization. The last argument in favor of pipe section concept is that the counting of these elements from an existing isometric drawing is much easier than counting the pipe length and the number of each significant piping discontinuity [2].

EPRI report has established a database using available pipe failure data from Licensee Event Reports, Nuclear Power Reliability Data System and other data sources. This database was used to derive the frequencies of failure per section and per hour, on each size group.

In Ref. 2 is derived also a correction factor which considers the plant age. The population failure rate shows a decreasing trend with plant age, reflecting the corrective actions that have been implemented throughout the nuclear industry in overcoming the generic causes of pipe failures.

Because the Ref. 2 makes the subject of a License Agreement, in the present document are not given details regarding the methodology or the preliminary parameters obtained by applying this method.

3.2   Application of EPRI methodology to NPP Goesgen

In KKG power plant, on time window from initial criticality (01.01.1979) to September 2008, no rupture events were recorded on any pipe size category of ASME Class 1. The following number of pipe sections, for this ASME Class were counted:

Table 1 – Number of pipe sections for each diameter class

	10≤Dn<50	50≤Dn<150	Dn≥150
No. of pipe sections	40	33	34
No. of ruptures	0	0	0

By applying Bayes method using as generic values the frequencies per section and hour, given in Ref. 2 and updating it with plant specific evidence from above, the values obtained for rupture frequency for ASME Class 1 systems (composed mainly by RCS) are indicated in Table 2. On the third row of this table are given the failure frequencies considering the age of 29 years of KKG plant. The error factors of these values are calculated in [2] assuming a Poisson process with upper and lower uncertainty bounds of the failure rate using the Chi-squared distribution at 95% and 5% and with 2n+2 and respectively 2n degrees of freedom. The resulted error factors are variable in the interval (10, 30).

Table 2 – Rupture frequency considering no ageing and plant age by a power law

Hypothesis	Z_s (1/y)	Z_m (1/y)	Z_l (1/y)
Failure frequency, no plant age	7.89E-05	4.59E-06	4.27E-06
Failure frequency with plant age	4.76e-05	2.77e-06	2.58e-06

Where:

Z_s is the frequency of small breaks with equivalent diameter between 10 and 50 mm. This represents a complete rupture for pipes within this diameter range, or leaks for pipes with diameter larger than 50mm, having equivalent break area between 10 and 50 mm.

Z_m is the frequency of breaks having equivalent diameter between 50 and 150 mm. This represents complete ruptures for pipes within this diameter range or leaks for pipes with diameters larger than 150 mm, having equivalent break area between 50 and 150 mm.

Z_l is the frequency of complete rupture for pipes with diameter larger than 150 mm.

4   EVALUATION OF LOCA FREQUENCY FOR NPP GOESGEN USING MARKOV MODEL

4.1   Markov modelling technique

As an effort to develop the technology for Risk Informed In Service Inspection (RI ISI) evaluations, this method include a Markov modelling technique for predicting the reliability of components that can be repaired. The method could be used for piping reliability assessment and for predicting the

influence of alternative inspection strategies on piping system reliability [1] The objective of this approach was to explicitly model the interactions between failure mechanisms that produce failures and the inspection, detection and repair strategies that can reduce the probability of failures occurrence. The cases when cracks or leaks will progress to ruptures before being detected and repaired were also taken into account (modelled).

The model starts with the representation of the "piping system" as a set of discrete and mutually exclusive states. At any moment in time, the system is allowed to change the state in accordance with whatever competing processes are appropriate for the plant state. In this application of Markov model, the states refer to various degrees of piping system degradation, starting from flaws and progressing to leaks and ruptures. The change of state is given by the various failure mechanisms and by the inspection and repair activity performed before progression of a flaw into rupture. This method was found to meet the requirements of an up-to-date analysis of piping reliability. Some of these requirements are mentioned below:

- account for statistical evidence and engineering insights of plant experience;
- evaluate the impact of changes in In-service Inspection strategy, like adding or removing of the locations to the existing ISI program or even changing from fixed to randomly selected locations from one inspection interval to another;
- address uncertainties in the reliability assessment and account for it in estimating pipe ruptures and in Core Damage Frequency (CDF) and Large Early Release Frequency (LERF). [1]

In a PSA model, pipe ruptures are considered as initiating events. These initiating events are normally assumed to be independent of plant age (constant failure rate model). With Markov model it is not necessary to make this assumption as the question of whether the failure frequency is constant or not is evident in the solution of a particular model, this solution involving a time dependency.

The set of differential equations are built based on the general Markov model. [1]
The model involves four different states:
- Success (S),
- Detectable Flaw (F),
- Detectable Leak (L)
- Rupture (R).

The solutions to differential equations represent the time dependant probabilities of pipe system to occupy each of these states and these solutions can be determined either numerically or analytically. Further, to determine the system failure rate or hazard rate, first it should be determined the system reliability function for the generic model and then it should be derived the hazard rate as a function of the reliability function (according to the definition of the hazard rate).

Since we are primarily concerned about pipe ruptures and we intend to estimate pipe rupture frequencies, it is assumed that any state except R is a success state. Using this concept, the reliability function of the Markov model, r{t}, is given by:

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

The hazard rate for pipe ruptures, h{t}, is given by:

$$h\{t\} = -\frac{1}{r\{t\}}\frac{dr\{t\}}{dt} = \frac{1}{1-R\{t\}}\frac{dR\{t\}}{dt}$$

It is demonstrated that the time dependant hazard rate starts at 0 at t=0 and gradually increases towards an asymptotic hazard rate, h_{SS}, over a system time constant determined by the value of the transition rate parameters of the specific model. [1]

In practice, the growth of the time dependent hazard rate is too slow to reach the asymptotic value within a plant lifetime. Therefore it can be said that the Markov model is showing a monotonically slowly increasing failure rate over the plant lifetime.

Comment: the model presented in [1] can be expanded in order to incorporate a more detailed representation of flaw detection probabilities, taking into account the different efficiency of different methods of detection.

4.2 Application of the Markov model

To apply this method, both databases were used (OPDE database and NPP Goesgen pipe failure database).
The relevant information for the present study was given by failure and degradation events on ASME Class 1 pipe systems.

4.2.1 Goesgen NPP specific parameters

4.2.1.1 Classification of the events in OPDE and Goesgen NPP pipe failure database

A thorough evaluation of types of events included in both database (records referring to welds on ASME Class 1 system) led to the conclusion that 4 categories of events can be considered:

- Minor flaws inside the welding seam, like gas intrusions, lack of fusion, pores, weld root failures, found with volumetric tests (Ultrasonic and X-Ray tests), which can evolve into a more severe, surface degradation. These types of welding failures cannot be found in OPDE database.

- Signs of visible deterioration (using surface tests Penetration Liquid and Magnetic Particle tests) like Crack-Part and Crack-Full, representing indications of degraded conditions but without active leaks. After checking the records regarding Reportable Events it was concluded that this type of events can be included also into the second category. These types of Crack-Part, Crack-Full and Reportable Events can be found in OPDE and in KKG pipe failure database also.

- Increasing spectrum of leaks, named P/H Leak, Small Leak, Leak, Large Leak.

- Rupture and Severance events. A rupture represents a major structural failure resulting in a significant through-wall flow rate. A severance implies a 360^0 circumferential, through-wall crack [5]. From OPDE database it was found that these events took place in pipe diameters < 60mm, as a result of fabrication error, water hammer events and stress corrosion cracking.

The Table 3 is summarizing in figures all the 4 categories of events in KKG pipe failure database and in OPDE database, for events related to welds on ASME Class 1:

Table 3 – Category of events

Category	KKG events	OPDE events
2*	18	-
3	3	46
4	-	115
5	-	4

* - Category 1 is considered to be the success state

As it can be observed from the table, the OPDE failure data are biased toward what could be defined as important failure events (Category 3, 4 and 5), with the tendency to neglect the possible

precursors. Therefore, in calculation of point estimate of parameters of Markov model, for Category 2 flaws it was considered only KKG experience.

4.2.1.2 Description of the Markov model for KKG plant

Considering the particularities of ISI program in KKG, the Markov model from Figure 1 was proposed:

Pipe Element States

C_1 - Success, no detectable damage state
C_2 - Category 2 events, welding failures
C_3 - Category 3 events, part-cracks, full-cracks, reportable events
C_4 - Category 4 events, through-wall leaks
C_5 - Rupture or severance events

State Transition Rates
φ – welding failures occurrence rate
λ_1 – part-crack failure rate, given welding failures
λ_2 – leak failure rate, given part-crack failures
λ_R – leak failure rate given welding failures
λ_T - part-crack failure rate given success state
ρ_3 – rupture failure rate given leaks
ρ_2 – rupture failure rate given part-crack failures
ω – repair rate of part crack failures
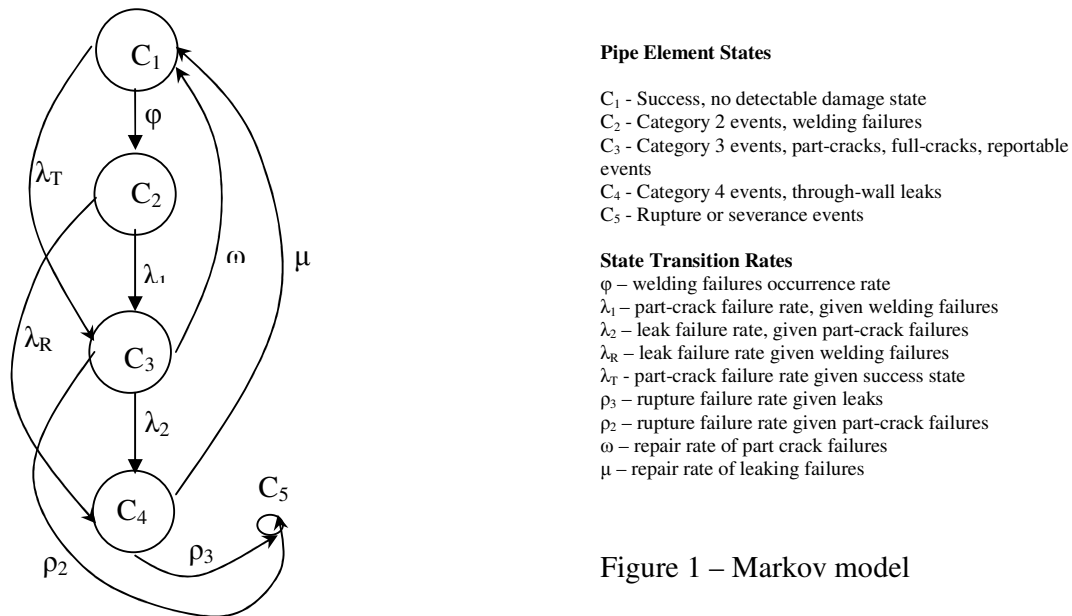μ – repair rate of leaking failures

Figure 1 – Markov model

The present model has been build under the following assumptions, based on the observed data (from data collection system in KKG) and on approach to Markov model [1]:
- leak before break model which states the transition from success to break state cannot happen directly, at least in the inspected amount of pipe components.
- it has to exist always a form of indication like weld root failure, weld layer stratification or wall thinning, part-crack, before a leakage can happen, at least in the inspected amount of pipe components.
- repair actions are performed only on visible pipe component deterioration and on leak seepages, and the repair action is fully restoring the component to its original, success state.
- an existing degradation within the limits of Category 2 will be detected with 0.9 probability of detection, given the pipe component is inspected. [1]
- an existing degradation within the limits of Category 3 will be detected with 1 probability of detection.
- the major contributors to a pipe failure were considered the weld zones, in accordance to Ref. 4, pag. 114. This assumption was confirmed by the statistics in OPDE database for the relevant pipe category: From the total of 327 events in OPDE for PWR plants and for ASME Class 1 systems, a number of 167 events are related to welds and the rest to other pipe components like elbows, straight pipe elements, fittings, nozzles, etc. It results that roughly the proportion between weld and other pipe elements contribution to failure is equally shared.
- the failure causes considered in this study were: stress corrosion cracking, design/ manufacturing/ construction errors and fatigue (caused by vibrations or temperature). These were the main failure causes found in OPDE database and also in KKG database, applicable for PWR plants, ASME Class 1 pipe systems.

In order to compute the time dependant probability for the pipe components in each state (C_1, C_2, C_3, C_4 or C_5), a set of differential equations were built:

$$\frac{dC_1}{dt} = -C_1(\varphi + \lambda_T) + C_3 \cdot \omega + C_4 \cdot \mu$$

$$\frac{dC_2}{dt} = C_1 \cdot \varphi - C_2(\lambda_1 + \lambda_R)$$

$$\frac{dC_3}{dt} = C_1 \cdot \lambda_T + C_2 \cdot \lambda_1 - C_3(\omega + \rho_2 + \lambda_2)$$

$$\frac{dC_4}{dt} = C_2 \cdot \lambda_R + C_3 \cdot \lambda_2 - C_4(\mu + \rho_3)$$

$$\frac{dC_5}{dt} = C_3 \cdot \rho_2 + C_4 \cdot \rho3$$

Since the five states are mutually exclusive, at any given time moment t, we have

$$C_1 + C_2 + C_3 + C_4 + C_5 = 1$$

4.2.1.3   Boundary Conditions of the Markov model

These conditions have been established considering the KKG plant experience.
From Komponentenprüfplan – the situation of findings on welds of system YA pipes it was found a number of 12 distinct indications dating from late period 1977-1987, which can be interpreted as types of welding failures existing already at the beginning of plant operation.
Therefore, the hypothesis of Ref. 1 that all safety related pipes are free of detectable flaws at the beginning of operation cannot be sustained.
At the moment t=0, it was considered that from the total of inspected welds, 12 welds were having fabrication failures. All of these 12 welds were located in pipes with diameter bigger than 100 mm.
The success state at the moment t=0 is:

$$C_1\{t = 0\} = 1 - \frac{12}{625 * 0.25},$$
$$C_1\{t = 0\} = 0.92$$

$C_2\{t = 0\} = 0.08$

$C_3\{t = 0\} = 0$

$C_4\{t = 0\} = 0$

$C_5\{t = 0\} = 0$

Because the calculations are split according to 4 different diameter intervals, it can be assumed at the starting moment t=0 for the calculations on 150≤Dn<220 and t=0 for the calculations on Dn≥220, to have the following point values of state probability:

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$C_1\{t = 0\}=0.92$

$C_2\{t = 0\}= 0.08$

$C_3\{t = 0\}=0$

$C_4\{t = 0\}=0$

$C_5\{t = 0\}=0$

For 50≤Dn<150, since half of this interval is covering the Dn > 100 condition, it was assumed as initial conditions:

$C_1\{t = 0\}=0.96$

$C_2\{t = 0\}= 0.04$

$C_3\{t = 0\}=0$

$C_4\{t = 0\}=0$

$C_5\{t = 0\}=0$

For Dn<50 diameter interval, it was assumed that initial conditions are free of fabrication flaws:

$C_1\{t = 0\}=1$

$C_2\{t = 0\}= 0$

$C_3\{t = 0\}=0$

$C_4\{t = 0\}=0$

$C_5\{t = 0\}=0$

4.2.1.4   Development of Markov model parameters

The following set of tables gives the model parameters (in bold letters) and their additional values (indicated always before the model parameter description), their definition, source of data and formula used for calculation. Also, where it was considered necessary, additional explanations regarding parameter derivation were given.

Table 4 - Derivation of occurrence rate of flaws within Category 2 (welding failures)

Parameter	Definition	Source or method used for estimation	Formula used	Value
n_{1s}	Number of occurences within Category 2, Dn<100 mm	KKG pipe failure database		0
N_{0s}	Number of pipe components (welds) that provided the n_{1s} occurences	Isometrics of Safety Class 1 systems, Dn<100 mm		484

f_s	Fraction of pipes Dn<100 mm inspected according to the KKG inspection plan	SVTI- Festlegung NE-14 – In Service Inspection Program, rev. 6/ 01.01.2005	Median value between 10% and 5%	0.075
T_1	Time over which flaws of Category 2 were collected	KKG pipe failure database		22 years
P_{FD}	Probability that a flaw within Category 2, Dn<100 mm will be detected given this pipe component will be inspected	Ref.1		0.9
φ_s	**Category 2 events occurrence rate for Dn<100 mm**	**Bayes update (0 failures) of a non-informative prior distribution**	$\dfrac{1}{2 \cdot \tau}$ **τ – number of weld-years,** $\tau = N_{0s} \cdot f_s \cdot T_1$	**6.95E-04/y**
n_{1l}	Number of occurences within Category 2, Dn≥100 mm	KKG pipe failure database		18
N_{0l}	Number of pipe components (welds) that provided the n_{1l} occurrences, Dn≥100 mm	Isometrics of Safety Class 1 systems		141
f_l	Fraction of pipes Dn≥100 mm inspected according to the KKG inspection plan	SVTI- Festlegung NE-14 – In Service Inspection Program, rev. 6/ 01.01.2005		0.25
T_1	Time over which flaws of Category 2 were collected	KKG pipe failure database		22 years
P_{FD}	Probability that a flaw within Category 2, Dn≥100 mm will be detected given this pipe component will be inspected	Ref.1		0.9
φ_l	**Category 2 events occurrence rate for Dn≥100 mm**		$\varphi = \dfrac{n_1}{N_{0l} \cdot f_l \cdot T_1 \cdot P_{FD}}$	**2.57E-02/y**

Comment: The φ_s value compared to φ_l is explainable if we take into consideration the type of failures (actually minor flaws) and the difference in amount of material to be searched for flaws. Still, this result is in disagreement with the generic tendency of failure rate in small pipe diameters, which usually is bigger than that in large pipe diameters.

Table 5 - Derivation of occurrence rate of Category 3 type (part-cracks, full cracks), given the total of inspected welds

Parameter	Definition	Source or method used for estimation	Formula used	Value
n_2	Number of occurrences of Category 3 (part-cracks)	KKG pipe failure database		3
N_1	Number of pipe components that provided the n_2 occurrences (total of surface and volumetric tests on different locations on ASME Class 1)	Explanation bellow this table		250
T_2	Time over which n_2 occ. were collected	KKG pipe failure database		22 years
λ_1	**Category 3 type crack-parts events failure rate from the volumetric and surface inspections**	**KKG pipe failure database**	$\lambda_1 = \dfrac{n_2}{N_1 \cdot T_2}$	**5.45E-04/y**

From "KKG Komponentenprüfplan- tabelle for Haupkülmittelleitung YA10/20/30 Z" internal document it was found a number of approximate 48 different weld locations included in the In Service Inspection Program. If account also for weld locations on pipes which connects YA system with YP, TA and TH (only ASME Class 1 piping), this means a total number of approximate 250 different locations inside boundaries of ASME 1 piping system where ND measurements are performed. This value represents 40% of the total number of welds on ASME Class 1, and this fact could be an indication that the In Service Inspection program in Goesgen NPP is oversized (fact confirmed by the QM specialists) by an approximate factor of 3.5, in the ASME Class 1 pipe systems. This fact is observed in the pipe diameters larger than 100 mm of TH and YA systems. Because this is an approximation only and have to be sustained by further calculations, for the rest of the parameters estimation will be used the values specified by SVTI for percentage of inspections (paragraph 2.1). However, sensitivity check on the real percentage of tested welds on Goesgen NPP may reveal interesting insights related to the efficiency of testing activity.

Table 6 - Derivation of repair rate of part-cracks

Parameter	Definition	Source or method used for estimation	Formula used	Value
P_{Is}	Probability that a pipe component flaw within Category 3 will be inspected per inspection interval, for Dn<100.	SVTI- Festlegung NE-14 – In Service Inspection Program, rev. 6/ 01.01.2005	Median value between 10% and 5%	0.075
P_{II}	Probability that a pipe component flaw within Category 3 will be inspected per inspection interval, for Dn≥100.	SVTI- Festlegung NE-14 – In Service Inspection Program, rev. 6/ 01.01.2005		0.25
P_{FD}	Probability that a flaw within Category 3 will be detected given this pipe component is inspected.	Estimation		0.9
T_{FI}	Inspection interval			10 years

Parameter	Definition	Source or method used for estimation	Formula used	Value
T_R	(includes time for cooldown, isolate, repair itself, testing and start-up) estimated from discussion with KKG ISI engineers to be between 4 days and 1 month, depending on the pipe diameter.	This term is very small compared to inspection interval.		0
ω_s	**Repair rate for crack-part (i.e. Cat.3 flaws), for Dn<100**	**Ref. 1**	$\omega_s = \dfrac{P_{Is} \cdot P_{FD}}{(T_{FI} + T_R)}$	**6.75E-03/y**
ω_l	**Repair rate for crack-part (i.e. Cat.3 flaws), for Dn≥100**	**Ref. 1**	$\omega_l = \dfrac{P_{Il} \cdot P_{FD}}{(T_{FI} + T_R)}$	**2.25E-02/y**

Table 7 - Derivation of failure rate of part-cracks given success state

Parameter	Definition	Source or method used for estimation	Formula used	Value
n_{2s}	Number of occurrences of Category 3, with Dn<100	KKG pipe failure database		2
n_{2l}	Number of occurrences of Category 3 from KKG database, with Dn≥100	KKG pipe failure database		1
N_{Ts}	Number of pipe components that provided the n_2 occurrences (total number of welds), with Dn<100	Isometrics of Safety Class 1 systems		484
N_{Tl}	Number of pipe components that provided the n_2 occurrences (total number of welds), with Dn≥100	Isometrics of Safety Class 1 systems		141
T_2	Time over which n_2 occ. were collected	KKG pipe failure database		22 years
f_s	Fraction of pipes Dn<100 mm inspected according to the KKG inspection plan	SVTI- Festlegung NE-14 – In Service Inspection Program, rev. 6/ 01.01.2005		0.075

Parameter	Definition	Source or method used for estimation	Formula used	Value
f_l	Fraction of pipes Dn≥100 mm inspected according to the KKG inspection plan	SVTI- Festlegung NE-14 – In Service Inspection Program, rev. 6/ 01.01.2005		0.25
P_{FD}	probability that a flaw within Category 3 will be detected given this pipe component will be inspected	Ref. 1		0.9
λ_{Ts}	**Point estimate of frequency of crack-parts given the total success state, for Dn<100**	Ref. 1	$$\lambda_{Ts} = \frac{n_{2s}}{N_{Ts} \cdot T_2 \cdot f_s \cdot P_{FD}}$$	**2.78E-03/y**
λ_{Tl}	**Point estimate of frequency of crack-parts given the total success state, for Dn≥100**	Ref. 1	$$\lambda_{Tl} = \frac{n_{2t}}{N_{Tl} \cdot T_2 \cdot f_l \cdot P_{FD}}$$	**1.43E-03/y**

Table 8 - Derivation of leak failure rate given part-crack failures

Parameter	Definition	Source or method used for estimation	Formula used	Value
n_{leaks}	Number of Category 4 events (leaks)with specified failure causes	OPDE database		115
n_{ev}	Total number of failure events for welds in PWR plants, ASME Class 1, with specified failure causes	OPDE database		165
$\%P_{l,fc}$	Percentage of leaks occurred due to specified causes, from the total leak events	OPDE database		0.973
$\%P_{lc,fc}$	Percentage of cracks and leaks occurred due to specified causes, from the total events	OPDE database		0.95
N_R	Number of reactors	OPDE database		76 reactors
T	Time window	OPDE database		35 years
λ_2	Leak events failure rate from Category 3 events	Explanations bellow this table	$$\lambda_{leakcrack} = \frac{n_{leaks} \cdot \%P_{l,fc}}{n_{ev} \cdot \%P_{lc,fc} \cdot N_R \cdot T}$$	2.68E-04/y

λ_{2Bayes}	Leak events failure rate from Category 3 events after Bayes update	Bayes update of generic value using plant specific data		2.29E-04/y

This failure rate could be precisely determined if one would know, for the specified failure causes, what amount of cracks has evolved into active leaks. Since this is difficult to know, a estimation was made, considering the number of leaks from the total number of failures and the percentage on which these leaks are developed due to specified causes.

A search made on OPDE database, for PWR plants, in case of ASME Class1 systems, for pipe component "*weld*" and for failure type "crack*" and "leak" revealed the results indicated in Table 9.

Table 9 – Contributions for each failure cause for welds

Pipe Component	Failure Type	Apparent Failure Cause	%
Welds	Cracks	Design/manufacturing/construction errors	15
		Stress corrosion cracking	70
		Fatigue (thermal, vibration)	15
	Leaks	Design/manufacturing/construction errors	21.7
		Stress corrosion cracking	16.5
		Fatigue (thermal, vibration)	59.1
	Cracks and Leaks from total events	Design/manufacturing/construction errors	20
		Stress corrosion cracking	30
		Fatigue (thermal, vibration)	45

As it can be noticed from the above table, these three failure causes together dominates the spectrum of registered failure causes, for welds category in ASME Class 1, for PWR plants.

The number of cracks is 40. The number of leaks is 115.

The total number of failures (cracks, reportable indications, leaks, rupture, severance) is 165.

If we consider the leaks happened during a period of 76 reactors years multiplied by the time interval between the first and the last observation of a leak or crack (i.e. exposure interval), we obtain $\lambda_{leak/crack}$ due to one of these failure causes, derived from OPDE database:

$$\lambda_{leakcrack} = \frac{n_{leaks} \cdot \%P_{l,fc}}{n_{ev} \cdot \%P_{lc,fc} \cdot N_R \cdot T}$$

$$= 115*0.973/ (165*0.95*76*35)$$

$$= 2.68E-04/y$$

If this value is Bayes updated, using Goesgen NPP experience of zero leaks in 22 years times/ 21 events, assuming a lognormal prior distribution with error factor 5, it will be obtained the frequency of a leak evolving from cracks in Goesgen plant: 2.29E-04/y.

Table 10 - Derivation of leak failure rate given welding failures

Parameter	Definition	Source or method used for estimation	Formula used	Value
n_3	number of occurrences of Category 4 (leaks)	KKG PFDb		0

N_1	Number of pipe components that provided the n_2 occurrences (total of surface and volumetric tests on different locations, ASME Class 1)	KKG pipe failure database	250
T	Exposure time		22 years
λ_{Rs}	Category 4 type leak events failure rate from Category 1 events, Dn<100	Explanations bellow this table	3.6E-05/y, EF=5
λ_{Rl}	Category 4 type leak events failure rate from Category 1 events, Dn>100	Explanations bellow this table	1.07E-05/y, EF=5
$\lambda_{RsBayes}$	**Category 4 type leaks events failure rate after Bayes updating with specific data, Dn<100**	**Bayes update of above generic failure rate**	**2.87E-05/y, EF=4**
$\lambda_{RlBayes}$	**Category 4 type leaks events failure rate after Bayes updating with specific data, Dn>100**	**Bayes update of above generic failure rate**	**9.86E-06/y, EF=4.7**

Conditional failure rate of having a leak considering that we have a Category 2 flaw event is estimated considering the following:
- In KKG plant there were no active leak events on welds, ASME Class1 systems, in 22 reactor-years of monitoring;
- In KKG plant there is an approximate number of 250 welds tested on ASME Class systems;
- In OPDE database there is a number of 115 leaks on PWR ASME Class 1, weld components in a number of 61 reactors multiplied by 35 years in average plant life, multiplied by the average number of welds inspected on PWR. Westingouse PWR units has a number of 1605 welds on ASME Class 1 [1].

The inspection for leaks does not rely on ND examinations, but rather on shiftly routines and observations on operator crews. This means that the failure that grew such that it produces a leak has as exposure parameter the entire population of welds at risk for failure, not only the amount of welds checked for ND examinations.

However, in our model, the meaning of λ_R is that the existing leaks evolved directly from a previous flaw state (minor welding failure), which means that for our purpose is necessary to consider that an amount of 7.5% of them are inspected for Dn<100, respectively 25% for Dn≥100.

Therefore we can use the assumption that only a 10% of total leaks on OPDE database in the class of interest are discovered during ND examinations, the rest of them being discovered by routines and operational checks on primary circuit systems.

To resume, for OPDE database, we have a hypothetical number of 11.5 leak events from a previous flaw state. The exposure of these leaks is 61 reactors multiplied by 35 years times, multiplied by 1605 welds with 0.075 inspected for pipe diameters Dn<100 and respectively 0.25 for pipe diameters Dn≥100. The result obtained from OPDE database is further Bayes updated using KKG plant specific data, given information above.

The results are given in Table 10.

Table 11 - Determination of detection and repair of a leak state

Parameter	Definition	Source or method used for estimation	Formula used	Value
P_I	Probability that a leak within Category 4 will be inspected per inspection interval.	Ref. 1		0.9
P_{LD}	Probability that the leaks Category 4 will be detected per inspection interval.	Inspection practice and KKG ND experts estimates		1
T_{LI}	Leak detection interval, it ranges from immediate to frequency of routine inspections for leaks or ASME required leak tests.	Assumed based on Ref.1		1
T_R	Temporary repair time, estimated also to be between 4 days and 1 month, including all the intermediate times.			4.7E-02 years
μ	**Detection and repair of a leak state**		$$\mu = \frac{P_I \cdot P_{LD}}{(T_{LI} + T_R)}$$	**8.6E-01/y**

Table 12 - Derivation of rupture/severance failure rate given an existing leak

Parameter	Definition	Source or method used for estimation	Formula used	Value
ρ_3	**Occurrence rate of a rupture/severance from a Category 4 state**	**Explanations bellow this table**		**1.23E-02/y, EF=4**

The rupture failure rate given a leak, ρ3, is estimated as follows: Once a leak exists, the probability of a rupture is theoretically quite large, given the existence of failure mechanisms which can propagate the leak into a rupture, such as water hammer. In reality, both the probability of inspection and detection leaks are closed to 1, considering the ASME Class 1 systems, due to the fact that we have an immediate annunciation in control room.

Therefore, the rupture failure rate given a leak has to consider:

- the leak failure rate,
- the probability that the leak is not inspected, detected and repaired into a given time interval and
- the probability that in the given time interval exist a failure mechanism which propagate the leak into a rupture.

All these factors are already included in the set of differential equation written based on the Markov model above.

If a leak already exists, it is considered that a rupture event can happen only follow a water hammer event, whose frequency was found to be in the area of 1.97E-02/y. [1]

This result is in accordance with the findings on ASME Class 1 piping of KKG, where no events of water hammer happened in 29 years of operation. A Bayesian updating of the generic data found, considering an error factor of 5 and a prior lognormal distribution leads to an updated frequency of water hammer events in KKG of 1.23E-02/y, with error factor 4.

Table 13 - Derivation of rupture/severance rate given an existing part-crack state

Parameter	Definition	Source or method used for estimation	Formula used	Value
$P_{r|crack, <50}$	Conditional probability of rupture given a crack event, for small pipes (Dn<50mm)	OPDE database		0.1
$P_{r|crack, 50-150}$	Conditional probability of rupture given a crack event, for medium pipes (50≤Dn<150)	Ref.3	$P_{r|crack} = \dfrac{2.5}{D_n}$	2.5E-02
$P_{r|crack, 150-220}$	Conditional probability of rupture given a crack event, for medium pipes (150≤Dn<220)	Ref.3	$P_{r|crack} = \dfrac{2.5}{D_n}$	1.35E-02
$P_{r|crack, >220}$	Conditional probability of rupture given a crack event, for large pipes (Dn≥220mm)	Ref.3		1E-02
N	Number of plants with failures in corresponding pipe diameter class	OPDE database		76
T	Time window of plants having failures in corresponding pipe diameter class	OPDE database		35 years
$\rho_{2,<50}$	**Occurrence rate of a rupture/severance from a Category 3 state (crack), Dn≤50**	**Explanations bellow this table**	$\rho_2 = \dfrac{P_{r|crack}}{N \cdot T}$	**3.75E-05/y**
$\rho_{2,50-150}$	**Occurrence rate of a rupture/severance from a Category 3 state (crack), 50<Dn≤150**	**Explanations bellow this table**	$\rho_2 = \dfrac{P_{r|crack}}{N \cdot T}$	**9.39E-06/y**
$\rho_{2,150-220}$	**Occurrence rate of a rupture/severance from a Category 3 state (crack), 150<Dn≤220**	**Explanations bellow this table**	$\rho_2 = \dfrac{P_{r|crack}}{N \cdot T}$	**5.07E-06/y**

| $\rho_{2,>220}$ | Occurrence rate of a rupture/severance from a Category 3 state (crack), Dn>220mm | Explanations bellow this table | $\rho_2 = \dfrac{P_{r \vert crack}}{N \cdot T}$ | 3.75E-06/y |

The conditional probability of a rupture or severance given a through wall crack was calculated, for pipe diameters Dn<50mm, from a direct estimate from OPDE database, as there is a number of 4 ruptures and severances on welds from ASME Class 1 systems, PWR plants, considering as failure causes: fatigue, stress cracking corrosion and manufacturing/ design/ installation errors, on corresponding class diameters. The total number of cracks in OPDE, considering the same boundary conditions is 40. This result in $Pr_{\vert crack,<50}$ - from Table 13.

For pipe diameters 50<Dn≤250, the estimation of Beliczey and Schultz (1990) mentioned in [3] was used, with 2 intermediate pipe diameters dictated by the KKG plant model on previous LOCA Initiating Event frequency calculation. This was performed in terms of equivalent area, which results into the following diameter ranges:
SLOCA with Dn<50 mm
SMLOCA with 50≤Dn<150 mm
LMLOCA with 150≤Dn<220 mm
LLOCA with 220≤Dn≤750 mm
Therefore in estimation of crack frequencies are considered these diameter classes.

Table 14 – Summary table with values of transition failure rates

Name	Value(1/y)	Description
φ_s	6.95E-04	Rate of occurrence of welding failures for Dn<100 mm
φ_l	2.57E-02	Rate of occurrence of welding failures for Dn≥100 mm
λ_1	5.45E-04	Crack failure rate from the total of inspected welds
ω_s	6.75E-03	Repair rate for part-cracks, for Dn<100
ω_l	2.25E-02	Repair rate for part-cracks, for Dn≥100
λ_{Ts}	2.78E-03	Part-cracks, full-cracks failure rate given success state, for Dn<100
λ_{Tl}	1.43E-03	Part-cracks, full-cracks failure rate given success state, for Dn≥100
λ_2	2.29E-04	Leak failure rate from part-crack, full-crack events
λ_{Rs}	2.87E-05	Leaks failure rate from welding failures, for Dn<100
λ_{Rl}	9.86E-06	Leaks failure rate from welding failures, for Dn≥100
μ	8.6E-01	Detection and repair of a leak state
ρ_3	1.23E-02	Rupture/severance failure rate from leaks
$\rho_{2,<50}$	3.75E-05	Rupture/severance failure rate from crack, Dn<50
$\rho_{2,50-150}$	9.39E-06	Rupture/severance failure rate from crack, 50≤Dn<150
$\rho_{2,150-220}$	5.07E-06	Rupture/severance failure rate from crack, 150≤Dn<220

$\rho_{2,>220}$ 3.75E-06   Rupture/severance failure rate from crack, Dn≥220mm

4.2.2   *Results of the analysis*

The results are calculated using Matlab 7.3.0 program, with the solver as ode45 function, with the initial conditions specified in paragraph 4.2.1.3 and having the constant parameters given in Table 14. The results represent the time dependent failure probabilities of C_1(success), C_2(minor flaws), C_3(cracks), C_4(leaks) or C_5(rupture), for the 4 pipe diameter categories mentioned above.
The graphical form of the C_4(leaks) and C_5(rupture) failure probability variation with time for each class of diameters are given below:

Figure 2 – Time dependence of failure probability C_5(rupture) for Dn<50
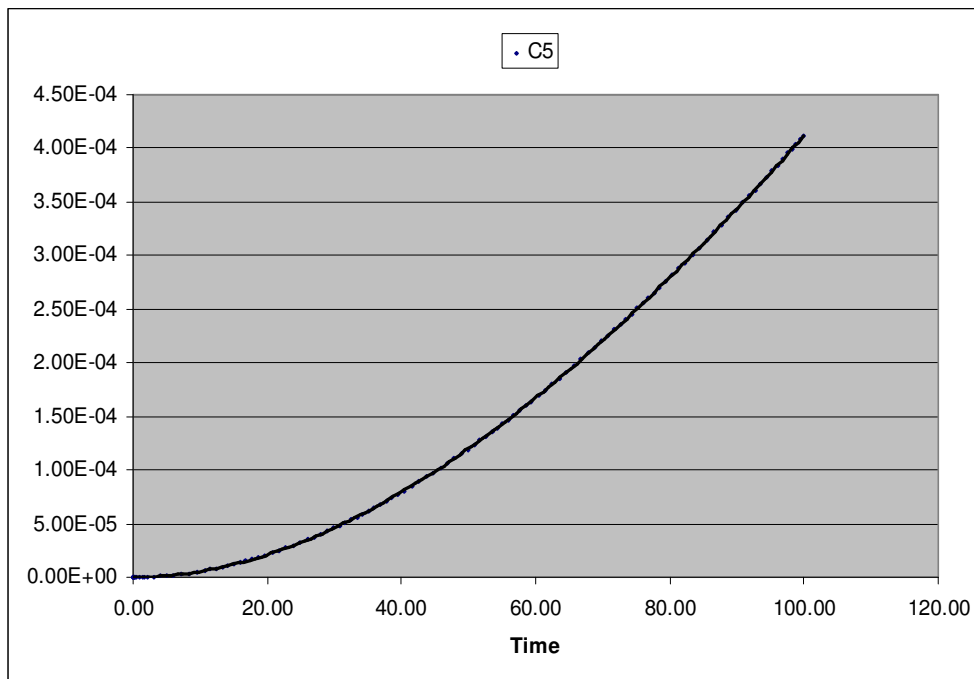
Figure 3 – Time dependence of failure probability C_4(leaks) for Dn<50
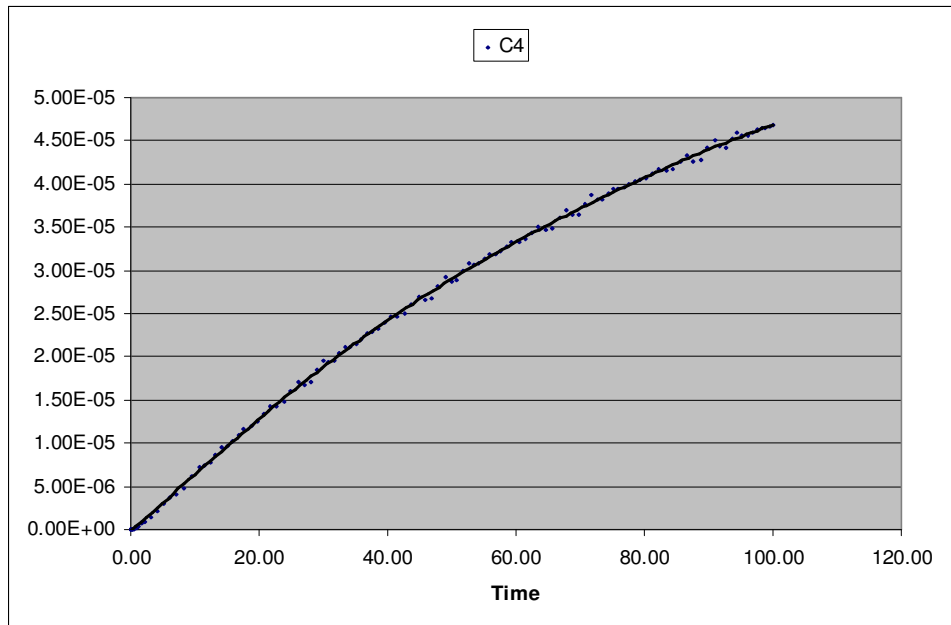
Figure 4 – Time dependence of failure probability C_5(rupture) for $50 \leq Dn < 150$
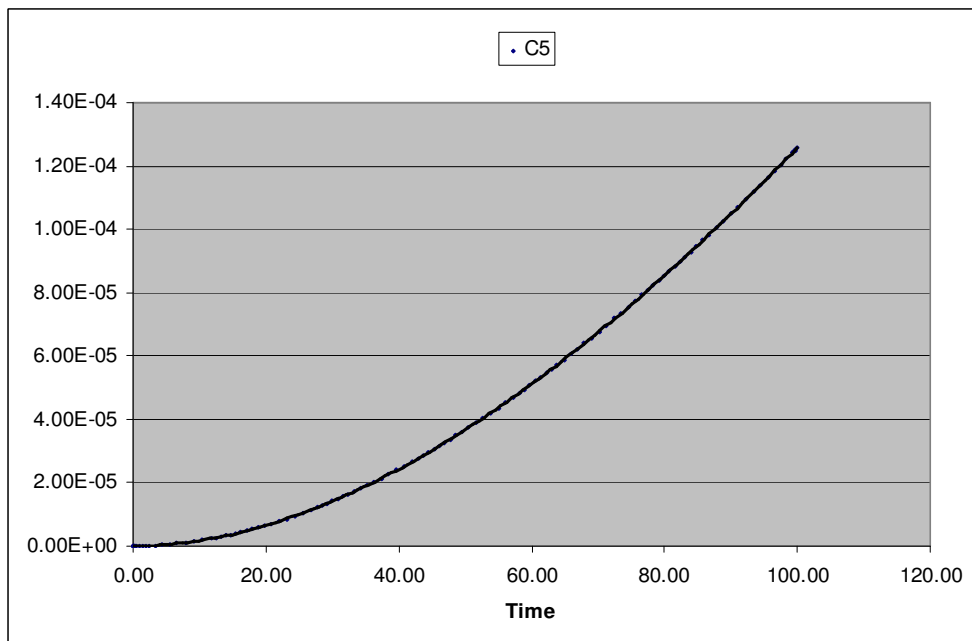
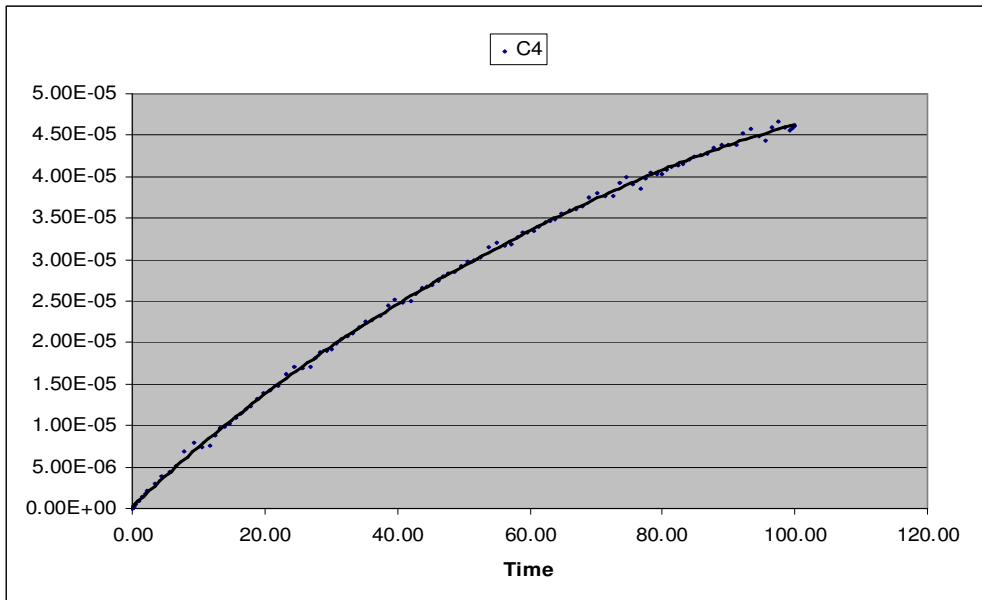Figure 5 – Time dependence of failure probability C_4(leaks) for $50 \leq Dn < 150$

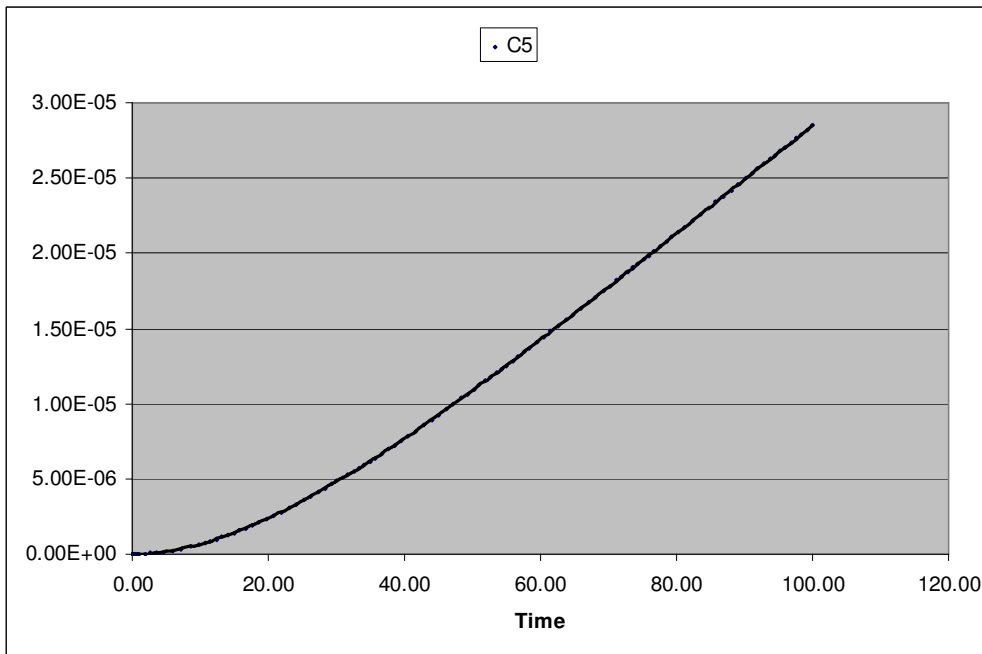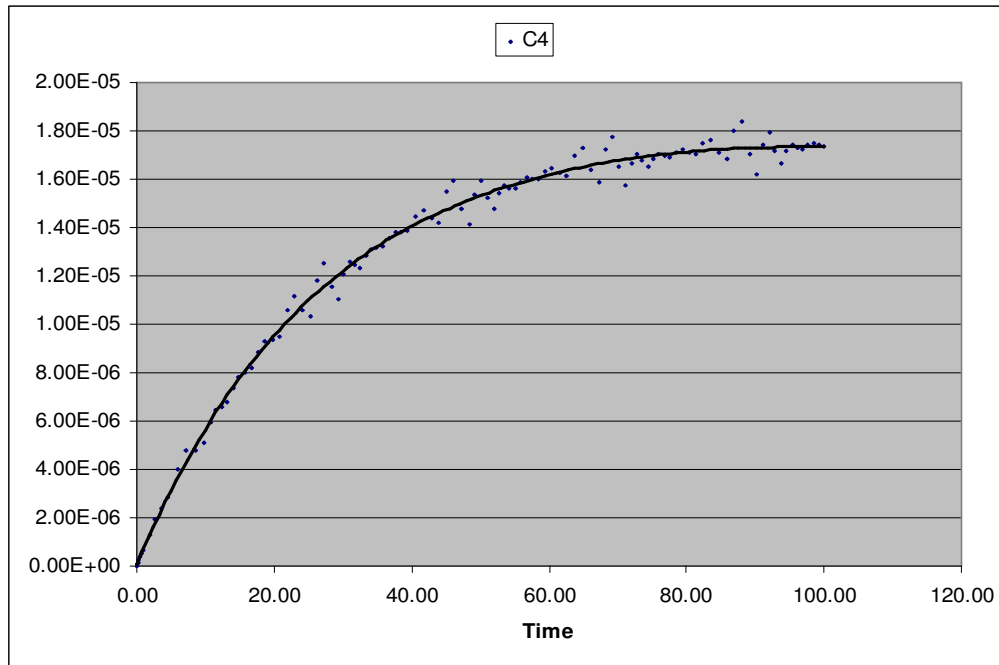Figure 6 – Time dependence of failure probability C_5(rupture) for 150≤Dn<220

Figure 7 – Time dependence of failure probability C_4(leaks) for $150 \leq Dn < 220$

Figure 8 – Time dependence of failure probability C_5(rupture) for $Dn \geq 220$
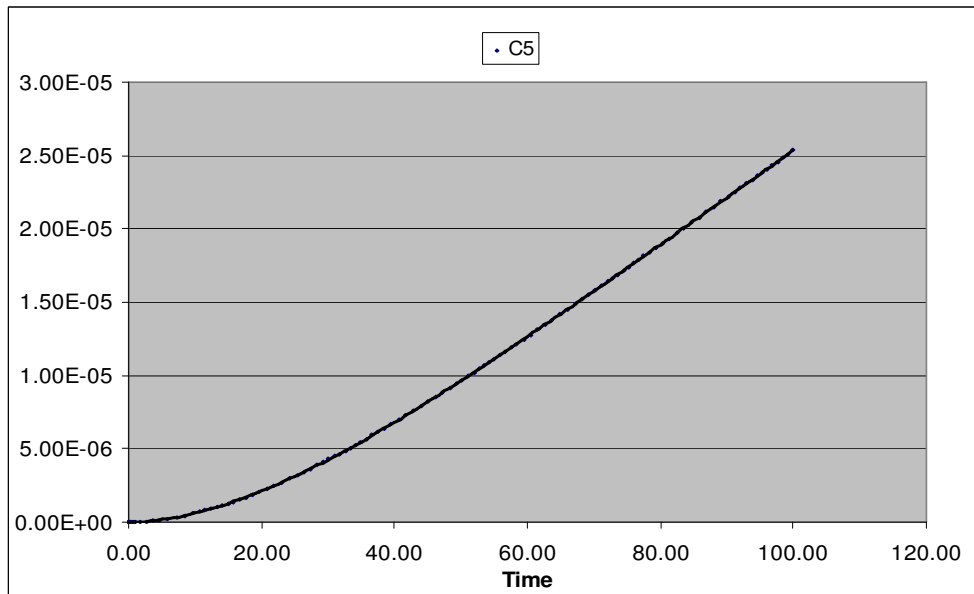

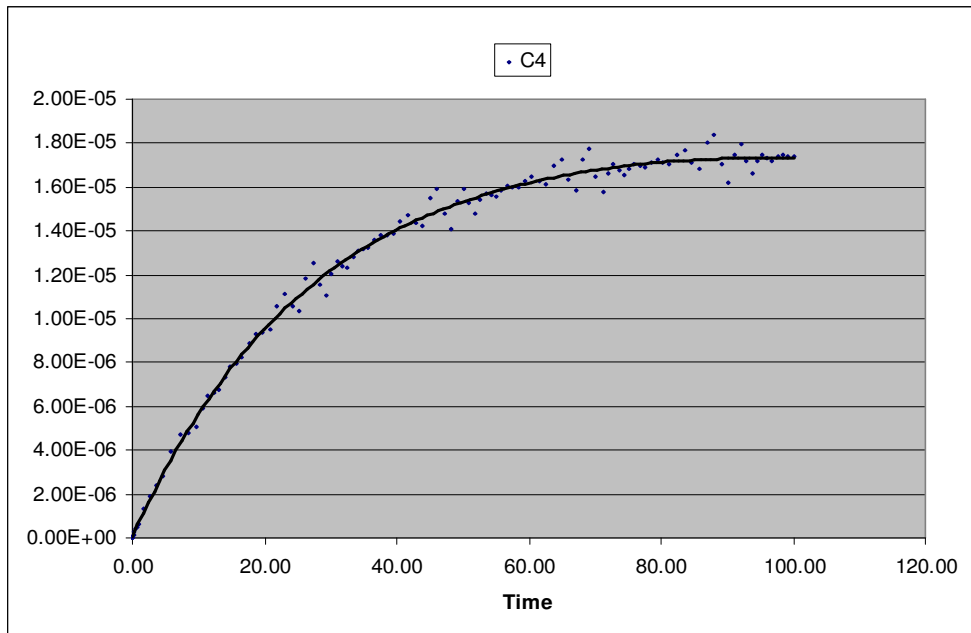Figure 9 – Time dependence of failure probability C_4(leaks) for $Dn \geq 220$

Table 15 - point estimate of rupture failure rates, expressed in events per year, at different time moment of Goesgen NPP plant:

Age (Years)	Rupture rate Dn<50	Rupture rate 50≤Dn<150	Rupture rate 150≤Dn<220	Rupture rate Dn≥220
1	8.50E-08	3.54E-08	1.43E-08	1.27E-08
29	2.78E-06	8.53E-07	2.73E-07	2.4E-07
40	3.67E-06	1.11E-06	3.02E-07	2.68E-07
60	5.00E-06	1.53E-06	3.42E-07	3.03E-07

A sensitivity check on the real percentage of tested welds on Goesgen NPP, based on the finding that the percentage of the inspected welds is larger than the basic percentage indicated by ASME Code XI (paragraph 2.1) revealed the following values of the rupture failure rates, expressed in events per year, at different moment of time.

Table 16 –Rupture failure rates at different age

Age (Years)	Rupture rate Dn<50	Rupture rate 50≤Dn<150	Rupture rate 150≤Dn<220	Rupture rate Dn≥220
1	2.00E-08	1.30E-08	8.27E-09	7.65E-09
29	4.65E-07	1.70E-07	1.24E-07	1.10E-07
40	5.56E-07	2.29E-07	1.31E-07	1.15E-07
60	6.63E-07	2.78E-07	1.50E-07	1.31E-07

The comparison graphs are shown below:

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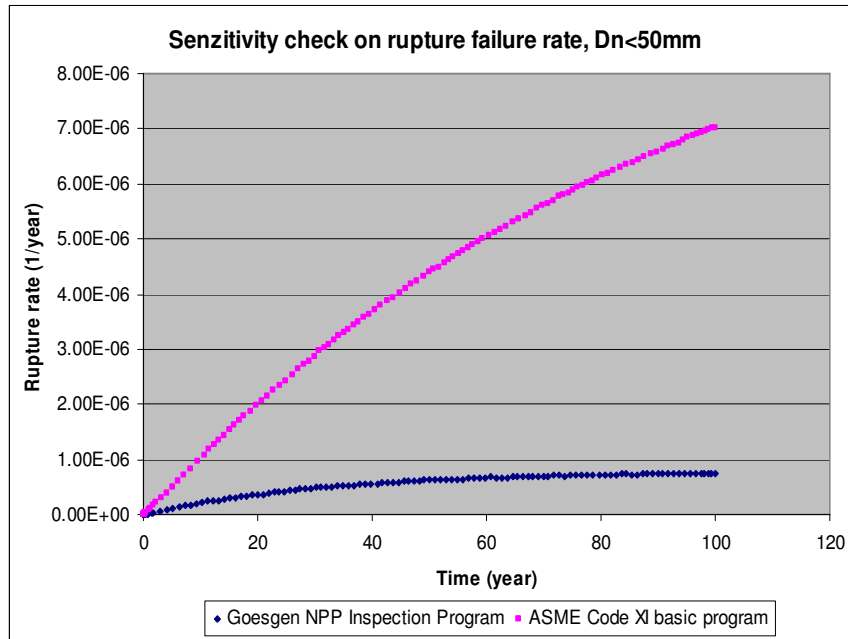Figure 10 – Sensitivity results for rupture failure rate, for Dn<50

Senzitivity check on rupture failure rate, Dn<50mm

Figure 11 – Sensitivity results on rupture failure rate, for 50<Dn<150

Senzitivity check on rupture failure rate, 50<Dn<150 mm
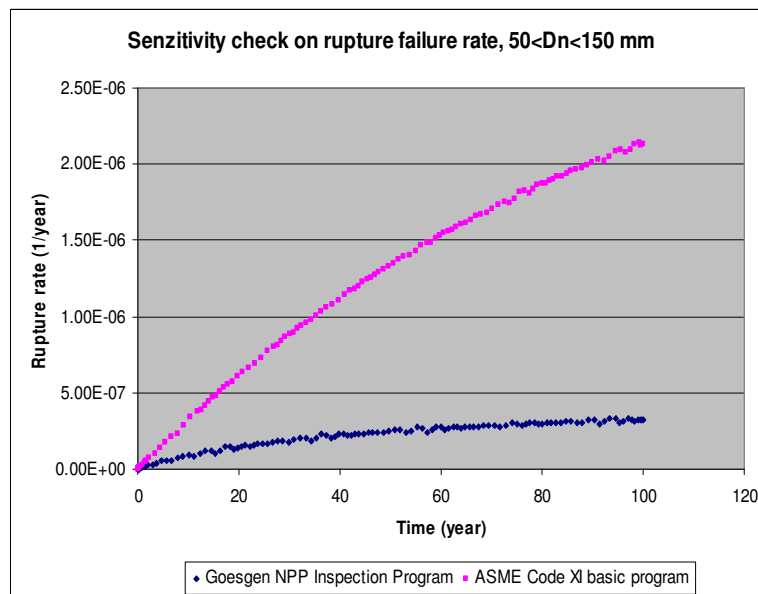
Figure 12 – Sensitivity results on rupture failure rate, for 150<Dn<220

Senzitivity check on rupture failure rate, 150<Dn<220 mm

Y-axis: Rupture rate (1/year)
X-axis: Time (year)

Legend: ◆ Goesgen NPP Inspection Program   ■ ASME Code XI basic program
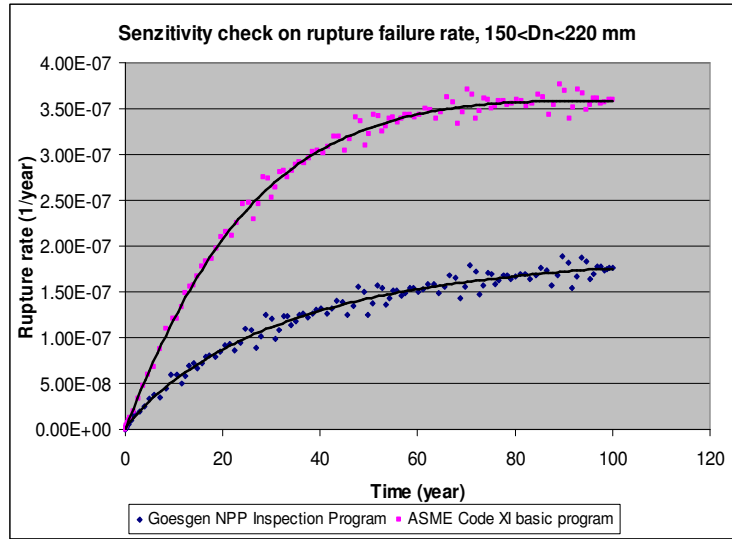
Figure 13 – Sensitivity results on rupture failure rate, for 220<Dn

Senzitivity check on rupture failure rate, 220<Dn mm

Y-axis: Rupture rate (1/year)
X-axis: Time (year)

Legend: ◆ Goegen NPP Inspection Program   ■ ASME Code XI basic program
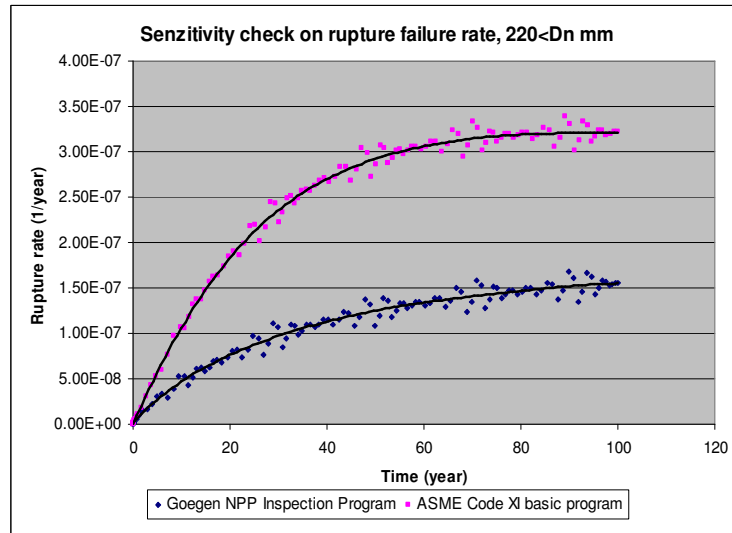
The result of sensitivity analysis shows an approximate 5.5 times larger value at age of 29 years between the rupture rates corresponding to small pipe diameters (Dn<150 mm) and an approximate 2 times larger value at the same age, between rupture rates corresponding to large pipe diameters. This difference in findings between pipe diameters is realistic since the smaller pipes have a larger bias from the basic value than larger pipes, in terms of percentage of pipe inspected. The difference is significant and indicates the effect of over-testing on the piping reliability, however, the economical plant effort of this bias is not considered.

5   SUMMARY AND CONCLUSIONS

The approaches used in the study are very different under aspect of methodology and results:
The EPRI method is using direct statistical estimates of pipe failures from U.S. plants service experience to develop a model which accounts for conditional probabilities of leaks and ruptures in different pipe diameters given the equivalent size breaks in the respective pipes. The method is easy to apply once all the generic values of conditional probabilities and failure rate per section and hour are available in the referenced documentation. The number of pipe section then is relatively easy to estimate given good isometric drawings available for a specific plant. Different degradation mechanisms are account for in a statistical manner, deriving several coefficients which factors out the influence of a specific degradation mechanism when it is known form experience that the mechanism is unlikely to occur in a specific plant.
Ageing influence is studied from the statistical point of view using available data, building the plot of failure rate and deriving the corresponding law by which the failure rate is varying with time.
This plot indicates a decreasing trend of rupture failure rate with age, suggesting a learning process undergone over the whole interval considered (approximately 30 years). This fact is in accordance with expected tendency of pipe failure rate, considering the new technologies used for early detection of pipe flaws, as well as the increasing maintenance crew capability to repair the pipe components damaged by known failure mechanisms.

The Markov method models the piping system as a set of discrete and mutually exclusive states, with the change of state according to occurrence of a failure or a repair instance. The different states are represented by different degree of pipe degradation, under a known set of failure mechanisms. The method is used in several U.S. plants to study the impact of alternative strategies for ISI and leak detection.
The application presented considers the transition rates as point estimates and uses them as constant values into the set of differential equations built. Therefore, the uncertainty in the parameter estimates and its propagation through the model to the final hazard rate distribution remains to be evaluated. In the present model, failure mechanism of interest are those which affect mainly the Reactor Coolant System pipes, i.e. stress corrosion cracking, design/ manufacturing/ construction errors and fatigue caused by vibrations or temperature. These were the main failure causes found in OPDE database and also in KKG database, applicable for PWR plants, ASME Class 1 pipe systems.

The comparison between the values of rupture frequencies and the failure rates obtained using EPRI methodology can be made only on the pipe diameters bigger than 150mm, on both methods, by summing the results obtained for rupture frequencies with Markov on intervals 150<Dn<220 and 220<Dn, as the significance of rupture frequency in Markov model is different from that of EPRI methodology. This comparison reveals differences of about one order of magnitude between the results of the two methods, in the specified interval.

To conclude, some failure mechanisms are more likely to be present early in plant life, like design, manufacture and installation errors, while others will manifest themselves through in-service life, such as cyclic fatigue or erosion/ corrosion, and therefore they can only cause an increase in the failure rate with plant age. According to EPRI pipe section method, this increase seems to be compensated over the plant lifetime by other factors, while according to Markov model, over the plant lifetime the failure mechanisms will lead to a slow and monotonically increase of failure rate during time.

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European Commission

Abstract
The report presents two different models for derivation of plant specific frequency, in case of Loss of Coolant Accident (LOCA), using specific data from Goesgen NPP, as well as data from the OPDE-database. The first model is using the EPRI methodology of pipe section, and the second model is using the Markov modelling for piping reliability assessment.
For both methods, the pipe boundaries are considered to be ASME Class 1 pipes, with diameters between 10 and 750 mm.
The information gathered provides valuable insights with respect to Goesgen pipe reliability and can be used for different applications, as for example the evaluation of LOCA or the frequency of internal floods. The information gathered also provides insights with respect to evaluation of the efficiency of the plant-specific ageing management program.

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