Strål säkerhets myndigheten

Swedish Radiation Safety Authority

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Research

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Reliability Data Handbook for Piping Components in Nordic Nuclear Power Plants – R Book, Phase 2

SSM perspective

Background
The Nordic PSA Group (NPSAG) has undertaken to develop a piping reliability parameter handbook for use in risk-informed applications that involve the consideration of structural integrity of piping systems. The scope of the handbook is to establish high quality reliability parameters that account for the Nordic and worldwide service experience with safety-related and non-safety-related piping systems in a consistent and realistic manner. The report aims to demonstrate the complete workaround process including modeling approaches.

While the work to develop the handbook was finalised at the beginning of 2010, the planning for its preparation has been underway for fifteen years. An important step towards the handbook development project was the SKI SLAP (SKI LOCA Affected Pipes) database work. This research project started in 1994 and the very first goals was to investigate possibilities for deriving pipe failure rates and rupture probabilities from service experience with piping components in commercial nuclear power plants, as an alternative to probabilistic fracture mechanics.

The SLAP database was handed over to the OECD Nuclear Energy Agency in late 90-ies when the international cooperative effort through the OECD begun to maintain and further develop the event database (called OPDE) which have provided the necessary input to the work with the Reliability Data Handbook for Piping Components in Nordic Nuclear Power Plants (the R-Book).

The first phase of the R-Book project in 2003 was initiated by the stakeholders when it was evident that LOCA frequencies are treated in a non-consistent manner between Nordic NPP utilities.

Objectives
The Swedish Radiation Safety Authority (SSM) strives in its research activities within the research field "Safety Analysis" to establish harmonized guidance documents within the nuclear industry, for a variety of analyses and applications. This report represents such a guide and this report describes a harmonized method to estimate piping reliability parameters and present them in a handbook for use in risk-informed applications.

Results
An important step towards the handbook development project has been the international cooperative effort through the OECD Nuclear Energy Agency to create an event database (OPDE) on the service experience with piping in commercial nuclear power plants; an event database, which provides the necessary input to the work with the NPSAG handbook. This first version of the R-Book comprises rupture frequencies and failure rates for all systems where ASME Code Class 1 or 2 events could be found

in the OPDE database. Nordic and Non-Nordic data are presented separately. Worldwide experience data is used to set up the relevant calculation cases, i.e. intersections of attributes for which there are at least one event present. This "data driven" strategy also implies that there are fewer zero-point cases analysed for the larger Non-Nordic plant population than for the smaller Nordic population. The advantage of this strategy is that no possible events are disregarded just because they are "hidden" in the comparably small Nordic population.

The report provides further directions and a good basis for risk-informed decision making. The outcome of the project together with the outcome of several other NPSAG projects forms an excellent base for risk-informed principles of enforcement strategies and systematic safety work.

Needs for further research
The guidance document is new and therefore its applicability should be tested and evaluated in real applications.

Project information
Project leader at SSM: Ralph Nyman
Project number: SSM 2008/227, 1086-01

References to other similar research projects and/or reports:
Since mid of the 90-ies a significant number of SSM (earlier SKI) research reports as well as conference papers have been published about e.g., collection of piping reliability data, quality assurance of piping reliability data, methods development. In this section some of the SSM reports are listed. All these reports can be downloaded from the homepage of SSM at www.stralsakerhetsmyndigheten.se

SSM Report 2008:1, Reliability Data for Piping Components in Nordic Nuclear Power Plants "R-Book" Project Phase I, Anders Olsson and Bengt Lydell, January 2008.

SKI Report 1995:58, Reliability of Piping System Components.
Volume 1: Piping Reliability – A Resource Document for PSA Applications.

SKI Report 1995:59, Reliability of Piping System Components.
Volume 2: Review of Methods for LOCA Frequency Assessment.

SKI Report 1995:60, Reliability of Piping System Components.
Volume 3: A Bibliography of Technical Reports and Papers Related to Piping Reliability.

SKI Report 1995:61, Reliability of Piping System Components.
Volume 4: The Pipe Failure Event Database.

SKI Report 1996:20, Piping Failures in United States Nuclear Power Plants: 1961-1995.

SKI Report 1996:24, An Overview of Stress Corrosion in Nuclear Reactors from the Late 1950s to the 1990s.

SKI Report 1996:39, Failure Frequencies and Probabilities Applicable to BWR and PWR Piping.

SKI Report 1997:26, Reliability of Piping System Components.

SKI Report 1998:30, Failure Rates in Barsebäck-1 Reactor Coolant Pressure Boundary Piping.

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This report concerns a study which has been conducted for the
Swedish Radiation Safety Authority, SSM. The conclusions and view-
points presented in the report are those of the author/authors and
do not necessarily coincide with those of the SSM.

TABLE OF CONTENT

1. EXECUTIVE SUMMARY

This report presents results of a long research and development project financed by the regulatory body Strålsäkerhetsmyndigheten (SSM) (former SKI), the Swedish nuclear power plant licensees. The report presents a harmonized method for estimating Reliability Data for Piping Components in ASME code class 1 and 2 piping components (R-Book). Data in the R-Book is measured based on "data driven" strategy.

This first version of the R-Book comprises rupture frequencies and failure rates for all systems where ASME Code Class 1 or 2 events could be found in the OECD OPDE database. Nordic and Non-Nordic data are presented separately. Worldwide experience data is used to set up the relevant calculation cases, i.e. intersections of attributes for which there are at least one event present.

I denna rapport redovisas resultat från ett långvarigt forsknings- och utvecklingsprojekt som finansierats av Strålsäkerhetsmyndigheten (SSM) och de svenska tillståndshavarna för kärnkraftverk. Rapporten presenterar en harmoniserad metod för att uppskatta tillförlitlighetsdata på rörkomponenter som tillhör ASME code klass 1 och 2.

Denna första version av Tillförlitlighetsdata rörande brottfrekvenser och felsannolikheter på rörkomponenter tillhörande ASME code klass 1 och 2, baserar sig på händelser som finns i OECD OPDE databasen. Nordiska och icke-nordiska data presenterar var för sig i R-Boken. Den världsomfattande erfarenhetsdata som finns i OPDE används för att definiera relevanta beräkningsfall t.ex. koppling till händelser som det finns minst en rapporterad händelse på. Data i R-Boken är baserad på en data influerad strategi.

2. INTRODUCTION

The Nordic PSA Group (NPSAG) has undertaken to develop a piping reliability parameter handbook for use in risk-informed applications that involve the consideration of structural integrity of piping systems. The scope of the hand book is to establish hig h quality reliability parameters that account for the Nordi c and Worldwide service experience with safety-related and non-safety-related piping systems in a consistent and realistic manner.

While the work to devel op the handbook was finalised at the beginning of 2010, the planning for its pr eparation has been underway for well over ten years. An important step towards the handbo ok development project was the international cooperative effort thr ough the OECD Nuclear Energy Agency to create an event database (OPDE) on service experience with pipin g in commercial nucle ar power plants; an event databa se, which provides the necessary input to the work with the Reliabilit y Data Handbook for Piping Comp onents in Nordic Nuclear Power Plants (the R-Book).

Before the actual R-Book develop ment work started in 2008 a pilo t project was carried out. The aim of the pilot project was to define the content and outline of the proposed handbook. The pilot project is summarized in SKI Report 2008:01 [1] (January 2008, avail able from www.ssm.se). The report provides detailed inf ormation about technical considerations for how to deri ve realistic pipe failure rates from the available service experience dat a, together with the requirements defined for R-Book.

At the beginning of the R-Book project the scope was to cover all piping that is r epresented in the OPDE database, thereby forming the basis for any leak frequency originating from inside and outside the containment i.e. Loss of Coolant Ac cident (LOCA), flooding and High Energy Line Break (HELB frequencies). A revis ed primary scope has however been necessary in order to shorten the turnaround time. The revised scope implies that Code Class 1 and 2 components are primarily analyzed. This re striction does not mean that Code Class 3, 4 and non-code is of no importance, but that prio rity is given to components with the greatest need for ne w updated data, i.e. components that are like ly to contribute to LOCA frequencies. The co mponents that are primarily excluded from R-Book failure data for these components can be derived from the EPRI study [7]. It should be stressed though, that EPRI is based on US data and might have less validit y for the Nordic situation.

This first version of R-Book comprises rupture frequencies and failure rates for all systems where ASME Code Class 1 or 2 events could be found in the OPDE dat abase. Nordic and No n-Nordic data are presented separately. Worldwide experience data is used to set up th e relevant calculation cases, i.e. intersections of attributes f or which there are at least one event present. This "data driven" strategy also implies that there are fewer "zero-point" cases analyzed for the larger

Non-Nordic plant population than f or the smaller Nordic p opulation. The advantage of this strategy is that no "hidden" events are disregarded. Thus, a fund amental statement is t hat OPDE comprises enough data for any theoretically p ossible event to appear, irrespective of pipe size.

The database version used in the R-Book project is OPDE Light 2007:2.

3. Modelling approach – the basic idea

A simple model of piping reliability components makes use of nuclear power plant reliability models originally developed to investigate alternative inspection strategies for different piping systems. The model takes advantage of the presence of a precursor event, i.e. rupture (R) is preceded by failure (F). Equation (1) is a representation of this model:

$$\rho_{ikx} = \sum_{k=1}^{M_i} \lambda_{ik} P_{ik}\{R_x|F\} \qquad (1)$$

Where:

ρ_{ikx} = Rupture frequency of piping component i due to damage mechanism k for failure mode x.

λ_{ik} = Failure rate of piping component i due to damage mechanism k. In general, a point estimate of this frequency is given by the number of failure events divided by the product of the total exposure time over which failure events were collected (normally expressed in Reactor Critical Years) and the component population that provided the observed failures.

$P_{ik}\{R_x|F\}$ = Conditional probability of "rupture" mode x given failure for pipe component i and damage mechanism k.

M_i = Number of different damage mechanisms for component i.

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.

A Bayesian approach is used to develop uncertainty distributions for the parameters in equation (1). The term λ_{ik} is assessed by updating a slightly informative prior with failure events retrieved from the OPDE database. The conditional probability of structural failure $P_{ik}\{R_x|F\}$ is represented by a Beta distribution with parameters A and B interpreted as:

A: The number of structural failures of a certain kind i.e. ruptures.

B: The number of degraded conditions, i.e. defects that did not result in ruptures.

Firstly, a point estimate of $P_{ik}\{R_x|F\}$ is based on expert judgment. A technical basis for defining prior Beta distribution parameter is documented in references [2, 3]. The chosen A-prior and B-prior are anchored in the current "state-of-knowledge" about degradation mechanisms, mitigation and inspection practices, and field experience. The B parameter is derived in a straightforward manner once A-prior and a mean have been defined:

$$B = (A/mean) - A \qquad (2)$$

Secondly assuming a binomial likelihood and associating ruptures (R) with the A parameter and failures that did not result in structural failure (F - R) with the B parameter (i.e. "successes") the posterior parameters are analytically derived:

$$A_{post} = A + R \qquad (3)$$

$$B_{post} = B + (F - R) \qquad (4)$$

3.1 Break Flow Thresholds

In order to distinguish between break sizes in different pipe dimensions it is necessary to define break flow thresholds. The break flow is mainly a function of pipe/break size and system pressure. Since R-Book will focus on Nordic nuclear power plants, a mapping has been performed regarding different break flow limits that has been used in different PSA:s.

Since a leak can give rise to several break flows it is necessary to convert each threshold to an equivalent piping diameter in order to exclude piping that are too small related to a certain break flow category. The conversion is made using the Moody break flow model, see e.g. [4].

Using equations (5) and (6) below the threshold diameter can be calculated according to equation (7).

$$FR = G*A \qquad (5)$$

$$A = \pi*D2/4 \qquad (6)$$

$$D = [4*FR/(G*\pi)]1/2 \qquad (7)$$

Using 7 MPa for BWR and 15,5 MPa for PWR G-values of approximately 39500 kg/m^2,s (BWR) and 53000 kg/m^2,s (PWR) are obtained. This will give the corresponding threshold diameters as described in Table 1.

Table 1: Break flow thresholds and their corresponding diameters

Threshold Flow Rate (*FR*)	BWR Diameter	PWR Diameter
>5 kg/s	>13 mm	>11 mm
>20 kg/s	>25 mm	>22 mm
>100 kg/s	>57 mm	>49 mm
>400 kg/s	>114 mm	>98 mm

4. DATA PROCESSING ROUTINE

The most challenging " executive" work behind R-Book ha s been to sort and categorize the vast amount of OPDE d ata properly in orde r to get meaningful and useful output, i.e. freque ncies that are easily interpreted and implemented by the PSA analyst.

Hence, besides distinguishing between different damage/degradation mechanisms for BWR and PWR, OPDE data are subdivided by the following attributes:

- Nordic/Non-Nordic

- ASME Code Class 1-2 (BWR [5] and PWR [6])

- Component type (welds bends, T-joints and base metal).

- Material; SS (Stainless Steel) or CS (Carbon Steel).

- Pipe size; since the rupture frequencies distingu ish between possible flow r ates, it is n ecessary to record the piping diameter for each component.

4.1 The Processing Routine Step By Step
This section addresses the necessary steps in the R-Book routine, which starts by e xtracting raw data f rom the databases available and ends up with calculations and presentation of the results obtained.

4.1.1 Extracting Data from OPDE Light
The first step of R-Book routine is to extract data from the event database, i.e. OPDE. F or each system the database is filt ered with respect to p lant type (BWR or PW R), Completeness Index[1] (CI 3 is discarded) and the relevant degradation mechanisms. Queries are then defined to interse ct the resulting tables with respect to pipe dimensions, piping com ponents and material, counting the failures in each intersection. In p rinciple a set of calculation cases are to be defined for each combination of degradation mechanism and component type.

4.1.2 Plant Population Data – Defining the Exposure Term
The exposure term (the denominator of the failure rate point estimate) is composed of the number of ite ms observed and their time "in operation". This term is input to th e Poisson process updating the prior (using the R-DAT Plus analysis tool). The relevant informatio n should be found in any database comprising a complete picture of the components of a certain populatio n. In R-Boo k, the information on Non-Nordic plants is obtained from the PIPExp[2] database. The Nordic

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[1] Completeness Index (CI) 1 to 3 used in OPDE is described in the OPDE Coding Guideline [8] where CI 1 and 2 means that the failure record data has been validated but for CI 2 some non-critical information might be missing, CI 3 means that the validation still is ongoing.
[2] PIPExp: Scandpower proprietary - OPDE "parent database"

populations are mapped separately and solely for the purp ose of R-Book.

4.1.3 Qualitative Analysis

At an early stage a qualitative exa mination of the service experience history is carried out. The aim is to e xamine the level of homogeneity of the background data, i.e. if there are any ob vious biases (e.g. with respect to time). Seco ndly a first review of the query results is performed. The focus is on e liminating ambiguous classification and to sharpen the bound aries between stated categories. It is also decided whether the b asis for statistical analysis is sufficient, e.g. if information on the complete component population is available for the events at issue.

4.1.4 Definition and Set Up of Calculation Cases

The most critical stage of the data processing routine is the definition and set up of calculation cases. Th e task comprises several pitfalls that will be discussed separately (see Section 0 and 0). However, the basics are as follows:

a. **Matching of susceptibility vs. actual observations**: The case definition should be based upon some kind of information on which degradation mechanisms are relevant to a certain system as well as an examination of the relations between degradation mechanisms and component types.

This "matching routin e" aims at answering the following crucia l questions:

- *Are all observed events valid?* Basically this is a question of whether or not a calculation ca se should be defined for each and every observed event. T he natural objection is that there might b e combinations of degradation mechanism, code class, component type, material and dimension that are h ighly unlikely (or even logica lly impossible) due to water chemistry, mitigation programs etc. This in turn implies that the co rresponding events, if any, should be screened out or reclassified.

- *Does the empirical situation reflect what is in fact possible?* This question is a sked to avoid the erroneous conclusion that the pre sent events are the on ly possible ones. Whenever any "hidden" event is considered possible a calculation case should be def ined (and t he update carried out for zero failures).

b. **Compiling the empirical input**: After having defined the cases, the complete set of failur es for the solving of equation (1) has to be composed. These are:

- The failures that, toget her with th e exposure term, are used to update the failure rate prior distribution.

- The input t o the upda ting of the (Beta) dist ribution of conditional probability of structural failure. This is, for each flow rate threshold, matching the relevant number of ruptures to the corresp onding failures. Here "rupture" is understood as a failure causing a flow above a certain threshold, and the corresponding f ailures are all OPDE events for that specific ca se grouped by th e smallest possible dimension to cause the breach.

- The total number of relevant components and the corresponding observation time (Reactor Critical Years) . Together these two will constitute the exposure term which is representing the process that produced the failures.

c. ***Matching of populations***: To complete the inp ut data set the above t hree populations have t o be match ed. This is carried through as follows:

Firstly, in so far as the failure rate (λ) is concerned, all OPDE e vents belonging to a certain case are matched to the corresponding component population. In this matching *dimension* is not a relevant grouping criterion because failu res are considered to occu r independently of pipe si ze (the exc eption is failures due to Vibration Fatigue that is more likely in small bore piping). Howe ver, an event should be excluded from the input dat a set if there is n o corresponding dimension in the component po pulation, otherwise the event population will " exceed" the component population and th e frequency is overestima ted. This might be the case with small-bore piping because they a re not always covere d by an y inspection program.

Secondly, for each bre ach threshold (Small Breach, Breach, Larg e Breach and Major Breach respectively), ruptures have to be matched to the corresponding smallest dimension (see Table 1). Here the component population is irrelevant simply because the beta distribution is independent of exposure, i.e. it just expre sses the relation between "failure and rupture". Therefore no failures should be skipped due to lack of exposure data.

4.1.5 Presentation and Interpretation of Results
Finally, the results for each calculat ion case are presented. The unit is failure/(component*year) or failure/(system*year) where failure is understood as a breach of a certa in magnitude. The failure rate (λ), i.e. failure irrespective of potential flow, is also presented.

When the analyst wants to implement rupture frequencies for different flow rates (used for different LOCA categories in a PSA for exa mple) it is therefore necessary that a mapping is made for piping component

population so it can be matched to the rupture frequencies for each specific case. Then the number of all piping components (e.g. welds) in a subsystem matc hing the attributes an d the different flow rates/diameters is multiplied with the rupture frequency given by R-Book.

4.2 Experiences with the Identification of Relevant Degradation Mechanisms

This section addresses some experienced difficulties relate d to the definition of calculation cases, as well as an alternative strategy.

4.2.1 The Original "Top-Down" Strategy

The case definition should be based upon some kind of statement on whether a s ystem or a combination of attributes is vulnerable to a certain degradation mechanism. Earlier this work was carried out prior to the case def inition and a sharp dividing line was drawn between the "a priori" information and the executive process of compiling calculation cases. T he beforehand information was presented in so calle d *DM-evaluation tables* (DM – Damage Mechanism).

However, this approach raises so me knotty problems. Firstly, the beforehand evaluation needs to be extremely detailed, or else it gives no clue of the upper limit of "zero- point-cases" to be defined, i.e. *the sample space is not clearly defined*. Basically this is a q uestion of whether or not a calculation case should be defined for *each and every possible combination* of attributes. Here, as in th e case of incorrectly classified events (see Section 3.1.4 a), the objection is that many of these combinations represent events that are highly unlikely or even logically impossible.

Secondly, in applications like OPDE, there are always deviations from the theoretical pict ure due to misclassification or omissions. Nevertheless, it must b e presupposed that the deviation may be due to imperfection of the theoretical evaluation. The fact is that an ultimate evaluation or set of calculation ca ses cannot be brought about, simply because the proce dure of working out a complete evaluation is circular; it presupposes a "bottom-up" verification of the background itself. The only way to h andle this within the scope of R-Book would be to scrutinize every "outlier" in detail, and set some reasonable upper limit for how many "zero-point-cases" we are willing to accept. But at the same time i t must be acknowledge d that the principle of completeness is itself violated, and that a lot o f time will be consumed, not least because e very statement must be carefully motivated and documented. What is needed is a straightforward and simple guiding rule.

4.2.2 A Change of Perspective

According to the original strat egy, the relevant degradation mechanisms was cho sen prior t o glancing at the OPDE e vent population, and then ite ratively adjusted in t he light of OP DE data. This approach has the merit of taking all "hidden" failures into account (at least in principle). But as stat ed above, it has some serious drawbacks as well.

The suggestion was therefore to use the OPDE Worldwide picture to determine what degradation mechanisms are possible within a certain context, taking explicit credit of th e abundance of data stored in OPDE. This means that for Non-Nordic plants, few "zero-point-cases" will be defined, while for the Nordic plants these cases may even be dominating (because the Nordic p opulation is comparably small). OPDE will also determine what components are being demanded from the component databases and future mapping of plant populations.

This data driven "bottom-up" strategy provides a straightforward and simple rule of guidance. Perhaps it does not lea d us to the "ultimate" result, but it is unam biguously and transparently based on the empirical knowledge available and thereby perfectly trace able and easy to revise. This strategy makes R-Book a more powerful tool for feedback to OPDE as well as to theoretical assessments of various kinds.

It might objected that this new strategy is presupposing the old "top-down" strategy since only hypothesizes on how mechanisms work can form a basis for the classification of events. The answer is that this is correct, but nevertheless that such considerations have to be left outside R-Book framework. The basis for classification (i.e. some kind of "DM-evaluation") is viewed as part of the OPDE framework, i.e. preparatory to R-Book, and will as such not be questioned.

Finally it should be noticed that the DM-evaluat ions are by no means discarded. However, as far as degradation mechanisms are concerned, they are used as te chnical guides rather than g overning documents.

4.2.3 Criteria for Screening out an Event

Although the OPDE database itself will guide us to the final set of calculation cases we will need an agenda for the treatment of exceptional cases. These cases concerns:

- Events that are not completely identified in terms of the requisite attributes.

- Events that are completely but not correctly identified.

The former records will simply be screened out due to "incompleteness" and reported to OPDE. The latter are (of course) not directly accessible but will be measured against beforehand set up constraints on what materials and code classes are relevant to a certain system. This information is retrieved from the DM-evaluations. Any event deviating from the scheme will be screened out and reported to OPDE. It should be noted that *no reclassification of OPDE failure events will be made within R-Book framework*.

4.3 Revised Scope

At the beginning of the R-Book project the scope was that R-Book would cover all piping that is represented in the OPDE database, thereby forming the basis for any leak frequency originating from inside and outside the containment (i.e. LOCA flooding and HELB frequencies). A revised primary scope has however been necessary in order to shorten the turnaround time. The revised scope implies that Code Class 1 and 2 components are primarily analyzed. This restriction does not mean that Code Class 3, 4 and non-code is of no importance, but that priority is given to components with the greatest need for new updated data, i.e. components that are likely to contribute to LOCA frequencies. The components that are primarily excluded from R-Book failure data for these components can be derived from the EPRI study [7]. It should be stressed though, that EPRI is based on US data and might have less validity for the Nordic situation.

Thus, the first version of R-Book covers BWR and PWR systems for which there are OPDE-events in Code Class 1 or 2. These systems are:

- AFW (Auxiliary Feed Water)
- CRD (Control Rod Drive)
- CS (Containment Spray)
- CVC (Chemical & Volume Control)
- ECCS (Emergency Core Cooling)
- FW (Feed Water)
- MS (Main Steam Lines)
- RHR (Residual Heat Removal)
- RCS (Reactor Coolant - PWR)
- RPV-HC (RPV Head Cooling)
- RR (Reactor Recirculation - BWR)
- RWCU (Reactor Water Clean-Up)
- SLC (Standby Liquid Control)
- S/G (Steam Generator Blowdown System)

5. EXAMPLE OF RESULTS

5.1 Results for RCS system in PWR
In this cha pter some example of results for the Reactor Coolant System (RCS) for Pressurized light Water Reactors (PWR) is presented.

As described in Section 4.1 the first step is to extract the d ata from the event database and thereby creating a service experience history, see Table 2.

Table 2: Service experience history for RCS in PWR; Non-Nordic, Nordic and Worldwide population.

| Population, all failure modes	Pipe size [mm]	1970-1979		1980-1989		1990-1999		2000-2007		1970-2007	
		NTWC	TWC	NTWC	TWC	NTWC	TWC	NTWC	TWC	NTWC	TWC
Non-Nordic	Ø>250	1	-	1	-	-	-	1	1	*3*	*1*
	50 < Ø ≤ 250	-	1	1	1	-	3	6	-	*7*	*5*
	Ø ≤ 50	1	17	2	59	12	67	15	18	*30*	*161*
RCY	[year]	372		1316		1953		1634		*5274*	
Nordic	Ø>250	-	-	-	-	-	-	1	-	*1*	*-*
	50 < Ø ≤ 250	-	-	-	-	-	-	-	-	*-*	*-*
	Ø ≤ 50	-	2	-	-	2	-	-	-	*2*	*2*
RCY	[year]	6		27		30		24		*86*	
Worldwide	Ø>250	1	-	1	-	-	-	2	1	*4*	*1*
	50 < Ø ≤ 250	-	1	1	1	-	3	6	-	*7*	*5*
	Ø ≤ 50	1	19	2	59	14	67	15	18	*32*	*163*
RCY	[year]	377		1343		1982		1658		*5361*	
Abbreviations	NTWC: Non trough wall crack TWC: Trough wall crack RCY: Reactor critical years, i.e. exposure time										
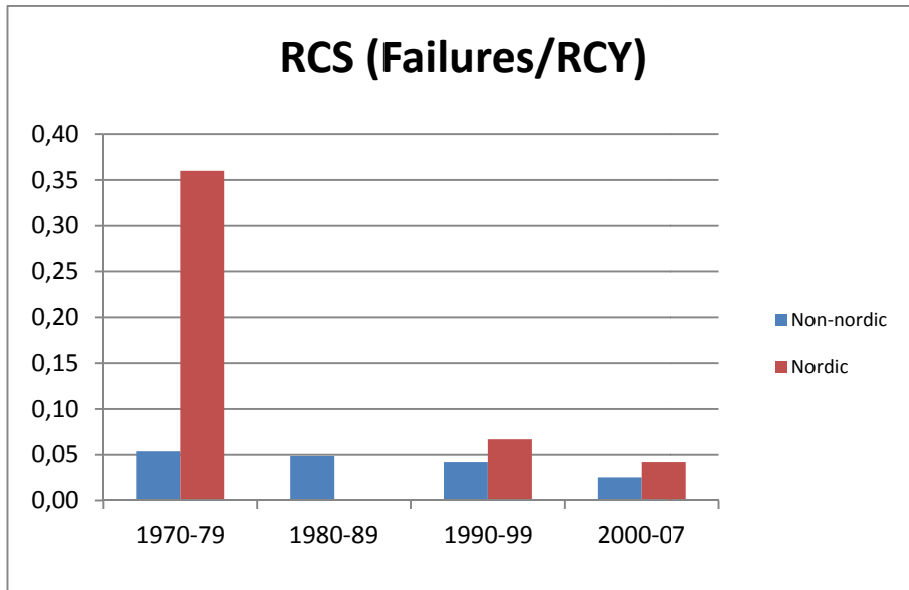
Figure 1. Service experience history for RCS in PWR; Non-Nordic and Nordic population

What is not displayed in Table 2 above is that the service experience history also contains information about those damage mechanisms that have caused the failures listed in Table 2. Since each damage mechanism has its own exposure term, see Figure 2, it is crucial to have this detailed information about the service experience data used in the analysis.
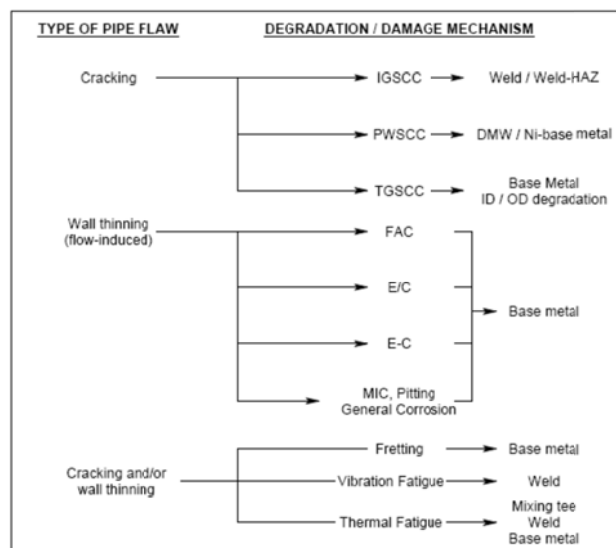

Figure 2. Correlation between flaw – mechanism – exposure terms

Since each damage mechanism has its own exposure term calculation can only be performed for those cases where piping population data exist. In the case of RCS, piping population data is currently available for welds only. This information constitutes the

empirical input to the analysis cases that have been defined, see Table 3 and 4.

Table 3. PWR - RCS/313 - Non-Nordic Events (5274 RCY) – ASME Code Class 1

Degr. Mech.	Component	Material	Failures	Population
D&C	Weld	SS	9	1003,5
SCC	Weld	SS	16	1003,5
TF	Weld	SS	3	1003,5
VF	Weld (DN <= 100)	SS	2	1003,5
Abbreviations	*D&C: Design and Construction* *SCC: Stress Corrosion Cracking* *TF: Thermal Fatigue* *VF: Vibration Fatigue* *SS: Stainless Steel*			

Table 4. PWR - RCS/ 313 - Nordic Events (8 6 RCY) – ASME Code Class 1

Degr. Mech.	Component	Material	Failures	Population
D&C	Weld	SS	0	518,3
SCC	Weld	SS	1	518,3
TF	Weld	SS	0	518,3
VF	Weld (DN <= 100)	SS	0	518,3
Abbreviations	*D&C: Design and Construction* *SCC: Stress Corrosion Cracking* *TF: Thermal Fatigue* *VF: Vibration Fatigue* *SS: Stainless Steel*			

Based on the number of failures per degradation mechanism, the exposure time, the piping population and the method described in Section 0 and 0 yield results in the form of failure rates for each degradation mechanism and piping component and adherent conditional leak rate probabilities per break flow threshold, see Table 1. In Table 5 and 6 the results for welds in stainless steel is presented for ASME Code Class 1, note that other degradation mechanisms than D&C and SCC have been left out from the tables.

Table 5. PWR - RCS/3 13 - Code Class 1 - Welds - Stainless Steel – Non-Nordic data

Case ID	Parameters	Rupture Mode	Mean	Percentiles		
				5%	50%	95%
Design & Construction Errors (Incl. Human Error)	Rupture Frequency	SB	1,3E-08	6,9E-10	7,7E-09	4,3E-08
		LB	1,1E-09	9,1E-11	8,5E-10	2,6E-09
		MB	8,3E-10	2,4E-12	3,4E-10	3,4E-09
	Failure rate	--	**1,8E-06**	**9,1E-07**	**1,6E-06**	**3,5E-06**
Stress Corrosion Cracking	Rupture Frequency	SB	2,2E-08	1,3E-09	1,4E-08	7,1E-08
		LB	1,7E-09	1,6E-10	1,6E-09	3,6E-09
		MB	1,7E-09	6,0E-12	7,0E-10	6,5E-09
	Failure rate	--	**3,2E-06**	**1,7E-06**	**2,9E-06**	**6,1E-06**

Table 6. PWR - RCS/313 - Code Class 1 - Welds - Stainless Steel – Nordic data

Case ID	Parameters	Rupture Mode	Mean	Percentiles		
				5%	50%	95%
Design & Construction Errors (Incl. Human Error)	Rupture Frequency	SB	2,3E-08	4,3E-11	2,0E-09	6,6E-08
		LB	2,2E-09	2,2E-12	1,5E-10	5,6E-09
		MB	1,6E-09	3,4E-13	5,8E-11	3,1E-09
	Failure rate	--	**2,5E-06**	**1,4E-08**	**3,2E-07**	**9,2E-06**
Stress Corrosion Cracking	Rupture Frequency	SB	1,6E-07	3,2E-09	6,3E-08	6,4E-07
		LB	1,1E-08	2,7E-10	4,6E-09	3,7E-08
		MB	8,3E-09	1,4E-11	2,0E-09	3,5E-08
	Failure rate	--	**1,8E-05**	**2,1E-06**	**9,5E-06**	**6,3E-05**

From Table 5 and 6 one conclusion is that the contribution from D&C errors cannot be negle cted when comparing to the con tribution per weld from SCC.

The data material provided in R-Book can be analyzed in many different ways. One such way is t o compare different systems with respect to failure rate for initial def ect. In Figure 3 and 4 t he failure

rate due to SCC for Non-Nordic BWR (Figure 3) and PWR (Figure 4) respectively is illustrated.
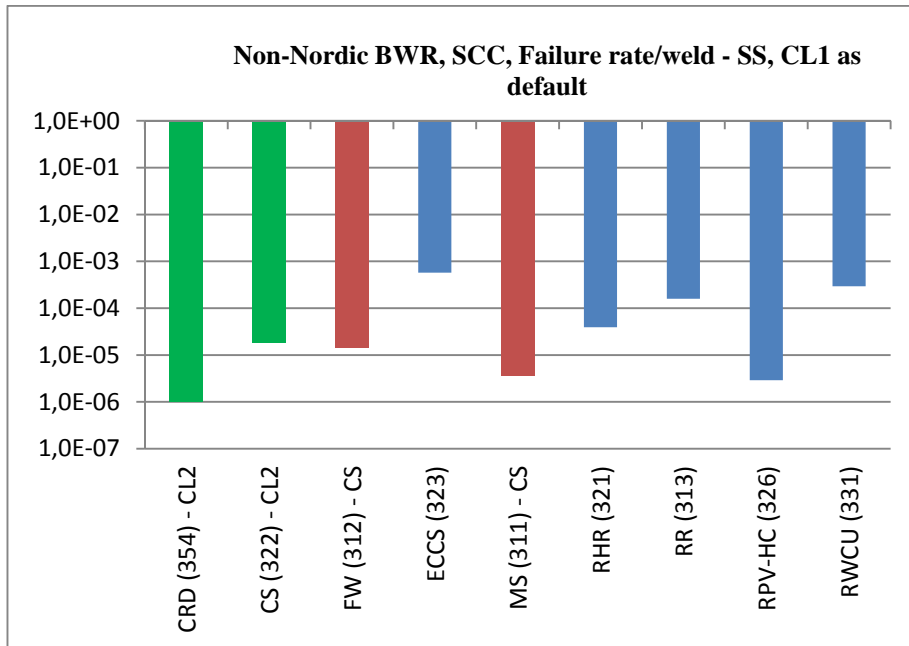
Non-Nordic BWR, SCC, Failure rate/weld - SS, CL1 as default

Figure 3. Failure rate for initial defect (Non-Nordic BWR, SCC, Weld – SS and Code Class 1 as default)

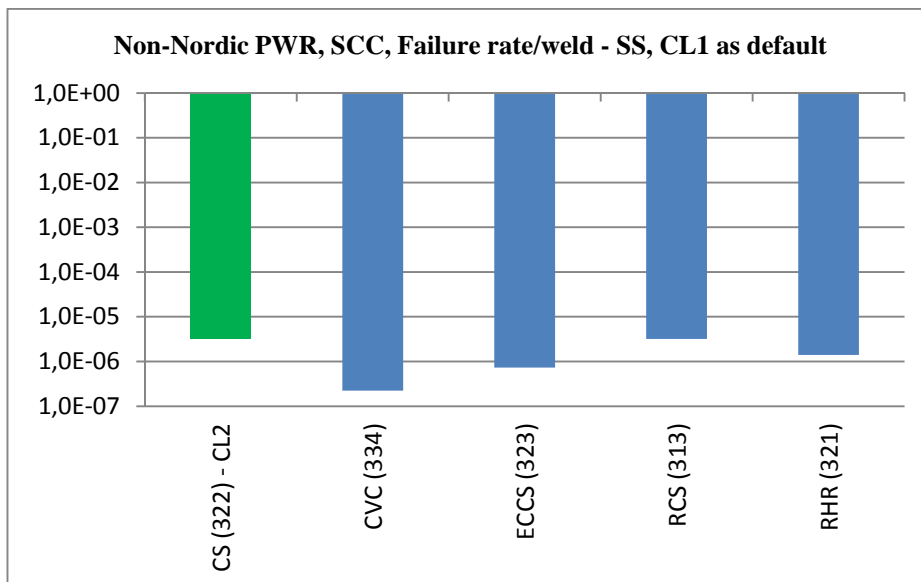**Non-Nordic PWR, SCC, Failure rate/weld - SS, CL1 as default**

Figure 4. Failure rate for initial defect (Non-Nordic PWR, SCC, Weld – SS and Code Class 1 as default)

The major conclusion from Figure 3 and 4 is that when it comes to failure rate for initial defect there are major differences between the

systems, the difference is almost three orders of magnitude between the system with highest and lowest failure rates for BWR, less difference for PWR though. It is th erefore very important to review and understand the different degradation mechanism's that are active for each system.

6. Outline of R-Book – Sub-reports

R-Book is built up of several sub-reports. Firstly there is a report (*34.800.021-R-000 - Theory*) presenting the theoretical fra mework of R-Book, e.g. the considerations b ehind defining prior distributions, statements on validation and verification etc. Secondly, the analysis of each system is presented in separate reports with all in formation and appendices needed for that specific system. The systems reports can thus be used independently.

There are 16 sub-reports included in R-Book. These are:

- 34.800.021-R-000 - Theory
- 34.800.021-R-001 - ADS (314)
- 34.800.021-R-002 - AFW (327)
- 34.800.021-R-005 - CRD (354)
- 34.800.021-R-006 - CS (322)
- 34.800.021-R-007 - CVC (334)
- 34.800.021-R-011 - FW (312,415)
- 34.800.021-R-014 - ECCS etc. (323)
- 34.800.021-R-016 - MS (311,411)
- 34.800.021-R-018 - RCS (313)
- 34.800.021-R-019 - RHR (321)
- 34.800.021-R-020 - RR (313)
- 34.800.021-R-021 - RPV-HC (326)
- 34.800.021-R-023 - RWCU (331)
- 34.800.021-R-025 - SG (337)
- 34.800.021-R-026 - SLC (351)

The naming of the reports helps id entifying a certain syst em by the following rule as exemplified by 34.800.021-R-001 - ADS (314):

34.800.021	Scandpower project number
R	Report
001	System index used in R-Book
ADS	US designation
(314)	Swedish designation/s

7. REFERENCES

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3. Chrun, D., Mosleh, A. and Lydell, B., 2010. *Technical Basis for Defining Prior Distribution Parameters for Conditional Pipe Failure Probabilities*, Technical Report 35.900.003/R1, University of Maryland and Sacandpower Inc.

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5. ANSI/ANS-52.1-1983, *Nuclear Safety Criteria for the Design of Stationary Boiling Water Reactor Plants*.

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7. EPRI 1013141, *Pipe Rupture Frequencies for Internal Flooding PRAs*, Revision 1.

8. OPDE PR01, *OPDE 2007:1 CODING GUIDELINE (OPDE-CG) & OPDE 2007:1 USER'S GUIDE,* B.O.Y. Lydell (OPDE Clearinghouse), 29-June-2007.

2011:06

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co–operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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