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Applications concerning OECD Pipe Failure Database OPDE

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Applications concerning OECD Pipe Failure Database OPDE

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Summary

This study mainly concerns analysis applications related to OECD Pipe Failure Database OPDE. This database covers all this far experienced nuclear power plant (NPP) piping degradation/failure mechanisms. The scope of potential OPDE database applications is relatively large. Examples of some notable OPDE applications carried out this far are reviewed in this study. From the viewpoint of probabilistic fracture mechanics (PFM) and risk informed in-service inspection (RI-ISI) applications the most useful ones of these applications are the Markov model for piping degradation state analysis by Fleming [8] and the R-Book Project approach for producing reliability data for piping components in Nordic NPPs by Lydell and Olsson [16], respectively.

It is concluded that OPDE data alone do not suffice for estimation of formation frequency and sizes of initial cracks nucleating during service in NPP piping components. For this purpose supplementary data concerning mainly smaller non-through wall flaws, size/shape data of all cracks and piping component populations are needed. These results on the applicability of OPDE were expected, as this database has not been primarily intended for statistical estimates concerning initial cracks. However, as OPDE is continuously developed further, it may in the future be better applicable for this purpose.

For estimation of leak/break frequencies of NPP piping components during service, data concerning e.g. their detected occurrences and occurrence relevant locations are needed. It is concluded that presently OPDE data alone do not suffice for estimation of leak/break frequencies of NPP piping components during service. For this purpose supplementary data concerning piping component populations are needed. However, besides this shortcoming the OPDE data are sufficient for this purpose.

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Preface

This report has been prepared under the research project PURISTA, which concerns Risk Informed In-service Inspection (RI-ISI) analyses of Nuclear Power Plant (NPP) piping systems. The project is a part of SAFIR2010, which is a national nuclear energy research program. PURISTA project work in 2010 was funded by the State Nuclear Waste Management Fund (VYR) and the Technical Research Centre of Finland (VTT). The work was carried out at VTT.

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Contents

1 Introduction

This study mainly concerns analysis applications related to OECD Pipe Failure Database OPDE. This database covers all experienced NPP piping degradation/failure mechanisms. The scope of potential OPDE database applications is relatively large. Examples of some notable OPDE applications carried out this far are reviewed in this study. Concerning the applicability of OPDE database for analysis purposes, this study focuses more on estimation of nucleation frequency and sizes of initial cracks as well as on estimation of leak/break frequencies. As suitable/sufficient piping data were not available, computational application was excluded from the scope of this study. However, the OPDE database was available for the preparation of this study, more precisely the 2009-1 edition.

Also considered in this study is the SCC and Cable Ageing Project (SCAP) database project. SCAP focuses on two degradation mechanisms, SCC and degradation of cable insulation. Unfortunately the SCAP database was not available to this study, thus the coverage is based only on the SCAP guideline [43]. Concerning the applicability of SCAP database for analysis purposes, this study more focuses on estimation of nucleation frequency and sizes of SCC induced initial cracks as well as estimation SCC induced leak/break frequencies.

Next up in Chapter 2 is an overview of OPDE database. It covers the contents of OPDE, potential OPDE applications as well as access to OPDE. Following that in Chapter 3 is a review of OPDE database applications carried out this far. Included in that are ageing trend analysis by Choi et al. [7], Markov model for piping degradation state analysis by Fleming [8], piping damage/rupture frequency analysis by Choi and Choi [9], R-Book Project for producing reliability data for piping components in Nordic NPPs by Lydell and Olsson [16], stochastic model for piping failure frequency analysis by Yuan et al. [21], and application activities in Japan [22]. Then in Chapter 4 is described and weighted the applicability of OPDE database for estimating piping degradation potential. This covers applicability of OPDE for estimating nucleation frequency and sizes of initial cracks as well as leak/break frequencies. Following that in Chapter 5 is considered the applicability of SCAP database for estimating NPP piping degradation potential. This covers an overview of SCAP, applicability of SCAP for estimating nucleation frequency and initial sizes of cracks nucleated by SCC, as well as applicability of SCAP for estimating leak/break frequencies. This study ends with Chapter 6 presenting summary and conclusions.

2 Overview of OPDE database

Several member countries of the Organisation for Economic Co-operation and Development (OECD) have agreed to establish the Piping Failure Data Exchange Project (OECD-NEA OPDE) organised by OECD and Nuclear Energy Agency (NEA) to encourage multilateral co-operation in the collection and analysis of data relating to degradation and failure of piping in nuclear power plants (NPPs). The scope of the data collection includes service induced wall thinning, partially through-wall cracks, through-wall cracks with and without active leakage, and instances of significant degradation of piping pressure boundary integrity [1].

The project was formally launched in May 2002 under the auspices of the OECD/NEA. Organisations producing or regulating more than 80 % of nuclear energy generation worldwide contribute data to the OECD-NEA OPDE data project. By February 2009 eleven countries [2] have signed the OECD OPDE 3rd Term agreement, those being Canada, Czech Republic, Finland, France, Germany, Korea (Republic of), Japan, Spain, Sweden, Switzerland and U.S.A. [1].

A key accomplishment of the OPDE project is the establishment of a framework for the systematic collection and evaluation of service induced piping degradation and failures. Numerous database application projects have been pursued by the project members. These applications have been essential in improving database structure and database field definitions [1]. Each database record consists of 63 database fields, which include narrative descriptions, numeric fields and fields that are represented by roll-down menus with key words for the many piping reliability attributes and influence factors. Included in the database are a NPP information library, and a set of cross-reference tables that address national metallic material designations (carbon steels, copper, stainless steels and nickel-based steels) and plant system nomenclature [20].

The OPDE database has been created with Microsoft® Access database application program, presently the 2007 version is in use. By using this application, it is straightforward to quickly retrieve the desired information from a database and to update and manipulate it. This platform provides various features for creating and editing tables, forms, and reports. Event data can be displayed, sorted, filtered, and grouped according any user-defined set of requirements. Additionally, Access 2007 enables the importing/exporting of data to/from external applications.

2.1 Contents of OPDE database

The OPDE database fields contain data of several types. These data are divided to the following categories (forms): event description, flaw size data, ISI history, root cause information and database management information. Thus besides flaw descriptions OPDE also includes other data, such as plant type, date of start of plant operation, date of flaw detection and material type of the component containing the flaw. Piping component population data, i.e. weld counts and pipe lengths by system and by pipe size, are not yet included in OPDE. As for degradation and failure of pipe components, the OPDE project collects and exchanges involved event data of several types and levels of severity. For non-through-wall cracks the OPDE scope encompasses degradation exceeding allowable design code limits concerning wall thickness or crack depth as well as such degradation that could have generic implications regarding the reliability of in-service inspection (ISI) techniques. In summary, an event involving pipe degradation/failure that results in an action by plant operator (e.g., repair or replacement) is eligible for inclusion in the database. The following types of degraded or failed conditions are considered [20]:

- Non-through wall defects (e.g., cracks, wall thinning) interpreted as structurally significant and/or exceeding allowable maximum size according to the design code in question.
- Through-wall defects without active leakage (leakage may be detected following a plant operational mode change involving depressurization and cool-down, or as part of preparations for non-destructive examination, NDE).
- Small leaks (e.g., pinhole leak, drop leakage) resulting in piping repair or replacement.
- Leaks, i.e. events involving through-wall leak rates within technical specification limits for “unidentified leakage” (typically 0.32 kg/s for BWR plants and 0.06 kg/s for PWR plants).
- Large leaks (through-wall flow rates well in excess of technical specification limits).
- Rupture, or significant structural failure with a significant through-wall flow rate.
- Severance, or structural failure of small-diameter piping.

It is noted that the data submittals by respective national coordinator reflect different national reporting levels and evolution of reporting levels with time. These differences might lead to discrepancies between countries and the extent by which partially through-wall defects are recorded in the database. The database content and structure supports a wide array of applications, including [20]:

- Trend analyses, including ageing analyses.
- Statistical analyses to determine pipe failure rates and rupture frequencies for use in risk-informed activities, e.g., loss-of-coolant-accident (LOCA) frequency assessment, internal flooding initiating frequency assessment, high-energy-line-break frequency assessment, risk informed in-service inspection (RI-ISI) delta-risk assessment.
- Source of data parameters for input to probabilistic fracture mechanics (PFM) based codes.
- Degradation mechanism analyses (DMAs) for development of RI-ISI programs. In such applications, the database provides detailed information on piping system degradation susceptibilities including information concerning precise locations of degradation.
- Development of defence measures against recurring (e.g. systematic) pipe failures.
- Exchange of service data in order to pinpoint potential generic implications of a specific, significant pipe failure.

OPDE addresses typical metallic piping components of the primary system, main process and stand-by safety systems, as well as support systems (i.e., ASME Code Class 1, 2 and 3, or equivalent, piping). It also covers such non-safety-related piping in case of which a leak could lead to common-cause initiating events, e.g. flooding of vital plant areas. In other words, the OPDE database covers degradation and failure of high-energy and moderate-energy piping as well as safety-related and non safety-related piping.

The final version of the 2nd term of the project, OPDE 2008:1, includes approximately 3600 records on pipe failure data from 321 NPPs representing ca. 8300 reactor years of commercial operation. 49 % of these records relate to pressurised water reactors (PWRs), 44 % to boiling water reactors (BWRs) and 4 % to pressurised heavy water reactors (PHWRs) [1]. Summaries of the contents of OPDE database are presented in Tables 2.1-1 and 2.1-2 in the following.

Table 2.1-1. Summary of the contents of OPDE database as a number of records by failure type against pipe size [1].

Nominal Pipe Size (NPS) [mm]	Number of Database Records by Failure Type		
	Non Through-Wall Crack / Wall Thinning	Active Leakage	Structural Failure
NPS ≤ 15	47	227	21
15 < NPS ≤ 25	127	882	41
25 < NPS ≤ 50	75	292	15
50 < NPS ≤ 100	214	240	14
100 < NPS ≤ 250	314	310	39
NPS > 250	544	180	29
Total:	1321	2131	159

Table 2.1-2. Summary of the contents of OPDE database as a number of records by failure type against degradation mechanism [1].

Degradation / Damage Mechanism	Number of Database Records by Failure Type		
	Non Through-Wall Crack / Wall Thinning	Active Leakage	Structural Failure
Corrosion (incl. crevice corrosion, pitting, galvanic corrosion, microbiologically induced corrosion)	45	272	5
Design, construction & fabrication errors	79	239	9
Erosion-corrosion & flow-accelerated corrosion	190	327	50
Stress corrosion cracking (incl., ECSCC, IGSCC, PWSCC, TGSCC)	837	273	0
Thermal fatigue (incl. thermal stratification, cycling and striping)	62	63	3
Vibration fatigue	60	810	48
'Other' (incl., erosion-cavitation, fretting, severe overloading/water hammer, strain induced corrosion cracking (SICC), 'classification pending')	48	147	44
Total:	1321	2131	159

2.2 Potential OPDE database applications

A selection of potential applications has been identified for the OPDE database [4]. Some of these applications will require additional information which is not currently planned to be included in the database.

The list of potential OPDE database applications is as follows [4]:

Applications related to analysis of material degradation;
- Trend analysis of degradation processes; general and related to specific systems or components,
- Identification of new degradation mechanisms,
- Effectiveness of ISI programs, flaws not detected by prior inspections,
- Effectiveness of mitigation measures,
- Understanding of root cause of failures,
- Hazard analysis (Weibull analysis).

Applications related to code development;
- Comparison of service data and PFM calculations using different codes,
- Leak rate versus flaw size correlations,
- Input to structural reliability codes,
- LOCA frequency calculation,
- Input to significance determination process (or equivalent) evaluations,
- Generic structural integrity evaluations.

Applications related to probabilistic safety assessment;
- Internal flooding initiating event frequency calculation,
- Pipe failure rate & rupture frequency calculation,
- High-energy line break frequency calculation,
- Accident sequence precursor evaluations.

Applications related to risk-informed regulation;
- Leak-before-break (LBB) evaluations,
- RI-ISI program development,
- Ageing management program input,
- Proactive materials degradation assessment.

General plant safety & operations support;
- Source (knowledge base) for solving practical piping problems,
- Source of information for specifying locations for measurements such as temperature,
- Classification of piping systems,
- Recommendation for content of incident reports,
- Operating experience feed-back,
- Input to training material for new generation of nuclear engineers.

2.3 OPDE Database access

OPDE is a restricted database and its access is limited to participating organizations that provide the input data. An OPDE Light database is available to enable contractors performing database related activities for project member organisations access to the necessary information. OPDE Light includes an excerpt of information from the restricted database version and any proprietary information has been excluded. Respective national coordinators are responsible for distribution of OPDE Light in their country [20]. Further information is available on the Nuclear Energy Agency website (www.nea.fr).

3 Review of OPDE database applications

A review of some notable OPDE database applications developed/performed this far is presented in the following.

3.1 Database insights and pipe failure rate estimations – Lydell and Fleming, USA

Lydell has made extensive analyses and illustrations on the database contents. Results and insights from OPDE first term (2002-2005) are summarised in [5]. As an example, following passive component risk-importance insights have been obtained from the OPDE service experience [5]:

- On a worldwide basis, socket weld failures in Code Class 1 and Class 2 piping are relatively frequent occurrences. Socket welded fittings are found in small-diameter piping such as instrument lines, drain lines and high-point vent lines. While of moderate safety significance, a socket weld failure invariably requires a forced reactor shutdown, cool down to cold shutdown, and containment entry by repair personnel. A typical outage lasts from a few days to more than a week. These failures tend to be caused by high-cycle vibratory fatigue, often in combination with a weld defect (for example, lack of fusion).
- The Service Water System is an important support system providing cooling water to various heat exchangers throughout a NPP. Depending on the type of piping material and chemical treatment of the raw water, this system is prone to various forms of corrosion as well as flow-induced pipe wall thinning. A structural failure of Service Water System piping could lead to major flooding of vital equipment areas and challenge the safe shutdown of a NPP.

Lydell has also performed together with Fleming several piping reliability analyses based on the OPDE database, such as high energy line break evaluations and raw water piping reliability analysis [27, 28]. The models and approaches used in estimating failure rates and rupture frequencies from piping event database are presented e.g. in [6]. Similar approach is applied in the R-book project. A significant uncertainty in estimating reliability parameters using OPDE database arises from the fact that the OPDE database does not include piping component and weld population data. In some applications, engineering judgement has been used to estimate the population data. Lydell has also used the PIPExp database, which is a proprietary database including the same failure data as OPDE, but also population data from 21 plants, including safety-related piping and non-code piping.

3.2 Ageing trend analysis - Choi et al., Republic of Korea

Choi et al. [7] presented the first study of ageing trend analysis using data from 212 PWRs contained in the OPDE data until 2004. The total sample consisted of 1424 records collected from January 1970 onwards, which is equivalent to 4609 operating years.

In order to assess the ageing trend the data was pooled according to ref. [7] in three different ways. Firstly, the pipe failure (leak) database was pooled to three reporting intervals, as follows: (1) 1970–1984, (2) 1984–1994, and (3) 1994–2004. The leak frequency in each interval was assumed to be constant. The leak frequency exhibited a decreasing trend. It decreases approximately from 0.6 leaks/year for 1984 group to 0.35 leaks/year for 1994 group to 0.3 leaks/year for 2004 group.

In the second method, the plants were categorized according to the operating years. Three groups were formed, as follows: (1) young plants with of age 0–15 years (28 plants, 284.6 reactor years), (2) intermediate plants with of age 15–25 years (119 plants, 2427 reactor years), and (3) old plants with of age 25–35 years (63 plants, 1863 reactor years). The leak frequency in older plants, being 0.4/year, was approximately four times higher than that in the young plant, being 0.1/year, respectively. The reasons for this were given as lower level of design, construction, and maintenance in old plants as compared to the newer plants.

In the last method, starting dates for all the plants were moved to a common origin: January 1, 1970. The entire data were categorized into six groups at an interval of five calendar years. This analysis showed that the leak frequency typically decreases with plant ageing and then it increases slightly for old plants after 20 years of operation.

It should be noted that this method groups data in a heuristic manner and adopts a constant frequency homogeneous Poisson process model for each data group.

3.3 Markov model for piping degradation state analysis – Fleming, USA

Fleming presented a Markov model application for piping degradation state analysis [8]. The objective of this approach is to explicitly model the interactions between failure mechanisms that produce failures, and the inspection, detection and repair strategies that can reduce the probability that failures occur, or that cracks or leaks will progress to ruptures before being detected and repaired. This Markov modelling technique starts with a representation of a system in a set of discrete and mutually exclusive states. At any time instant, the system is permitted to change state in accordance with whatever competing processes are appropriate for that plant state. In this application of the Markov model the states refer to various degrees of piping system degradation, i.e. the existence of flaws, leaks or ruptures. The flaws can be cracks or wall thinning depending on the prevailing failure mechanism at each pipe location. The processes able to create a state change are the failure mechanisms experienced by the pipe and the processes of inspecting or detecting flaws and leaks, and repair of damage prior to the progression of the failure mechanism to rupture.

The general four state Markov model for all experienced piping failure mechanisms is illustrated in Figure 3.3-1 below. The physical explanations of the associated parameters are given right after Figure 3.3-1.

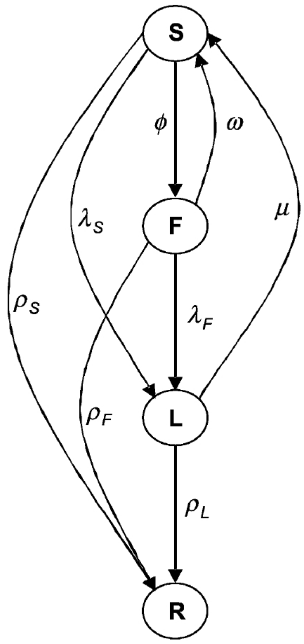

Figure 3.3-1. The general four state Markov model for all experienced piping failure mechanisms [8].

The physical explanations of the parameters in Figure 3.3-1 are as follows:

Pipe reliability states;

- S is success, no detectable damage,
- F is detectable flaw (non-through wall),
- L is detectable leak,
- R is rupture.

State transitions;

- ϕ is rate of non-through wall flaw occurrence,
- λ_S is leak failure rate given success,
- λ_F is leak failure rate given flaw,
- ρ_S is rupture failure rate given success,
- ρ_F is rupture failure rate given flaw,
- λ_L is rupture failure rate given leak,
- ω is repair rate in connection with ISI,
- μ is repair rate in connection with leak detection.

Each failure mechanism can cause a leak type failure mode, which is detected and repaired, a leak failure mode which remains undetected and later progresses to a rupture, or an immediate rupture failure mode without first causing a leak. The Markov model in Figure 3.3-1 accounts for all of these failure modes due to any known failure mechanism, or combination of failure mechanisms. These four mutually exclusive time dependent pipe states are obtained by solving a specified set of differential equations. Then the time dependent hazard rate for pipe ruptures, $h(t)$, is defined as:

$$h(t) = \frac{1}{(1-\mathrm{R})} \cdot \frac{d\mathrm{R}}{dt} = \frac{\rho_\mathrm{S} \cdot \mathrm{S} + \rho_\mathrm{F} \cdot \mathrm{F} + \rho_\mathrm{L} \cdot \mathrm{L}}{\mathrm{S} + \mathrm{F} + \mathrm{L}} \quad (3.3\text{-}1)$$

For estimating all of the Markov model parameters, i.e. those shown in Figure 3.3-1, Fleming [8] presents applicable strategies. Also, the general form of the Markov model presented in Figure 3.3-1 can be simplified somewhat for pipe locations that do not involve severe loading conditions but are susceptible to a damage mechanism such as SCC, erosion–corrosion, etc. For these locations, a leak or rupture can only occur from the state of an existing flaw, eliminating some of the transitions permitted by the general model. Then one or more of the model parameters become zero, which allows for easier solving of the associated differential equations.

In general, a point estimate of the frequency of pipe failure events, covering here both leaks and ruptures, is given by the following expression:

$$\lambda = \frac{n_{\mathrm{F}}}{N \cdot T} \qquad (3.3\text{-}2)$$

where n_{F} is the number of failure events including both leaks and ruptures in the service data, T is the total time over which failure events were collected, and N is the number of components that provided the observed pipe failures. Note that when using equation (3.3-2) to estimate conditional failure rates for the Markov model the failure events are counted only for the appropriate failure mechanism and the component population is only that portion of the total population that is susceptible to that failure mechanism.

The model for relating failure rates and rupture frequencies is given as follows:

$$\rho_{ijk} = \lambda_{ijk} \cdot P_{ik}\{\mathrm{R}|\mathrm{F}\} \qquad (3.3\text{-}3)$$

where: ρ_{ijk} is rupture frequency of pipe of size i in system j due to damage mechanism k,
λ_{ijk} is failure rate of pipe of size i in system j due to damage mechanism k,
$P_{ik}\{\mathrm{R}|\mathrm{F}\}$ is conditional probability of rupture given failure for pipe size i and damage mechanism k.

According to Fleming [8] the Markov model has been demonstrated to be a useful tool to study the impact of alternative strategies for in-service inspection and leak detection. Together with appropriate estimation of its input parameters, the model allows making reasonable predictions of time dependent piping system reliability as well as changes in risk due to changes in the leak detection and in-service inspection programs. The key input to the quantification of the Markov model is an appropriate set of input data that describe the frequency of piping system damage states and failure modes due to applicable failure mechanisms.

These input data can be obtained from piping system service data, pipe failure databases such as OPDE, LBB models, PFM models, and combinations of these. The frequency of piping flaws and cracks are conveniently estimated in terms of multiples of piping system failures that include both leaks and ruptures.

3.4 Piping damage/rupture frequency analysis - Choi and Choi, Republic of Korea

In the evaluation of nuclear piping failure frequency using the OPDE Database, Choi and Choi [9] used the information of Korean PWRs in the database to estimate the piping damage frequency and the piping rupture frequency. For a specific diameter pipe in a particular system, they used the following expression to calculate a point estimate for piping damage frequency:

$$\lambda = \frac{n_f}{\sum_{i=1}^{N_p} N_{c,i} \cdot T_i} \quad (3.4\text{-}1)$$

where n_f is the number of damage events for a specific pipe diameter in the system, N_p is the number of plants in question, N_c is the number of pipe components with the specified diameter and T_i is duration of the operational year for each plant. Clearly, this method requires the pipe component population data, which typically are not available. To evaluate the piping rupture frequency, the authors employed both Bayesian approach and the conditional rupture probability approach. Both approaches were found to give comparable results.

3.5 R-Book Project for producing reliability data for piping components in Nordic NPPs – Lydell and Olsson, Sweden

A current research and development project in Sweden, called The R-Book Project, is focused on producing reliability data for piping components in Nordic NPPs, see report [16]. This report constitutes a planning document for a piping component reliability parameter handbook for use in probabilistic safety assessment (PSA) and related activities. The Swedish acronym for this handbook is "R-Book." The objective of the project is to utilise the OPDE database to derive piping component failure rates and rupture probabilities for input to internal flooding PSA, high-energy line break (HELB) analysis, RI-ISI program development and other activities related to PSA. Phase 1 of the project has been documented in the report [16], and more recent developments are documented, for example, in conference papers [17]. A final report on the R-book project is forthcoming in 2011.

When completed, the R-Book will contain tabulations of piping reliability parameters that are organised according to plant system, material (e.g. carbon steel, stainless steel) and nominal pipe diameter. In addition to the derived statistical parameters (e.g. mean, median, 5th and 95th percentiles) of pipe leak rates and rupture frequencies, the handbook will also include qualitative information with respect to piping failure histories and the various structural integrity management programs that have been developed to address certain degradation mechanisms. The piping reliability parameters will be specialised in such a way that appropriate and reasonable account is taken of the Nordic design and inspection practices as well as service experience. Besides OPDE, leak and failure rate data are also collected e.g. from NUREG-1829 reports [25, 26], from EPRI Report No. 1012302 [27] and from pipe failure rates applicable to HELB analysis [28]. Scope for the R-book was revised [17] to include mainly Code Class 1 and 2 piping components, as EPRI data are available for other cases.

For assessment of pipe component rupture frequency the following reliability model, being a slightly modified version of that presented by Fleming [29], is proposed to be used in the R-book approach [17]:

$$\rho_{ix} = \sum_{k=1}^{M_i} \rho_{ikx} = \sum_{k=1}^{M_i} \lambda_{ik} \cdot P_{ik}\left\{R_x \middle| F\right\} \tag{3.5-1}$$

where: ρ_{ix} is total rupture frequency for pipe component *i* for rupture mode *x*, as corresponding to significant structural failure with through-wall flow rate well in excess of technical specification limits,
ρ_{ikx} is rupture frequency of pipe component *i* due to damage mechanism *k* for failure mode *x*,
λ_{ik} is failure rate of pipe component *i* due to damage mechanism *k*,
$P_{ik}\left\{R_x \middle| F\right\}$ is conditional probability of rupture mode *x* given failure for pipe component *i* and damage mechanism *k*,
M_i is number of different damage mechanisms for component *i*, and

Here the term “failure” implies any degraded state requiring remedial action: from part through-wall crack, pinhole leak, leak, large leak to a significant incapacitating structural failure. Types of remedial actions include repair (temporary or permanent), in-kind replacement or replacement using new, more resistant material. Depending on how this piping reliability model is to be used, the precise definition of failure may be important. For example, it may be important to make distinction between different through-wall flaw sizes and their localised effects or global effects on plant operation. PSA applications often require assessments of well differentiated pipe failure modes.

In general, a point estimate of the frequency of pipe failure, λ_{ik}, is given by the following expression:

$$\lambda_{ik} = \frac{n_{ik}}{f_{ik} \cdot N_i \cdot T_i} \tag{3.5-2}$$

where: n_{ik} is the number of failures (all modes including cracks, leaks and ruptures are included) events for pipe component *i* due to damage mechanism *k*,
T_i is the total exposure time over which failure events were collected for pipe component *i*, typically expressed in terms of reactor years (or calendar years),
N_i is the number of components per reactor year that provided the observed pipe failures for pipe component *i*, and
f_{ik} is the fraction of number of components of type *i* that are susceptible to failure from degradation/damage mechanism (DM) *k* for conditional failure rates given susceptibility to DM *k*, this parameter is set to 1 for unconditional failure rates.

When the parameter f_{ik} is applied the resulting failure rates and rupture frequencies are referred to as conditional failure rates as they are conditional on the susceptibility of the component to specific damage mechanisms. That is, for each component that these models are applied to, the damage mechanism susceptibility is known.

When the damage mechanism susceptibility is not known in advance the above equations are combined under the condition: f_{ik} = 1 to obtain the following expression for the point estimate of the rupture frequency:

$$\rho_{ix} = \sum_{k=1}^{M_i} \rho_{ikx} = \sum_{k=1}^{M_i} \lambda_{ik} \cdot P_{ik}\{R_x|F\} \cdot I_{ik} = \sum_{k=1}^{M_i} \frac{n_{ik}}{N_i \cdot T_i} \cdot P_{ik}\{R_x|F\} \cdot I_{ik} \qquad (3.5\text{-}3)$$

Depending on the type of piping system under consideration, the conditional failure probability may be obtained by direct statistical estimation, or using PFM, or expert judgment. Ultimately an estimated conditional failure probability needs to reflect existing service experience as well as structural integrity characteristics.

A Bayesian approach can be used to develop uncertainty distributions for the parameters in equations (3.5-1) to (3.5-3). Prior distributions are developed for the parameters λ_{ik} and $P_{ik}\{R_x|F\}$, which in turn are updated using the evidence from the failure and exposure data as in standard Bayes updating. The resulting posterior distributions for each parameter on the right side of equation (3.5-1) are then combined using Monte Carlo sampling to obtain uncertainty distributions for the pipe rupture frequency.

For the conditional pipe failure probability, four approaches are proposed to be used in the R-book approach [16]: 1) direct statistical estimation, 2) PFM, 3) expert judgment, or 4) combined approach using insights from data analysis, PFM and expert judgment. A limitation of the first approach is the scarcity of applicable data. Different PFM procedures have been developed and it is an area that continues to evolve.

For assessment of inspection effectiveness the Markov modelling approach presented by Fleming [8] is also proposed to be used in the R-book approach [16]. This approach enables the analysis of interactions between degradation/ damage mechanisms causing pipe failures and the inspection, detection and repair strategies that can reduce the failure probability, or that cracks or leaks will progress to major structural failure before being detected and repaired.

Ref. [17] presents an update to the R-book methodology based on the project work and experiences. This is an advancement from the phase 1 planning detailed in ref. [16]. The work process used to generate the piping failure rates based on the principle of equation (3.5-3) was completed in several steps, as described in the following:

- Extracting data from OPDE Light;
  In this step the data is filtered according to pipe dimensions, plant type (PWR/BWR) and degradation mechanisms. The aim is to obtain a set of calculation cases for each combination of component type and degradation mechanism.
- Plant population data – defining the exposure term;
  The exposure term is the denominator in equation (3.5-3), which includes the amount of observed items and their time in operation. These data are obtained from Scandpower proprietary PIPExp database.
- Qualitative analysis;
  The service history of the data is examined qualitatively. The aim is to establish the homogeneity level of the source data, and identify any notable biases. Additionally, any ambiguous classifications are eliminated and the boundaries between classes are sharpened. It is also determined if statistical analysis is possible for the examined population.

- Definition and set up of a calculation case;
  - Matching of susceptibility vs. actual observations;
    The calculation case should be based on an assumption on which degradation mechanisms are likely to be found in certain systems. The database includes cases which are highly unlikely in terms of combination of material, degradation mechanism, code class, component type and dimensions. Also such cases should be included for which there are zero observations (meaning prior data would be used in the Bayes process).
  - Compiling the empirical input;
    A complete set of failures is compiled, in order to solve equation (3.5-3). This includes: failures together with exposure term are used to update failure rate prior, relevant number of ruptures to the corresponding failures to update the prior for conditional probability of structural failure and the total number of components and corresponding observation time.
  - Matching of populations;
    The three populations from the previous step are matched so that all OPDE events belonging to a certain case are matched to the corresponding component population.
- Presentation and interpretation of results;
  The main results for each calculation case are presented. The unit is failure/(component*year) where failure is understood as a breach of a certain magnitude. The failure rate, λ, i.e. failure irrespective of potential flow, is also presented.

3.6 Stochastic model for piping failure frequency analysis - Yuan et al., Canada

The accurate estimation of piping failure frequency is an important support for PSA and RI-ISI of NPPs. Probabilistic models have been reported in the literature for analysing the piping failure frequency. Yuan et al. [21] propose a stochastic point process model that incorporates both a time dependent trend and plant specific (or cohort) effects on the failure rate. A likelihood based statistical method is proposed for estimating the model parameters. Yuan et al. [21] also present a case study for analysing the Class 1 pipe failure data given in the OPDE database.

Although pipe failures are affected by several factors, there are two time scales attached to each failure event. One is the calendar date and the other is plant age.

NPPs constructed and operated during different time periods employ different levels of technological sophistication. The newer plants have more advanced technology, materials, construction and inspection tools, and are hence expected to have lower pipe failure rates than the older plants. Thus, depending on the calendar date of construction, plants can be categorised in different cohorts. This variation between the plants in pipe failure rates due to difference in the cohort age is referred to as the cohort effect. This effect is quantified by the plant cohort age, denoted by τ, which is the time interval between the date of start of operation and a reference date of January 1, 1960, as most NPPs were built after 1960. Theoretically, a larger cohort age means a newer plant, being technologically more advanced and consequently less prone to pipe failures.

The other time scale likely to affect the failure rate is the plant age, denoted by t, at the time of a pipe failure. It is simply the time interval between the date of start of operation and the time of a pipe failure event. In general, it is known that failure events of a system follow a bath-tub pattern [23], which includes a burn-in phase, randomly failing or service life and wear-out or ageing stage. Depending on the plant age, the failure rate may be decreasing, constant, or increasing. This is referred to as the ageing effect on the failure rate.

For a single NPP, let $0 \leq T_1 < T_2 < \ldots$ denote the failure times, i.e. plant age. It is proposed to consider these failures as a point process and $N(t) = \sum_{k=1}^{\infty} I(T_k < t)$ records the cumulative number of failures generated by the underlying point process. $I(T_k < t)$ is an indicator function, which equals 1 if $T_k < t$ and 0 otherwise. Quite often a point process can be described uniquely by the intensity function, $\lambda(t)$, defined as the instantaneous probability of an event occurring at time t. The proposed intensity function is as follows:

$$\lambda(t) = \alpha \cdot \beta \cdot t^{\beta-1} \cdot \exp(\gamma \cdot \tau) \qquad (3.6\text{-}1)$$

When $\beta < 1$ the pipe failure rate is decreasing, suggesting that the plant is in a burn-in stage. When $\beta = 1$, the piping failures follow a homogeneous Poisson process and the plant is in the random failing service life, whereas for $\beta > 1$ it is assumed that the plant is ageing.

The proposed non-homogeneous Poisson process model includes three unknown parameters: α, β and γ, which can be estimated with the maximum likelihood method. It is assumed that a sample for a plant consists of n failure times $t_0 \leq t_1 < t_2 < \ldots < t_n < t_e$, where t_0 denotes the starting time of the considered time span, which equals zero or the plant age on January 1, 1970, whichever is less, and t_e denotes the end of the considered time span, which equals the operational lifetime or plant age on June 30, 2007, whichever is less. The cumulative likelihood function for pipe component failures, L, is then expressed as [24]:

$$L = \exp\left\{-\int_{t_0}^{t_e} \lambda(u)du\right\} \cdot \prod_{j=1}^{n} \lambda(t_j) \qquad (3.6\text{-}2)$$

When the plant has not experienced failures during the observed time window from t_0 to t_e, the corresponding likelihood function is:

$$L = \exp\left\{-\int_{t_0}^{t_e} \lambda(u)du\right\} \qquad (3.6\text{-}3)$$

Assuming the failure events in one plant are independent of the failures in another plant, then the total log-likelihood function is just the summation of the log-likelihoods for each plant. Therefore, taking the intensity function in the form of equation (3.6-1), we have for the ith plant, with failure times $t_{i0} \leq t_{i1} < t_{i2} < \ldots < t_{in} < t_{ie}$, the log-likelihood function, l_i, as:

$$l_i = n_i \cdot (\log\alpha + \log\beta + \gamma \cdot \tau_i) + (\beta - 1) \cdot \sum_{j=1}^{n_i} \log t_{ij} + \alpha \cdot \exp(\gamma \cdot \tau_i) \cdot \left(t_{i0}^{\beta} - t_{ie}^{\beta}\right) \qquad (3.6\text{-}4)$$

Correspondingly, the log-likelihood function for a plant without pipe failures is:

$$l_i = \exp(\gamma \cdot \tau_i) \cdot \left(t_{i0}^{\beta} - t_{ie}^{\beta}\right) \qquad (3.6\text{-}5)$$

Further simplifications lead to the following expression:

$$l = N \cdot \log \alpha + N \cdot \log \beta + \gamma \cdot \sum_{i=1}^{m} n_i \cdot \tau_i + \beta \cdot \sum_{i=1}^{m} \sum_{j=1}^{n_i} \log t_{ij} + \alpha \cdot \sum_{i=1}^{m} \exp(\gamma \cdot \tau_i) \cdot \left(t_{i0}^{\beta} - t_{ie}^{\beta}\right) \qquad (3.6\text{-}6)$$

where $N(t) = \sum_{i=1}^{m} n_i$ is the total number of observed failures, and m is the total number of considered plants. Maximisation of equation (3.6-6) gives the maximum likelihood estimates of α, β and γ.

The novel feature of the non-homogeneous Poisson process model for describing the piping failure events proposed by Yuan et al. [21] is that it considers the cohort effect in a statistically consistent manner along with the ageing effect on the failure rate. The cohort effect is representative of the improvements in plant technology, design, and materials. The proposed model can be used to analyse any other stochastic event data. The OPDE data set regarding leakage in Class 1 piping of BWRs and PWRs in the U.S. were analysed in detail. According to ref. [21] statistically significant cohort effect is present in the leak rate. In general, the leak rate exhibits a decreasing trend with the plant age. This implies that the plants are not experiencing increase in leak rates due to ageing, or that the inspection/maintenance programs are effective in preventing leaks.

3.7 Application activities in Japan – Ogiya, Japan

The Japan Nuclear Energy Safety Organisation (JNES) has identified several application activities for the OECD database [22]:

- Development of countermeasures to prevent piping failure occurrences including improvement of operating experience feedback.
- Qualitative evaluations of failure trends and patterns applied to ageing management.
- Risk informed applications in support of development of RI-ISI program or PSA to determine pipe failure rates and rupture frequencies.
- Advanced applications supporting material science research, i.e. source of data parameters for input to PFM codes.

OPDE is used to review events reported in the database and derive lessons learnt from the information on incidents and failures in Japan and other countries. Further, the knowledge and information from OPDE is fed back to the ageing management programme, to enhance the technical basis for ageing management implementation. The implementation plans for risk-informed nuclear safety regulation include activities for data collection and preparation of parameters to be used in PSA, such as piping failure rates and initiating event frequencies, which are supported by using OPDE. JNES also provides improvement and verification activities concerning PFM codes.

4 Applicability of OPDE database for estimating piping degradation potential

The applicability of OPDE database for estimating piping degradation potential is considered in the following. On the top level the scope divides to two parts, which are:

- applicability of OPDE for estimating nucleation frequency and sizes of initial cracks in piping components,
- applicability of OPDE for estimating leak/break frequencies concerning piping components.

Due to limitations of the contents of OPDE the emphasis on the first part is mainly on the database and procedure development needs, with some examples concerning existing procedures for estimating the nucleation frequency and sizes of initial cracks in NPP piping components. Whereas the second part concerning the applicability of OPDE for estimating leak/break frequencies for piping components mainly provides discussion and recommendations concerning the procedures reviewed earlier in Chapter 3.

4.1 Applicability of OPDE for estimating nucleation frequency and sizes of initial cracks

Several targets of application can be envisaged for estimates concerning nucleation frequency and sizes of initial cracks in NPP piping components. Of the potential applications involving OPDE, as listed earlier in Section 2.2, these mainly concern applications related to analysis of material degradation, to code development and to risk-informed regulation.

When concerning PFM and RI-ISI applications, estimates of nucleation frequency and sizes of initial cracks are needed as input data in the involved computations. Together with an estimate of density of fabrication induced cracks/flaws they give an assessment of the scale and unit/system specific density of the expected piping degradation, as to be taken into account during the operational lifetime of NPPs.

On applicability of OPDE for estimating nucleation frequency of initial cracks

For estimation of nucleation frequency of initial cracks in NPP piping components during service, data concerning both detected cracks and crack nucleation relevant locations are needed. In addition to crack population data, also needed are data concerning associated degradation mechanism(s), pipe component material(s) and size, location of crack in pipe component (weld, HAZ or base material), plant type, system in question, start time of plant operation, time of crack detection as well as plant population data and piping component population data including weld counts. Having such data would allow producing degradation mechanism, material type, pipe size, plant and system specific statistical crack nucleation frequency estimates. It is realised, that dividing the already relatively scarce crack data to this many sub-groups would remarkably decrease the already limited accuracy of the possible estimates. Also, to take into account ageing phenomena and on the other hand improvements in accuracy of ISI techniques, the estimates should be at least on a crude/discrete level time dependent. For instance Bayesian approach can be used for updating the frequency estimates after plant modifications/changes, such as changes in process chemistry or temperature. As is typical in case of piping leak/rupture frequencies, also crack nucleation frequencies need to be expressed per year per relevant location (typically weld). The accuracy of statistical estimates can be improved with expert judgement analyses, for a detailed more recent application of this approach see NUREG-1829 report [25, 26]. The SRM approaches can be to a limited extent of use in improving the accuracy of crack initiation frequencies, and then mainly in form of comparisons. For instance, a SRM based procedure for initiation frequency of fatigue induced cracks is presented in the NUREG/CR-6674 report [30], whereas a procedure for initiation frequency of stress corrosion cracking (SCC) induced cracks in NUREG/CR-6986 report [31], respectively.

As for the database scope requirements, data concerning all detected cracks are needed when producing statistical estimations for nucleation frequency of initial cracks. Thus data on both all detected through wall and non-through wall flaws are needed. The crack data concerning the former category are well covered in OPDE. However, concerning detected non-through wall flaws, only such cases which have been interpreted as structurally significant and/or exceeding allowable maximum size according to the design code in question are included in OPDE. For instance, for shorter cracks the maximum allowable depth according to Section XI of the ASME Code [32] is 75 % of wall thickness. Thus it appears that a remarkable portion of detected non-through wall flaws are excluded from OPDE.

There are also other challenges related to estimation of nucleation frequency of initial cracks in NPP piping components. Namely, the degradation mechanism driving crack propagation may not be the same as the one that nucleated the crack. For instance, a crack nucleated by fatigue could be propagated by SCC, or vice versa. Here screening criteria provide at least part of needed additional information. For instance, only certain materials are susceptible to SCC and only under certain conditions, whereas under low-cycle conditions with relatively low load amplitudes susceptibility to fatigue is not significant. Also, erosion corrosion (E-C) and flow assisted corrosion (FAC) have been detected mainly from piping components of certain material type. However, after such screening still a notable number of cases is left for which the degradation mechanism having caused the crack initiation should be confirmed. The limitations in accuracy of ISI should also be taken into account when estimating frequency of cracks initiating during service. The capability of ISI to detect flaws is often estimated using probability-of-detection (POD) functions, and for NPP piping components applicable PODs are given e.g. in NUREG/CR-3869 [33] and NUREG/CR-6986 [31] reports.

Partly the grown cracks have started from flaws originating from manufacturing. The existing manufacturing flaws are typically relatively small, as the larger ones have been detected in the pre-service tests, and the associated components have been removed or repaired. Almost any degradation mechanism can start to propagate a manufacturing crack. However, it can be approximated that most manufacturing cracks are located in welds made in site. If more accurate data are not available, pipe size specific estimates of the density of manufacturing flaws in NPP piping welds given in ref. [34] may be used. Thus, when the population of all initial cracks have been estimated, it should be decreased by the estimated number of manufacturing cracks to obtain the estimated number of cracks initiating during service.

Having estimated the crack population data, the next step towards estimating the nucleation frequency of initial cracks is to obtain data concerning crack nucleation relevant locations. Often only piping welds are considered. However, in some cases a wider scope can be useful and/or more realistic. Berg et al. [35] discuss on degradation relevant locations in NPP piping systems. In addition to welds, locations with abrupt geometry change or with small radii can be prone to crack initiation, due locally elevated stresses and/or their fluctuations acting in such sites. Berg et al. [35] recommend turning to degradation databases such as OPDE when identifying possible degradation relevant locations. OPDE does contain quite detailed descriptions concerning the locations of the detected cracks. However, piping component population data, i.e. weld counts and pipe lengths by system and by pipe size, are not yet included in OPDE. In the current version of the OPDE Coding Guideline [36] it is mentioned that the development of piping population data is the responsibility of the respective National Coordinator. When domestic piping population data are not available, population data published in NUREG/CR-4407 report [37] or in SKI Report 98:30 [38] may be applicable.

When both the population of cracks initiating during service and population of crack nucleation relevant locations have been estimated, the next and final step would be to estimate the nucleation frequency of initial cracks. This could be realised using as modified equation (3.3-2) for point estimate of frequency of pipe failure events, which is almost the same as equation (3.5-2). The main difference between these two equations is that the latter one of them additionally introduces the parameter f_{ik} for the fraction of number of components of type i that are susceptible to failure from DM k for conditional failure rates given susceptibility to DM k. In case of equation (3.3-2), it could be modified/developed to allow estimating the nucleation frequency of initial cracks as follows:

$$\lambda = \frac{n_{\mathrm{CI}}}{N_{\mathrm{CL}} \cdot T_{\mathrm{CT}}} \qquad (4.1\text{-}1)$$

where as compared to equation (3.3-2) the parameter n_{F} is replaced with the estimated population of cracks initiating during service, n_{CI}, parameter N with the estimated number of crack nucleation relevant locations, N_{CL}, whereas parameter T with the total time over which the crack initiation data were collected, T_{CT}, respectively.

On applicability of OPDE for estimating sizes of initial cracks

For estimation of sizes of initial cracks in NPP piping components, data concerning all detected cracks are needed. In addition to crack sizes, also needed are data on associated pipe component shape, dimensions and material type, location of crack in the pipe component (weld, HAZ or base material), plant type, system in question, start time of plant operation, as well as load, process chemistry, ISI, repair, weld treatment (as-welded or post-weld heat treated) and replacement histories. Having such data would allow producing degradation mechanism, material type and process condition specific estimates of probabilistic size distributions for initial cracks. It is realised, that dividing the already relatively scarce crack data to this many sub-groups would remarkably decrease the already limited accuracy of the possible estimates. Typically separate probabilistic distributions in form of probabilistic density functions (PDFs) are developed for depth and length of initial cracks.

As for the scope requirements for the database, mainly size data concerning non-through wall flaws are needed when developing probabilistic distributions for sizes of initial cracks. As mentioned earlier, data on detected non-through wall flaws are poorly presented in OPDE. On the other hand, the lack of piping component population data in OPDE is not a drawback or obstacle in the size estimation of initial cracks.

The development of probabilistic distributions for initial crack sizes must at least partly be based on size data concerning detected grown cracks. In such a task involving recursive estimation SRM approaches, PFM in particular, and expert judgement are needed. Several approaches for recursive assessment of initial crack sizes can be envisaged. To better clarify these issues, two such approaches applicable to NPP piping components are briefly described in the following. The considered degradation mechanisms are the two most often encountered ones in the NPP piping systems, i.e. SCC and fatigue.

The first approach, leaning more to expert judgement, is to obtain the available and applicable crack data, assemble it as a function of relative number of cases from smallest to largest crack sizes (considering either depth or length), select a reasonably realistic initial crack size mean value and lower by offset the size data values so that the cumulative 50 % value equals the mentioned mean value and then fit a suitable probabilistic distribution function to thus treated data so that its integral over wall thickness equals one. This approach has been applied e.g. by Brickstad [39].

The second approach, being mainly based on PFM, also starts with obtaining the available and applicable crack data, and then assembling it as a function of relative number of cases from smallest to largest crack sizes (considering either depth or length). The next step is to select suitable fracture mechanics handbook equations or a fracture mechanics based analysis tool and applicable crack growth equation, and then calculate for a large enough number of crack sizes recursively the initial sizes, using as criterion mode I stress intensity factor, K_I [MPa√m], value for SCC and K_I range, ΔK_I [MPa√m], value for fatigue induced cracking, both of which values are obtained from fracture mechanics handbooks, and then fit a suitable probabilistic distribution function to thus treated data so that its integral over wall thickness equals one. When performing fracture mechanics based recursive computations, it must also be taken into account that the covered time span is not allowed to exceed the current time in operation. Typically crack growth equations for SCC are expressed as a function of time, whereas those for fatigue induced cracking as a function of load cycles, which in turn are composed of load transients that occur in time. This approach has been applied e.g. by Cronvall and Alhainen [40].

To summarise, the estimation of size distributions for initial cracks is in several ways a challenging task, containing several sources of uncertainty. As for crack data, these uncertainties relate to quality, amount, origin and type. Quality relates to correctness of diagnosing the degradation mechanism that caused cracking. Amount relates to problems associated with scarceness of available crack data. Origin relates to the applicability of crack data from other plants to the considered plant. Finally, type relates to the fact that existing crack data concern only grown cracks, and thus the sizes of the initial cracks have to be somehow assessed recursively. Based on their uncertainty analyses Simonen and Khaleel conclude [41] that input data concerning initial crack distributions are the greatest source of uncertainty in calculations of piping failure probabilities. On the other hand, the failure probability assessment accuracy requirements in RI-ISI do not necessitate highly accurate physical modelling of the prevailing degradation mechanisms and loads concerning them, instead it suffices to achieve a reasonable accuracy scale, e.g. one decade in the failure probability exponent.

Summary of applicability of OPDE for estimating nucleation frequency and sizes of initial cracks

For estimation of nucleation frequency of initial cracks in NPP piping components during service, data concerning both detected cracks and crack nucleation relevant locations are needed. When dividing the already relatively scarce OPDE data to data sub-sets e.g.

according to degradation mechanism, pipe size, plant type and system as well as time, it would remarkably decrease the accuracy of possible statistical estimates. The crack data concerning through wall flaws are well covered in OPDE, however data on non-through wall flaws are limited to cases that are interpreted as structurally significant and/or exceeding allowable maximum size according to the design code in question. Thus OPDE data need to be supplemented with data concerning smaller non-through wall flaws, as data covering all crack sizes are needed for estimation of nucleation frequency of initial cracks. Data screening of OPDE should be confirmed as well, as the degradation mechanism driving crack propagation may not be the same as the one that nucleated the crack. When the population of all initial cracks have been estimated, it should be decreased by the estimated number of manufacturing cracks to obtain the estimated number of cracks initiating during service. OPDE does not contain information concerning the origin of the cracks. Also needed are data concerning crack nucleation relevant locations. Piping component population data, i.e. weld counts and pipe lengths by system and by pipe size, are not yet included in OPDE. In the current version of the OPDE Coding Guideline [36] it is mentioned that the development of piping component population data is the responsibility of the respective National Coordinator.

It is concluded that OPDE data alone do not suffice for estimation of nucleation frequency of initial cracks in NPP piping components during service. For this purpose supplementary data concerning mainly smaller non-through wall flaws and piping component populations are needed. Also more extensive data screening and treatment need to be carried out than covered by the guideline documentation associated with OPDE. These results on the applicability of OPDE were expected, as this database has not been primarily intended for statistical estimates concerning initial cracks. However, as OPDE is continuously developed further, it may in the future be better applicable for this purpose.

For recursive estimation of probabilistic size distributions for initial cracks in NPP piping components, data concerning all detected cracks are needed. In addition to crack sizes, also needed are data on degradation mechanism, associated pipe component shape, dimensions and material type, location of crack in the pipe component (weld, HAZ or base material), plant type, system in question, time of start of plant operation, as well as load, process chemistry, ISI, repair, weld treatment (as-welded or post-weld heat treated) and replacement histories. Again it is realised, that dividing the already relatively scarce crack data to this many data sub-sets would remarkably decrease the accuracy of possible statistical estimates. Besides crack size/shape data, all other above mentioned data are well available in OPDE. Of the crack size/shape data in OPDE more than 90 % are leaks or breaks, i.e. through wall cases. In most/all of these cases no other crack shape data besides depth are given, i.e. the fields concerning crack aspect ratio and length have been left empty. So there is quite little crack shape data in OPDE. Thus in addition needing to supplement OPDE with data concerning smaller non-through wall flaws, as mentioned earlier, also crack aspect ratio and length data of all cracks are needed for estimation of sizes of initial cracks.

It is concluded that OPDE data alone do not suffice for estimation of sizes of initial cracks nucleating in NPP piping components during service. For this purpose supplementary data concerning mainly smaller non-through wall flaws and size/shape data of all cracks are needed. Also more extensive data screening and treatment need to be carried out than covered by the guideline documentation associated with OPDE. These results on the applicability of OPDE were expected, as this database has not been primarily intended for statistical estimates concerning initial cracks. However, as OPDE is continuously developed further, it may in the future be better applicable for this purpose.

4.2 Applicability of OPDE for estimating leak/break frequencies

Several targets of application can be envisaged for estimates concerning leak/break frequencies of NPP piping components. Of the potential applications involving OPDE, as listed earlier in Section 2.2, these mainly concern applications related to analysis of material degradation, to code development, PSA and to risk-informed regulation.

For estimation of leak/break frequencies of NPP piping components during service, data concerning both their detected occurrences and occurrence relevant locations are needed. In addition to leak/break data, also needed are data concerning associated degradation mechanism(s), pipe component material(s) and size, location of crack in pipe component (weld, HAZ or base material), plant type, system in question, start time of plant operation, time of leak/break detection as well as plant population data and piping component population data including weld counts. Having such data would allow producing degradation mechanism, material type, pipe size, plant and system specific statistical leak/break frequency estimates. Again it is realised, that dividing the already relatively scarce crack data to this many sub-groups would remarkably decrease the already limited accuracy of the possible estimates. Also, to take into account ageing phenomena the estimates should be at least on a crude/discrete level time dependent. For instance Bayesian approach can be used for updating the frequency estimates after plant modifications/changes. Like in case of estimating nucleation frequency of initial cracks, the accuracy of statistical estimates can be improved with expert judgement analyses, see e.g. NUREG-1829 report [25, 26]. The SRM approaches can be useful in improving the accuracy of leak/break frequencies, and then mainly in form of crack growth simulations. An applicable SRM analysis tool can be found e.g. amongst those benchmarked in the quite recent NURBIM (Nuclear Risk Based Inspection Methodology) project [42]. In NURBIM a benchmark study for SCC and fatigue induced crack growth was conducted with six established SRM codes, those being NURBIT, PRODIGAL, ProSACC, PROST, STRUREL and WinPRAISE.

Data concerning detected leaks/breaks are well covered in OPDE. Then the next step towards estimating leak/break frequencies is to obtain data concerning leak/break occurrence relevant locations. Often only piping welds are considered. However, in some cases a wider scope can be useful and/or more realistic, as described earlier in Section 4.1. Thus also here it is a drawback that OPDE does not yet contain piping component population data. When domestic piping population data are not available either, data published in NUREG/CR-4407 report [37] or in SKI Report 98:30 [38] may be applicable.

When both the population of leaks/breaks and population of relevant locations prone to leaks/breaks have been estimated, the next and final step would be to estimate the leak/break frequencies. This can be carried out using either equation (3.3-2) or equation (3.5-2).

It is concluded that presently OPDE data alone do not suffice for estimation of leak/break frequencies of NPP piping components during service. For this purpose supplementary data concerning piping component populations are needed. However, besides this shortcoming the OPDE data are sufficient for the present purpose. Moreover, among the planned developments concerning OPDE is to supplement it with piping population data, and when this has been completed OPDE as such will be a sufficient data source for estimation of leak/break frequencies of NPP piping components.

5 Applicability of SCAP database for estimating piping degradation potential

The applicability of SCAP database for estimating piping degradation potential is considered in the following. This begins with a brief overview of SCAP database. Following that is discussed the applicability of SCAP for estimating nucleation frequency and sizes of initial cracks. Finally is described the applicability of SCAP for estimating leak/break frequencies.

5.1 Overview of SCAP database

Two subjects, SCC and degradation of cable insulation, were selected as the focus of the SCC and Cable Ageing Project (SCAP) [43] due to their relevance for plant ageing assessment and their implication on nuclear safety. In order to achieve that goal, 14 NEA member countries joined the project in 2006 to share knowledge and three more countries joined during the course of the project. The International Atomic Energy Agency (IAEA) and the European Commission participated as observers.

The objective of this internationally coordinated project is to share the corporate knowledge and operating experience to understand SCC and cable ageing as well as identify effective techniques and technologies to manage and mitigate active degradation in NPPs. The specific objectives of the project are to [43]:
(1) establish a complete database with regard to major ageing phenomena for SCC and degradation of cable insulation through collective efforts by NEA members,
(2) establish a knowledge base in these areas by compiling and evaluating the collected data and information systematically,
(3) perform an assessment of the data and identify the basis for recommendable practices which help regulators and operators to enhance ageing management.

Concerning SCC the scope of the event database, knowledge base and recommendable practices covers class 1 and 2 pressure boundary components, reactor pressure vessel internals and other components with significant operational impact, excluding steam generator tubing. The ageing mechanisms included in the event database and materials affected, (base metal, weld metal and cladding) are [43]:

- IGSCC (intergranular SCC) of stainless steel,
- IGSCC of Ni-based alloy including PWSCC (primary water SCC),
- IASCC (irradiation assisted SCC),
- TGSCC (transgranular SCC),
- ECSCC (external chloride SCC),
- SICC (strain induced corrosion cracking),
- corrosion fatigue/environmental fatigue.

The entire SCC database consists of an event database and general information. The general information covers regulations/codes and standards, inspection/monitoring/qualification, preventive maintenance/mitigation, repair/replacement, safety assessment as well as research and development. Together these comprise the knowledge base.

In the top level the data in the Event database part is divided to event narrative, in-service inspection history, root cause information, and flaw size information. The flaw data are further divided to through-wall cracks without active leakage, partial through-wall cracks and different types of leaks. All in all there are 11 fields with information that characterizes the flaw.

Most members of the SCAP SCC working group are also members of the OPDE project. It was agreed at a very early stage that the SCAP-SCC event database would be based on the OPDE database following a review of the fields and identification of additional fields. Events could then be extracted from OPDE and comprise a major part of the SCAP-SCC event database. The SCAP event database contains more than 1600 data records, see Figure 5.1-1 below.

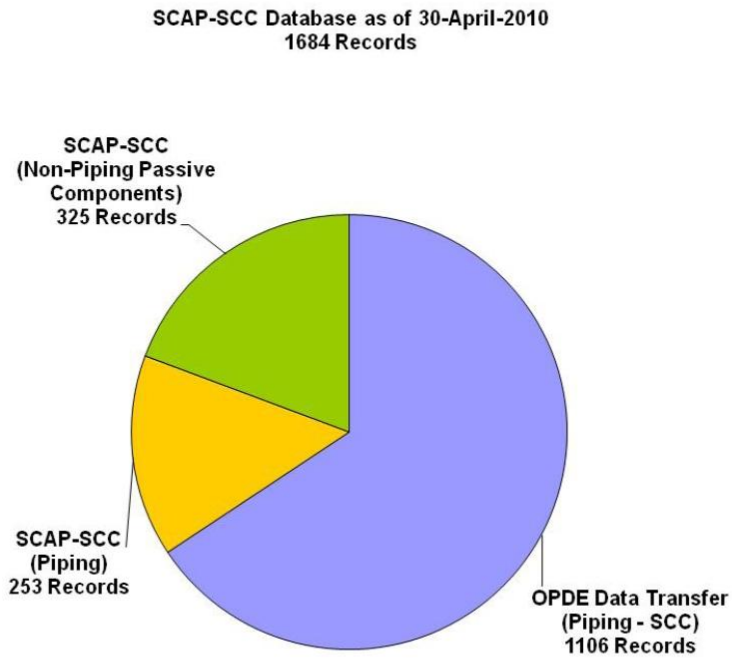

Figure 5.1-1. Distribution of the data populated in SCAP SCC database [43].

The cable database covers safety related cables that support emergency core cooling, safety cables (required to prevent and mitigate design basis event) and cables important to plant operation (cables whose failure could cause a plant trip or reduction in plant power). The scope of the database includes cables with voltage levels up to 15 kV AC and 500 V DC, including instrumentation and control (I&C) cables. The cable database is organised in 10 parts to document all the details of the cables including design, qualification, maintenance, condition monitoring and continuing research.

5.2 Applicability of SCAP for estimating nucleation frequency and sizes of cracks initiated by SCC

The scope of SCAP SCC database is similar to that concerning OPDE but limited to consider only SCC. Thus the approaches and limitations concerning estimating nucleation frequency and sizes of initial cracks in connection to OPDE described in Sections 4.1 and 4.2 also mostly apply to SCAP on the behalf of SCC, and therefore only summary on these issues is presented here.

For estimation of nucleation frequency of cracks initiated by SCC in NPP piping components during service, data concerning both detected cracks and crack nucleation relevant locations are needed. When dividing the already relatively scarce SCAP data to data sub-sets e.g. according to pipe size, plant type and system as well as time, it would remarkably decrease the accuracy of possible statistical estimates. The data concerning through wall SCC flaws are well covered in SCAP, however data on non-through wall SCC flaws are limited to cases that are interpreted as structurally significant and/or exceeding allowable maximum size according to the design code in question. Thus SCAP data need to be supplemented with data concerning smaller non-through wall SCC flaws, as data covering sizes of all SCC induced cracks are needed for estimation of nucleation frequency of cracks initiated by SCC. Data screening of SCAP should be confirmed as well, as the degradation mechanism that nucleated the crack may not be SCC. When the population of all cracks initiated by SCC have been estimated, it should be decreased by the estimated number of manufacturing cracks to obtain the estimated number of cracks initiated by SCC during service. SCAP does not contain information concerning the origin of the cracks. Also needed are data concerning SCC nucleation relevant locations. Piping component population data, i.e. weld counts and pipe lengths by system and by pipe size, are not yet included in SCAP.

It is concluded that SCAP data alone do not suffice for estimation of nucleation frequency of cracks initiated by SCC in NPP piping components during service. For this purpose supplementary data concerning mainly smaller non-through wall SCC flaws and piping component populations are needed. Also more extensive data screening and treatment need to be carried out than covered by the guideline documentation associated with SCAP. However, as SCAP is continuously developed further, it may in the future be better applicable for statistical estimates concerning nucleation frequency of initial SCC induced cracks.

For recursive estimation of probabilistic distributions of initial sizes of cracks nucleated by SCC in NPP piping components, data concerning all detected SCC cracks are needed. In addition to crack sizes, also needed are data concerning associated pipe component shape, dimensions and material type, location of crack in the pipe component (weld, HAZ or base material), plant type, system in question, start time of plant operation, as well as load, process chemistry, ISI, repair, weld treatment (as-welded or post-weld heat treated) and replacement histories. Again it is realised, that dividing the already relatively scarce crack data to this many data sub-sets would remarkably decrease the accuracy of possible statistical estimates. Thus SCAP data need to be supplemented with size/shape data concerning smaller non-through wall SCC flaws.

It is concluded that SCAP data alone do not suffice for estimation of initial sizes of cracks nucleated by SCC in NPP piping components during service. For this purpose supplementary data concerning at least smaller non-through wall flaws and size/shape data of all SCC induced cracks are needed. Also more extensive data screening and treatment need to be carried out than covered by the guideline documentation associated with SCAP. However, as SCAP is continuously developed further, it may in the future be better applicable for statistical estimates concerning sizes of initial SCC induced cracks.

5.3 Applicability of SCAP for estimating leak/break frequencies

The scope of SCAP SCC database is similar to that concerning OPDE but limited to consider only SCC. Thus the approaches and limitations concerning estimating leak/break frequencies in connection to OPDE described in Section 4.3 also mostly apply to SCAP on the behalf of SCC, and therefore only summary of this issue is presented here.

Data concerning detected SCC induced leaks/breaks are well covered in SCAP. Then the next step towards estimating frequencies of SCC induced leaks/breaks is to obtain data concerning leak/break occurrence relevant locations. Often only piping welds are considered. However, in some cases a wider scope can be useful and/or more realistic, as described earlier in Section 4.1. Thus also here it is a drawback that SCAP does not yet contain piping component population data. When domestic piping population data are not available either, data published in NUREG/CR-4407 report [37] or in SKI Report 98:30 [38] may be applicable.

When both the population of SCC induced leaks/breaks and population of relevant locations prone to SCC induced leaks/breaks have been estimated, the next and final step would be to estimate the frequencies of SCC induced leaks/breaks. This can be carried out using either equation (3.3-2) or equation (3.5-2).

It is concluded that presently SCAP data alone do not suffice for estimation of frequencies of SCC induced leaks/breaks of NPP piping components. For this purpose supplementary data concerning piping component populations are needed. However, besides this shortcoming the SCAP data are sufficient for the present purpose. Moreover, as SCAP is continuously developed also this missing piping component population data may be supplemented to it in the future.

6 Summary and conclusions

This study mainly concerns analysis applications related to OECD Pipe Failure Database OPDE. This database covers all experienced NPP piping degradation/failure mechanisms. The scope of potential OPDE database applications is relatively large, see Section 2.2. Examples of some notable OPDE applications carried out this far are reviewed in Chapter 3. From the viewpoint of PFM and RI-ISI applications the most useful ones of these applications are the Markov model for piping degradation state analysis by Fleming [8] and the R-Book Project approach for producing reliability data for piping components in Nordic NPPs by Lydell and Olsson [16], respectively.

Concerning the applicability of OPDE database for analysis purposes, this study focuses more on estimation of nucleation frequency and sizes of initial cracks as well as on estimation of leak/break frequencies. As suitable/sufficient piping data were not available, computational application was excluded from the scope of this study. However, the OPDE database was available for the preparation of this study, more precisely the 2009-1 edition. The main result of this study is the detailed assessment of applicability of OPDE for estimation of the above mentioned crack nucleation and leak/break frequencies as well as for probabilistic distributions of initial crack sizes.

For estimation of nucleation frequency of initial cracks in NPP piping components during service, data concerning e.g. detected cracks and crack nucleation relevant locations are needed. The crack data concerning through wall flaws are well covered in OPDE, however data on non-through wall flaws are limited to cases that are interpreted as structurally significant and/or exceeding allowable maximum size according to the design code in question. Also, OPDE does not yet contain piping component population data. It is concluded that OPDE data alone do not suffice for estimation of nucleation frequency of initial cracks in NPP piping components during service. For this purpose supplementary data concerning mainly smaller non-through wall flaws and piping component populations are needed. These results on the applicability of OPDE were expected, as this database has not been primarily intended for statistical estimates concerning initial cracks. However, as OPDE is continuously developed further, it may in the future be better applicable for this purpose.

For recursive estimation of probabilistic size distributions for initial cracks in NPP piping components, data concerning e.g. all detected cracks are needed. Of the crack size/shape data in OPDE more than 90 % are leaks or breaks, i.e. through wall cases. In most/all of these cases no other crack shape data besides depth are given, i.e. the fields concerning crack aspect ratio and length have been left empty. It is concluded that OPDE data alone do not suffice for estimation of sizes of initial cracks nucleating in NPP piping components during service. For this purpose supplementary data concerning mainly smaller non-through wall flaws and size/shape data of all cracks are needed. These results on the applicability of OPDE were expected, as this database has not been primarily intended for statistical estimates concerning initial cracks. However, as OPDE is continuously developed further, it may in the future be better applicable for this purpose.

For estimation of leak/break frequencies of NPP piping components during service, data concerning e.g. their detected occurrences and occurrence relevant locations are needed. Also, OPDE does not yet contain piping component population data. It is concluded that presently OPDE data alone do not suffice for estimation of leak/break frequencies of NPP piping components during service. For this purpose supplementary data concerning piping component populations are needed. However, besides this shortcoming the OPDE data are sufficient for the present purpose. Moreover, among the planned developments concerning OPDE is to supplement it with piping population data, and when this has been completed OPDE as such will be a sufficient data source for estimation of leak/break frequencies of NPP piping components.

Also considered in this study is the SCC and Cable Ageing Project (SCAP) database project. This project focuses on two degradation mechanisms, SCC and degradation of cable insulation. Unfortunately the SCAP database was not available to this study, thus the coverage was based only on the SCAP guideline [43]. Concerning the applicability of SCAP database for analysis purposes, this study more focuses on estimation of nucleation frequency and sizes of SCC induced initial cracks as well as estimation SCC induced leak/break frequencies.

For estimation of nucleation frequency of cracks initiated by SCC in NPP piping components during service, data concerning e.g. detected cracks and crack nucleation relevant locations are needed. The data concerning through wall SCC flaws are well covered in SCAP, however data on non-through wall SCC flaws are limited to cases that are interpreted as structurally significant and/or exceeding allowable maximum size according to the design code in question. It is concluded that SCAP data alone do not suffice for estimation of nucleation frequency of cracks initiated by SCC in NPP piping components during service. For this purpose supplementary data concerning mainly smaller non-through wall SCC initiated flaws and piping component populations are needed. However, as SCAP is continuously developed further, it may in the future be better applicable for statistical estimates concerning nucleation frequency of SCC induced cracks.

For recursive estimation of probabilistic distributions of initial sizes of cracks nucleated by SCC in NPP piping components, data concerning e.g. all detected SCC cracks are needed. Also, SCAP does not yet contain piping component population data. It is concluded that SCAP data alone do not suffice for estimation of initial sizes of cracks nucleated by SCC in NPP piping components during service. For this purpose supplementary data concerning at least smaller non-through wall flaws and size/shape data of all SCC induced cracks are needed. However, as SCAP is continuously developed further, it may in the future be better applicable for statistical estimates concerning initial sizes of SCC induced cracks.

Data concerning detected SCC induced leaks/breaks are well covered in SCAP. Then the next step towards estimating frequencies of SCC induced leaks/breaks is to obtain data concerning leak/break occurrence relevant locations. Thus also here it is a drawback that SCAP does not yet contain piping component population data. It is concluded that presently SCAP data alone do not suffice for estimation of frequencies of SCC induced leaks/breaks of NPP piping components. For this purpose supplementary data concerning piping component populations are needed. However, besides this shortcoming the SCAP data are sufficient for the present purpose. Moreover, as SCAP is continuously developed also this missing piping component population may be supplemented to it in the future.

A preliminary proposal for a joint SCAP-OPDE project has been prepared. As by now the OPDE project has been running for eight years and the SCAP project for four years, a new project based on these achievements is planned. The proposed project is to be named as “OECD Component Operational Experience, Degradation and Ageing Programme (CODAP)”. The aim of this project is to collect information on passive metallic component degradation and failures of the primary system, reactor pressure vessel internals, main process and standby safety systems, as well as support systems. It is planned that the new CODAP database project will be organized in a fashion similar to SCAP and OPDE, with Sigma-Phase being the information clearinghouse. The first planned actions for CODAP are to resolve the identified weaknesses of OPDE and SCAP databases, and how to integrate the two databases into CODAP. The first 3 year term of the CODAP project is planned to run from June 2011 to May 2014.

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