SKI Report 97:26 (3rd Edition)

Reliability of Piping System Components

Framework for Estimating Failure Parameters from Service Data

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December 1997

ISSN 1104-1374
ISRN SKI-R--97/26--SE

STATENS kÄRNKRAFTINSPEKTION
Swedish Nuclear Power Inspectorate

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SKI/RA-018/97

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Framework for Estimating Failure Parameters from Service Data

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Note to 3rd Edition

This new edition includes an updated Appendix B. Since the publication of the original report, the pipe failure database that resulted from the work documented herein has been continuously updated and maintained. Appendix B accounts for information added to this database since 1997. Except for minor editorial corrections, Sections 1 through 6 and Appendices A and C remain unchanged. Since the original work performed during 1994-97, there has been significant progress made in the pipe failure database management as well as practical database applications:

- Active database management under a strict QA program. At the end of 2004, the database included approximately 5,500 records on pipe degradation and failure. Since January 1999, monthly status reports have been compiled and distributed to interested parties.
- The OECD/Nuclear Energy Agency OPDE Project (OECD Pipe Failure Data Exchange) was established in 2002 as a multilateral cooperative effort comprising 19 organizations from 12 countries. The OPDE project is based on what was originally termed the "SLAP database" as it were at the end of 1998.
- Large number of database applications during the period 1999-2004. Insights from these applications have formed an important role in supporting the database management. Mainly, these applications have involved quantitative assessments of piping reliability in support of risk-informed activities (e.g., risk-informed ISI, internal flooding risk assessment, LOCA frequency assessments).
- Development of tools for parameter estimation including assessment of uncertainties.

In retrospect, all of the recommendations for further work identified in Section 6 of this report now have been implemented and peer reviewed. Additional information is available from the OPDE National Coordinator (Karen Gott, SKI), Ralph Nyman (SKI) or Bengt Lydell.

B. Lydell
January 2005

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SUMMARY

This report summarizes results and insights from the final phase of an R&D project on piping reliability sponsored by the Swedish Nuclear Power Inspectorate (SKI). The technical scope includes the development of an analysis framework for estimating piping reliability parameters from service data.

The R&D has produced a large database on the operating experience with piping systems in commercial nuclear power plants worldwide. It covers the period 1970 to the present. The scope of the work emphasized pipe failures (i.e., flaws/cracks, leaks and ruptures) in light water reactors (LWRs).

Pipe failures are rare events. A data reduction format was developed to ensure that homogenous data sets are prepared from scarce service data. This data reduction format distinguishes between reliability attributes and reliability influence factors. The quantitative results of the analysis of service data are in the form of conditional probabilities of pipe rupture given failures (flaws/cracks, leaks or ruptures) and frequencies of pipe failures.

Finally, the R&D by SKI produced an analysis framework in support of practical applications of service data in PSA. This, multi-purpose framework, termed ‘PFCA’ - Pipe Failure Cause and Attribute - defines minimum requirements on piping reliability analysis. The application of service data should reflect the requirements of an application. Together with raw data summaries, this analysis framewok enables the development of apriori and aposteriori pipe rupture probability distributions. The framework supports LOCA frequency estimation, steam line break frequency estimation, as well as the development of strategies for optimized in-service inspection strategies.

SAMMANFATTNING

Statens Kärnkraftinspektion (SKI) har under perioden 1994-97 bedrivit ett forsknings- och utvecklingsproject med avsikt att bestämma rörbrottssannolikheter utgående från drifterfarenheter. Föreliggande rapport utgör slutgiltlig dokumentering av resultat från projektarnbetet. Resultaten från arbetet utgörs av:

(1) Händelsebaserad databas över intäffade skador i kärnkraftverk under perioden 1970-1997. Tyngdpunkten ligger på amerikanska ock nordiska drift- erfarenheter. Storleksordningen 2400 skaderapporter har insamlats och bearbetats.

(2) Datahaneterings- och dataanalys baserad på tillämpning a begreppen 'tillförlitlighetsattribut' och 'influensfaktorer.' Resultaten datanalysen redovisas I form av rörskadefrekvenser och betingade brottsannolikheter.

(3) Generella riktlinjer för tillförlitlighetsanalys av rörsystem i kärnkraftverk. Dessa riktlinjer innhåller minimikrav beträffande uppläggning och dokumentering av analyser inom ramen för PSA-tillämpningar.

ACKNOWLEDGEMENTS

The authors of SKI report 97:26 greatfully acknowledge the extensive support and encouragement from numerous industry organizations and nuclear safety professionals throughout Europe and the USA. A special thank you is extended to Messrs. Rudolf Häussermann and Henk van Ojik of Kernkraftwerk Leibstadt AG (KKL, Switzerland), Messrs Ralph-Michael Zander and Adelbert Gessler of Kernkraftwerke Gundremmingen Betriebsgesellschaft mbH (KGB, Germany), Kalle Jänkälä (IVO International, Ltd.), Dr. Yovan Lukic (Arizona Public Service), and Dr. Ching Guey (Florida Power & Light).

This final project report benefitted from the constructive critique by Dr. Roger Cooke (Delft University of Technology, The Netherlands), Ms. Jette Paulsen (Risø National Laboratory, Denmark), and Mr. Sture Andersson (S-A Ingenjörsbyrå AB, Sweden).

SPECIAL NOTE ON TERMINOLOGY

The term ‘sterss corrosion cracking’ (SCC) is normally used to characterize a group of degradation mechanisms involving environment- and stress-induced crack propagation in austenitic stainless steel piping. Included among SCC-mechanisms are: intergranular SCC, transgranular SCC, irradiation induced SCC, etc. Throughout this report we have used SCC to mean stress corrosion in *PWR* environments, and IGSCC to mean stress corrosion in *BWR* environments.

Throughout SKI Report 97:26 the term ‘failure’ implies a degradation of the structural reliability resulting in repair or replacement of a section of piping or an individual pipe fitting. The mode of failur*e* is either a flaw/crack/thinning, leak or rupture corresponding to incipient, degraded and complete failure, respectively.

1

INTRODUCTION

This report summarizes results and insights from the final phase of an R&D project on piping reliability sponsored by the Swedish Nuclear Power Inspectorate (SKI)[1]. The technical scope includes the development of an analysis framework for estimating piping reliability parameters from service data.

The project has benefited from previous efforts to derive failure parameters from service data. It differs from these earlier efforts by having had access to a broader and more extensive database on piping failures, however. The present work has focused on practical, engineering-oriented interpretations of the service data. The purpose of this final report is to present the requirements on input and output activities of a five-step analysis framework for piping reliability analysis. Explorations of industry-wide and plant-specific operational data via conditional factors of piping reliability are central to this analysis framework.

1.1 Project History

Among the motivations behind this SKI-funded project were: 1) Define the requirements for appropriate and sufficient service data and analysis techniques for parameter estimation in support of PSA applications and PSA-based evaluations of licensee submittals involving piping system modifications; 2) Address the need for improved treatment of piping reliability in today's PSA studies; and 3) Address the need for improved analysis of service data on piping systems[2].

Traditionally, PSA studies have not included detailed analyses of passive component failures. Usually the passive components have been excluded from system models. The argument for doing so was that the failure rates were considered negligibly small. Furthermore, most PSAs modeled initiating events[3] caused by passive component failures as single basic events or 'black boxes.' As the nuclear power plants are getting older, a critical evaluation of these analysis practices is needed, however. Central to the project was the development of an event-based, relational database on the service experience with piping systems in nuclear power plants worldwide. The work also included the development of a framework for analyzing these data in the context of PSA application requirements. Initiated in the fall of 1994, the project has been performed in three phases:

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[1] Copies of earlier project reports and conference papers (from PSAM-III and PSA'96) are available from the Swedish Nuclear Power Inspectorate as hard copies or in PDF format.

[2] Includes PSA-based event analysis and precursor evaluations of piping system failures such as the one performed by VTT (1994)[1-1].

[3] As examples, loss of coolant accidents (LOCAs), intersystem LOCA (ISLOCA), internal flooding due to service water system piping break/rupture.

(1) Design of an event-based, relational database in MS-Access®, and preliminary gathering of data sources with emphasis on piping failures in Swedish and U.S. nuclear power plants and Russian-designed plants (i.e., RBMKs and WWERs).4 A first database version was available in the spring of 1995. At that time it included about 1,500 failure reports. Insights from reviews of an additional ca. 300 piping failures in non-nuclear facilities enabled a limited comparison between nuclear industry and chemical process industry data[5].

(2) Detailed review of previous efforts to develop failure parameters based on operational data. In addition, an extensive survey was performed on the estimation of loss-of-coolant-accident (LOCA) frequencies in over 60 PSA studies. The results of the Phase 2 of the project included a definition of requirements for a piping reliability analysis framework using operational data. The work in Phase 2 was documented in four SKI Reports published during 1996[1-2,3,4,5]. These reports included some preliminary insights from database explorations.

(3) The final phase has concentrated on the development of an analysis framework. This framework has been greatly influenced by insights from analyzing the operational data. The database development has continued throughout Phase 3, and it has benefited from access to proprietary service data from five European utilities. The analysis framework builds on the concept of 'conditional factors' of piping failure, which includes evaluations of the unique reliability attributes and influence factors affecting or controlling the piping integrity.

Throughout the R&D, the project team has sought input from the international nuclear industry and the research community. Volume 1 of the four technical reports generated by Phase 2 of the project were peer reviewed by a team of experts on plant operations, PSA and structural reliability. Peer review comments were received from Arizona Public Service, EQE International, Florida Power & Light Company, IVO Consulting Oy., Kernkraftwerk Leibstadt AG, and Scientech Inc. This final project report has been peer reviewed by Dr. Roger Cooke (Delft University of Technology, The Netherlands), Ms. Jette Paulsen (Risø National Laboratory, Denmark) and Mr. Sture Andersson (S-A Ingenjörsbyrå AB, Sweden).

1.2 Technical Scope & Organization of the Project

Based on the analysis of service data, this SKI-sponsored project attempts to improve the PSA-treatment of piping reliability. This R&D was prompted by a need to develop an integrated analysis approach to support PSA applications, including the evaluation of the impact on plant risk by modified in-service inspection programs. Also, the project addressed new requirements to be placed on the incorporation of piping reliability into PSA studies on older nuclear power plants. The technical scope was limited to evaluations

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4 Footnote added to 2nd Edition: Since end of 1997, this database has been subject to an ongoing, active database management effort. The database management is now part of an international program managed by the OECD Nuclear Energy Agency.

[5] Among the conclusions from this comparison were: a) the data from non-nuclear facilities have little or no relevance to the piping systems in nuclear power plants; and b) the coverage and completeness of the non-nuclear operating experience data repositories is limited.

of event data extracted from licensee event reports. The intended applications of the event database and the analysis framework include the following:

– LOCA frequency estimation. Under an assumption that the piping systems that are part of the reactor coolant pressure boundary (RCPB) have been evaluated in terms of number of components (e.g., welds, straight sections, elbows, tees), material, and operating experience, the data and the analysis framework support plant-specific LOCA frequency estimation.

– Initiating event (IE) estimation. For IEs such as main steam line break, internal flooding due to service water system pipe rupture, the data and analysis framework support plant-specific IE frequency estimation.

– PSA applications. The data together with the analysis framework support plant-specific, optimization of in-service inspection (ISI) programs. The pipe rupture frequency is calculated for individual pipe sections. Based on plant risk, a modified inspection approach would eliminate low-risk pipe sections.

Piping reliability is a very complex topic and this final project report should be viewed as a first step to develop detailed analysis guidelines, which are acceptable to PSA practitioners and safety engineers. Additionally, the final project report develops a basis for guidelines on how to report and evaluate piping failures. Specifically, this report covers the following aspects of piping reliability: 1) The determination of the frequency of piping degradation or failures including cracks, leaks and ruptures; 2) Estimation of the probability of pipe rupture given a degradation of a piping system; and 3) Estimation of piping reliability parameters for input to PSA models. The report also identifies areas in need of additional work. Future efforts, especially in the area of data collection and data analysis, should be pursued within the international cooperative nuclear safety R&D programs.

Coordinated by the SKI Project Manager, Mr. Ralph Nyman (Department of Plant Safety Assessment), the technical work was performed jointly by ENCONET Consulting Ges.m.b.H. and RSA Technologies. Phase 1 of the project, initiated in October of 1994, produced the database design, while Phase 2, initiated in April of 1995, included surveys of the PSA state-of-analysis-practice with respect to LOCA frequency assessment. In Phase 3, Mr. Bengt Lydell (RSA Technologies) was the principal investigator and the author of the final project report.

During the fall of 1996, preliminary data analysis insights from Phase 3 were presented to OKG AB and IVO Consulting Oy, respectively. Comments and recommendations from these two Nordic industry organizations were incorporated in the data reduction and analysis efforts performed during the 2nd half of 1996 and the 1st half of 1997.

Furthermore, an information exchange was also established with the parallel Nordic Nuclear Safety Research Program 'NKS/RAK-1.2: Strategies for Reactor Safety - Preventing Loss of Coolant Accidents' in which a probabilistic fracture mechanics model was developed to calculate pipe break probabilities due to IGSCC in Swedish BWRs. The

‘International Seminar on Piping Reliability’[6], held on September 30 and October 1, 1997, represented the formal conclusion of the SKI R&D project.

1.3 Piping Reliability Considerations

The reliability of piping system components is of great importance to the nuclear industry. Piping systems are used extensively, and the degradation or failure of piping has significant safety and financial implications. The modern PSA studies should account for potential piping failures by acknowledging the available operating experience. Also, systematic evaluations of the experience with non-destructive examination (NDE) and in-service inspection (ISI) would benefit from the access to a comprehensive database on the operating experience with piping systems to determine the effectiveness of NDE/ISI. In part, this project was motivated by the ongoing Swedish plant renovation and modernization projects and the requirements for improved treatment of LOCA frequency estimation in the Swedish PSA studies.

As expressed by the American Society of Mechanical Engineers (ASME) Research Task Force on Risk-Based Inspections[1-6]: *“... the task of estimating piping reliability is complex, uncertain and costly ...”* There is no one best method to estimate failure probabilities. Therefore, the estimation process has to rely on insights from the relatively large number of incipient and degraded failures, which have occurred in NPPs worldwide. Since major structural failures are rare events, safety engineers and PSA practitioners should always consider the broadest possible database on operational events. Because of the complex nature of piping reliability, it is equally important that there exists synergy between PSA and structural mechanics including probabilistic fracture mechanics (PFM). The methods for assessing piping reliability use a combination of techniques as indicated in Figure 1-1.

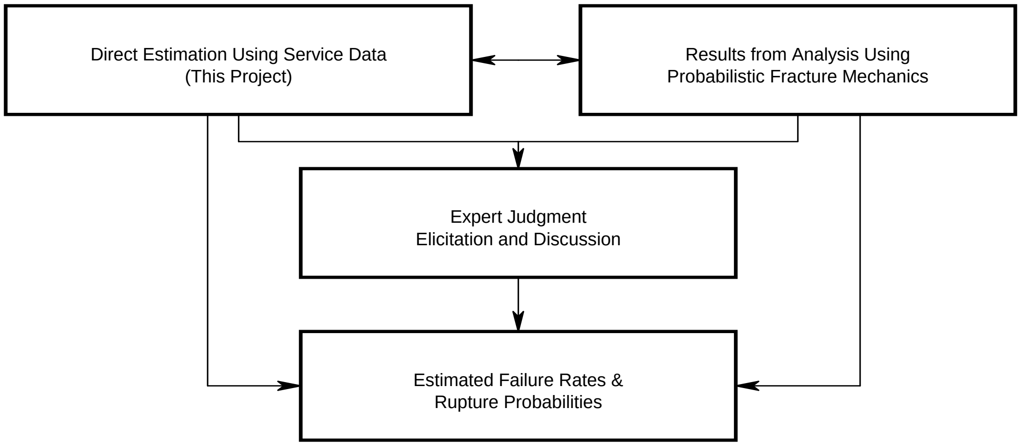

Figure 1. Approaches to Estimating Piping Reliability

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[6] Seminar on Piping Reliability: Presentation of Piping Reliability Research in Support of the Nordic PSA Program & Other SKI Sponsored Projects, September 30 - October 1, 1997, Sigtuna (Sweden). Copies of the Proceedings of the seminar (SKI Report 97:32) are available from the Swedish Nuclear Power Inspectorate.

With emphasis on applications of historical data (i.e., service data), the analysis framework addresses the different options available in parameter estimation. This framework encompasses requirements on probabilistic fracture mechanics studies; e.g., degradation mechanisms to consider, qualification of input and output data.

In PSA, a lack of quantitative models (i.e., decomposition and holistic models of reliability) and failure data has directed practitioners to WASH-1400 (the Reactor Safety Study of 1975). The validity of LOCA frequencies and piping failure rates often has been cited solely on the basis of referencing the WASH-1400, and without questioning the old data or the approach to deriving or inferring failure parameters in that study. In the opinion of the authors of this SKI Report, the available operational data should always be systematically explored when deriving LOCA frequencies. It is especially important that the available, current experience data be explored by comparing industry-wide and plant-specific service data. Analysts should take into account the current state-of-knowledge about structural mechanics and degradation mechanisms.

1.4 Framework for Piping Reliability Analysis

The analysis framework, developed by the project, was fashioned after the results and insights from analyzing a large volume of service data. Therefore, this framework is data-driven. Parameter estimation based exclusively on experience data is not advisable, nor feasible for all intended applications, however. Throughout an estimation process, it is highly recommended that expert judgment by structural expertise be considered. The analysis framework, which is called the '*Pipe Failure Cause and Attribute Framework*' (PFCA), is a top-down approach favoring decomposition of a given piping reliability problem according to reliability attributes and influences; *c.f.* Figure 1-2. It is a top-down approach since an analysis would begin by specifying the requirements of an application. That is, the framework builds on the analysts' understanding of the design and operational factors, operating history, inspection history, and environmental influences that affect piping reliability. The framework consists of five steps with inputs, analytical activities or deliberations, rules and outputs:

(1) Application Requirements. The input consists of descriptions (e.g., isometric drawings, material specifications) of a piping system, and service history. The output is a concise description of the planned application; e.g., estimation of LOCA or main steam line break (MSLB) frequency. The intended application determines how to select generic piping reliability parameters. It also determines how reliability attributes and influences are evaluated and used. Finally, the application requirements determine which piping system component boundaries to use; e.g., piping section/segment definitions. Examples are given of typical requirements with discussion of the implications for the subsequent analysis steps.

(2) Raw Data, Piping Population Data & Generic Reliability Parameters. The framework includes the necessary analysis techniques and raw data for calculating plant-specific parameters. The framework comes with tabulations of raw data and piping component population data for a selection of different plant types and systems. Pipe failures are rare events, and the framework includes consideration of Bayesian statistics. First, application-specific priors are developed, and second, the

user performs a detailed evaluation of plant-specific operating experience (including inspection records and other relevant information) to estimate the plant-specific parameters. Hence, the framework makes a distinction between *application-specific* and *plant-specific* parameters. The former enables the selection of the most appropriate and relevant operating experience to be used.

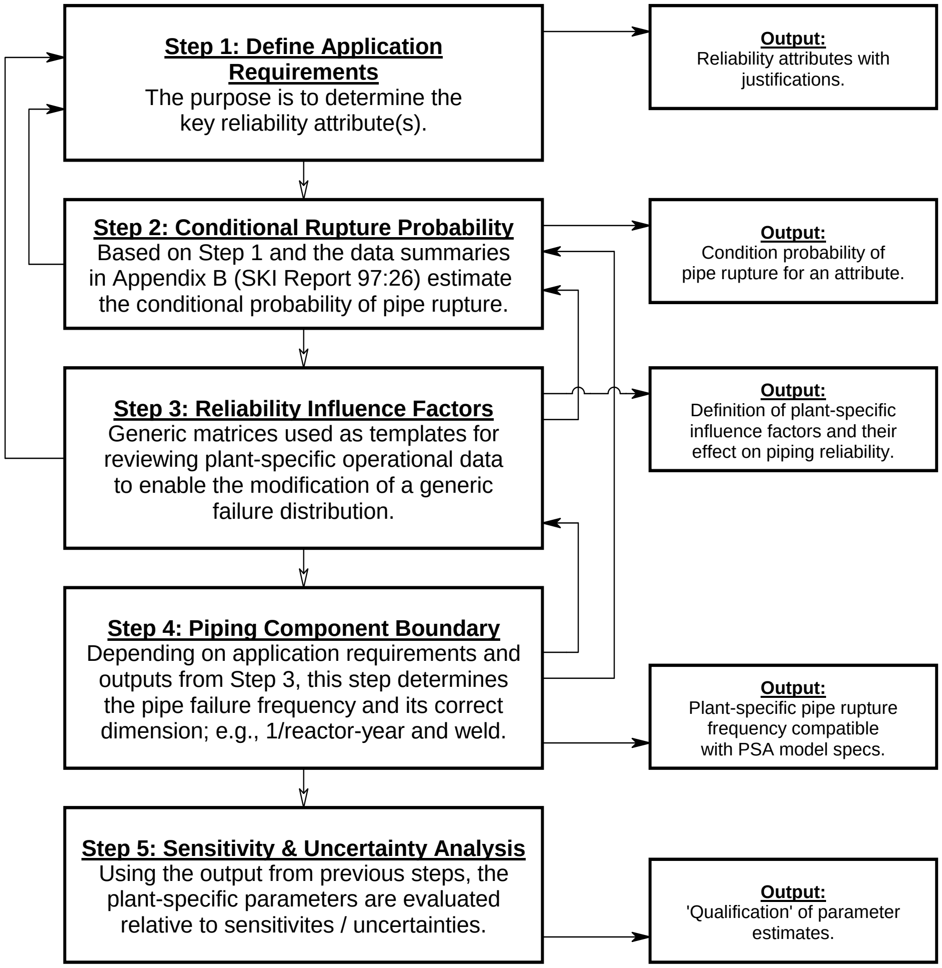

Figure 2. The Five-Step PFCA Framework for Piping Reliability Analysis

(3) <u>Reliability Influences & Review of Plant-Specific Experience</u>. The step from application- to plant-specific parameter estimation is taken via application of reliability influence matrices (or checklists). Extracted from SKI's pipe failure event database (SLAP; *c.f.* Figure 1-3), the framework provides detailed influence matrices (by major degradation or failure mechanism) that list potential plant-specific influences and their relative contribution to reliability. These matrices are the templates to be used by PSA practitioners, who are familiar with model requirements, and structural experts intimately familiar with the piping system designs, the operating experience, and the NDE/ISI practices.

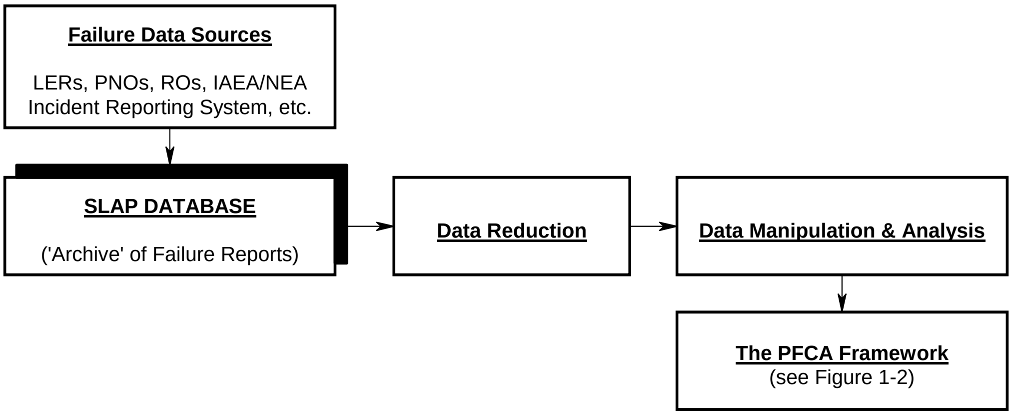

Figure 3. The SLAP Database and the ‘PFCA? Framework

(4) Piping Component Boundary Definition. The review in Step 3 should be done on the basis of isometric drawings, and the output could be in the form of pipe section/segment definitions, and a quantitative basis for modifying generic reliability parameters, with proper justifications. *The purpose of Step 4 is to define the dimension of the parameter estimates and the PSA model representation of piping failures*. The dimension (e.g., failure/system-year, failure/‘length-of-piping’-and-year, failure/weld-and-year) is a function of the predominant degradation or failure mechanism, material, system layout, etc. With respect to the model representation, the question addressed by Step 4 is whether piping reliability should be considered at the cutset level or at a different level in the PSA model structure? In the opinion of the project team, whenever PSA-based applications or risk monitoring requirements have been defined, a high level of model discrimination is preferred over 'black box' models. Most importantly, the boundary definition should be a function of the type of degradation or failure mechanism affecting a piping system.

(5) Statistical Analysis & Uncertainty Analysis. The framework recognizes the importance of analyzing uncertainties. The sources of uncertainties are identified and evaluated in Step 5. It is recognized that in the final derivation of plant-specific parameters, expert judgment elicitation and engineering evaluations will be combined with estimates that are based on operational data. Ultimately the goal of performing uncertainty analysis is to *qualify* those conclusions that are made about piping reliability based on point estimate evaluations. It should also be used to identify where improving the state of knowledge can lead to maximum benefit with respect to an accurate assessment of piping reliability.

Depending on the scope of an analysis, an application of the framework may involve only Steps 1 and 2, or all five steps. Rigorous applications would be relatively time-consuming, and could require extensive inputs from structural expertise. The users of this framework are encouraged to explore the raw data on piping failures beyond the scope of the present report. It is invariably expected that the user is team of experts, which determines what the unique failure modes and degradation and mechanisms are, and where faults (e.g. flaws/cracks, leaks) in a given piping system are most likely to occur.

1.5 Work Scope Limitations

The R&D-project considered service data involving degradation mechanisms (or aging mechanisms, due to corrosion, erosion/corrosion, stress corrosion cracking) and failure mechanisms (such as severe overloading due to water hammer, inadvertent over-pressurization); *c.f.* Table 1. The emphasis was on degradation mechanisms acting on piping systems within the RCPB, however. Additional study scope limitations included:

- The survey of service data emphasized leaks and ruptures as documented in public information sources (e.g., Swedish and U.S. licensee reporting systems). Service data on flaws/cracks were selectively considered; e.g., significant events with potential generic implications. Information on flaws/cracks typically is included in ISIS summary reports. Such reports were not available to the project, however.

- The study did not include a systematic and detailed determination of the frequency of water hammer events in piping systems. Only water hammer events, which resulted in significant pipe damage (e.g., major leak, rupture or severance) were considered;

- The study did not collect piping component population data. This report emphasizes the estimation of relative pipe failure parameter estimates rather than absolute estimation. Detailed collections of piping component population data will evolve with the number of plant-specific applications of a piping reliability analysis framework such as the PFCA. Appendix B includes a selection of component population data for different piping systems and types of nuclear power plants. These population data were extracted from public domain documents.

Table 1. Examples of Stressors, Degradation Mechanisms / Failure Mechanisms & Failure Modes of Piping Systems[7]

Stressors	**Degradation / Aging Mechanisms**	**Failure Mechanisms**	**Failure Modes**
Single-phase flow Two-phase flow Temperature gradients and transients	Erosion / corrosion Erosion / corrosion Fatigue		Crack / leak / rupture d:o d:o
Environmental stress / sensitization	Stress corrosion cracking (PWSCC / IGSCC / TGSCC)		Crack / leak / rupture d:o
Vibration Water hammer / seismic events / testing / drop of heavy load		Fatigue / overload Fatigue / overload / overpressurization	Crack / leak / rupture d:o + severance / deformation / distortion

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[7] Adapted from Conley, D.A., J.L. Edson and C.F. Fineman, 1995. *Aging Study of Boiling Water Reactor High Pressure Injection Systems*, INEL-94/0090 (NUREG/CR-5462), Idaho National Engineering Laboratory, Idaho Falls (ID).

– The study did not consider degradation or failures of internal reactor components such as jet pump risers in some BWRs[8]. In other words, only piping system components external to the reactor pressure vessel were considered.

1.6 The Intended User of the ‘PFCA’ Framework & Data

This report does not include processed failure parameters for direct input to PSA models. It is a ‘basis document’, which identifies the unique aspects of piping reliability that require detailed, explicit consideration in the parameter estimation. Therefore, the report is intended for the advanced PSA practitioner with prior experience of data analysis. By using the raw data summaries (in Appendix B) and an analysis framework (Section 5), the practitioner is given the necessary tools and techniques to pursue plant-specific applications of a data-driven model of piping reliability.

The proposed analysis framework is not a prescriptive, step-by-step analysis procedure. Instead, the framework defines a minimum set of requirements on piping reliability analysis based on interpretations of service data. The user of the framework is encouraged to explore the service data beyond the presentations and representations of this report.

1.7 Database Availability

The project has produced a large, relational database in MS-Access® on pipe failures in nuclear power plants worldwide. The computer file size (in compacted form) of the current version is approximately 2.5 Mb. Each data record (i.e., failure event) consists of 54 data fields, which provide design information (material specifications, size), event narratives, results from event analyses (e.g., root cause analyses), and information on the effect on plant operation[1-7]. The database content is proprietary to the SKI. Nuclear safety professionals and PSA practitioners interested in reviewing and applying the full database must contact the SKI in writing to establish the terms-and-conditions for database access[9].

1.8 Organization of the Report

The report consists of six sections and three appendices. Section 2 includes a statement on the unique passive component reliability issues. Also included in Section 2 is an overview of the potential interfaces between data-driven models and probabilistic fracture mechanics, followed by a brief discussion on the role of material sciences in PSA. The technical basis for the PFCA Framework is developed in Sections 3 and 4. With the objective of summarizing sources of statistical uncertainties, Section 3 describes the operational data on piping failures, and the coverage and completeness of the SLAP database. This presentation sets the stage for Section 4, which describes the conditional factors of piping failures. Specifically, Section 4 presents the definitions of piping reliability attributes and influence factors and how they are used to reduce, manipulate and

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[8] As an example, see U.S. NRC Information Notice 97-02 (February 6, 1997): Cracks Found in Jet Pump Assembly Elbows at Boiling Water Reactors.

[9] Limited to the database version SKI-PIPE dated 12/31/1998. Letters should be forwarded to the following address: Swedish Nuclear Power Inspectorate, Plant Safety Assessment - Dept. RA, Att.: Mr. Ralph Nyman, SE-106 58 Stockholm, Sweden.

analyze the service data in the SLAP database.

Section 5 describes each of the five steps of the PFCA Framework, discusses the activities pertinent to each step, and presents the rules or recommended implementations for each step. The section illustrates the use of the framework, and includes a discussion on statistical uncertainties as they apply to piping reliability analysis. Finally, Section 6 presents recommendations for pilot applications and future short- and long-term R&D, together with the conclusions.

There are three appendices to the report. Appendix A presents the pipe failure event data sources used in developing the SLAP database. Appendix B is a compilation of a selection of raw data to be used as input to the PFCA Framework. Appendix C, finally, contains a list of abbreviations and acronyms together with a glossary of technical terms.

1.9 References

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(1-3). ibid, *Volume 2: PSA LOCA Database; Review of Methods for LOCA Evaluation Since WASH-1400*, SKI Report 95:59, Stockholm (Sweden).

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2

UNIQUE PROBLEMS IN PIPING RELIABILITY ANALYSIS

The development of comprehensive databases and analysis frameworks for passive component (e.g., piping) reliability has lagged behind the corresponding efforts for active component reliability. In part, this discrepancy is a function of the complex nature of piping reliability. While a consensus exists regarding the analytical treatment of active component reliability, no such consensus has evolved for passive components. This section investigates the unique differences between active and passive component reliability. The motives of the SKI-funded R&D are delineated in this section.

2.1 Passive vs. Active Component Reliability

Piping systems are designed to high quality standards. These systems represent an important safety barrier, which forms one of several elements in the defense-in-depth concept of nuclear safety. Catastrophic piping failures are rare events, thus proving the effectiveness of the design codes and standards. Piping systems are susceptible to aging effects, however. Since piping systems cannot be subjected to the same maintenance and replacement strategies as the active components, a fundamental question arises relative to the importance of aging effects: How should the limited service data be used to address these aging effects in today's PSA applications? An overview of the basic differences between passive and active component reliability is found in Table 2.

Table 2. Basic Differences Between Passive & Active Component Reliability

Feature	Passive Component	Active Component
Component Boundary Definition	Continuous (or 'extended'; the piping system boundary is defined by the plant system boundary. That is, the boundary of a feedwater piping system is defined by the feedwater system boundary.	Discrete well (uniquely) defined component boundaries. Data collections such as the Nordic 'T-Book' or IEEE Std. 500 contain details on component boundaries.
Failure Rate Dimension	1/(Time · Extension) -- the 'extension' cannot be universally defined. Could be length of piping, number of pipe sections, number of piping system components.	Uniquely defined by: dimension 'time' or 'demand'.
Frequency of Failure	Rare events	Frequent events
Component Type	Many different types distinguished by material, diameter, environment, process medium, operating environment, etc.	Standard types
Failure Modes and Failure Causes	A spectrum of failure modes; from small to large leaks to ruptures. The susceptibility to failure strongly dependent on design and degradation and failure mechanisms. Difference with respect to cause and severity.	Limited number of failure modes (e.g., failure to start, failure to run).

2.2 Component Boundary & Estimation of Failure Parameters

By definition, a component boundary clearly relates all interfaces of a specific component to other components in the system with which it interfaces via hardware and software. Therefore, a failure of a component relates to a clearly defined component boundary. In other words, the physical location of a failure corresponds with a boundary definition. Unlike active components (e.g., MOVs, pumps, electrical breakers/switches), for piping systems one cannot define a universal piping component boundary, however. The problem of estimating pipe failure rates and failure probabilities from scarce service data is compounded by the fact that the large volume of piping in a nuclear power plant (NPP) consists of many different types of piping systems.

The piping systems range from small-diameter to large-diameter piping, primary system piping to support system piping, etc. Furthermore, the piping systems differ according to material, process medium and operating conditions. The failure susceptibilities are functions of the design and operational characteristics. Obviously, the analysis of service data on piping failures must differentiate between type of piping system, operating environment, cause and severity. Subsequently, the estimation of failure parameters and the definition of appropriate component boundaries should reflect these unique features of a piping system (i.e., type, environment, and cause/severity). We calculate the failure rate of piping from:

$$\lambda_{PIPING} = (Number\ of\ Failures)/(Time \times Extension) \qquad (2\text{-}1)$$

where ‘Extension’ = Length of piping, or number of piping system components in the system for which the failure parameter is estimated. Could be number of pipe sections; a section could be a segment of piping between major discontinuities such as valves, pumps, reducers, tees.

The estimation of failure parameters builds on access to homogenous data on events within a clearly defined component boundary. This means that the service data must be pooled according to type of system, environment, cause and severity, and component boundary. The extension follows on having a full understanding of ‘*why-where-how*’ piping systems fail.

2.3 PSA vs. PFM

The unique differences between passive and active component reliability, and the difficulties associated with failure parameter estimation using scarce service data have been recognized and debated for a long time. As an alternative to the ‘data-driven models’ of piping reliability, the material sciences have proposed the application of fracture mechanics models. These models enable the calculation of failure probabilities assuming that a piping system is susceptible to *anticipated* degradation mechanisms; especially aging effects (such as stress corrosion cracking), which develop over a long time period.

There is a long-standing debate (at least since the early 1970’s) between PSA and material sciences disciplines regarding the areas of applicability of data-driven models and PFM. To the PSA practitioners the analytical problems associated with rare events are well understood. According to the material sciences, it is impossible to make realistic estimates of the probability of pipe rupture when the service experience is zero failures in, say, 8,500 reactor years[10]. For this reason alone, direct estimation using service data should not be pursued. In fact, the pursuit of service data collections has been questioned. What are the areas of applicability of data-driven models and PFM models? In its most basic form, the frequency, f_R, of a pipe rupture is calculated from the following symbolic expression:

$$f_R = f_{FAILURE} \times p_{RUPTURE\,|\,FAILURE} \qquad (2\text{-}2)$$

where f_R = frequency of a pipe rupture;
$f_{FAILURE}$ = frequency of a pipe failure (e.g., flaw/crack, leakage);
$p_{RUPTURE\ |\ FAILURE}$ = conditional probability of rupture given a flaw/crack or leakage.

The difference between PSA and PFM lies in the way the conditional probability of pipe rupture is calculated; *c.f.* Table 3. In PSA the estimation is performed through detailed evaluations of service data combined with application of Bayesian statistics (in the case of zero failures) and expert judgment. The material sciences use fracture mechanics models and expert judgment.

Table 3. The Difference between PSA and PFM

Method	**Estimation of $f_{FAILURE}$**	**Estimation of $P_{RUPTURE\ \vert\ FAILURE}$**	**Comment**
PFM	Direct estimation from service data	Application of fracture mechanics theory to the analysis of crack growth	Assumes anticipated degra-dation (i.e., long time between crack initiation → leak → rupture) in austenitic steels. No treatment of uncertainties. Requires population data. Explicit treatment of the reliability of in-service inspection methods. Parametric models which enable sensitivity analysis.
PSA	Direct estimation from service data	Direct estimation from service data	Requires population data. Implicit treatment of the reliability of in-service inspection methods. Parametric studies feasible. Controversial in the context of LOCA frequency estimation.

As summarized in Table 3, the approach to the estimation of pipe rupture frequency in PFM *and* PSA builds on interpretations of service data. An outstanding issue is the estimation of the conditional pipe rupture probability. Ultimately, the requirements that are placed upon an analysis determine the selection of methodology. The R&D by SKI to develop a comprehensive database on the service experience with piping systems and the analysis framework, PFCA, supports both technical approaches.

A basic difference between the two approaches is found in the estimation of the conditional rupture probability. Under a similar set of boundary conditions, the two methods tend to produce similar (i.e., the same order-of-magnitude) results, however. The statistical uncertainties are considerable, no matter the technical approach. The proper merging of PSA and PFM depends on the full recognition of the methodological differences. Possibly more important than these methodological differences, PSA and material sciences use different terminology and definitions. Much could be gained from

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[10] According to IAEA data, at the end of 1996 the worldwide NPP operating experience was about 8,500 reactor-years. During that time there have been no ruptures in medium- to large-diameter piping inside the RCPB.

using common terminology:

- On Pipe Failure Mode Definitions: The material sciences tend to define ‘failure’ as a ‘double-ended-guillotine-break’ (DEGB) where the pipe ends are axially displaced or completely separated. PSA distinguishes between ‘flaw/crack’, ‘leak’ and ‘rupture’. In PSA a small leak from a large-diameter pipe could have the same consequence as a large leak from a small-diameter pipe.

- On LOCA definitions: Material sciences only consider the DEGB that results in a loss of process medium beyond the make-up capability of safety injection systems. That is, the material sciences are concerned with the LOCA concept as defined by the design basis accident (DBA) in deterministic safety analysis. PSA considers a spectrum of pipe ruptures that could cause a small-small to large LOCAs with or without make-up capability.

A major advantage of PFM lies in its application of parametric models, which enable sensitivity studies, and the evaluation of leak detection and ISI reliability. An advantage of data-driven models is the relative ease by which the applications can be performed. The quality and completeness of the pipe failure databases limit the applications of service data, however.

2.4 Discussion

The R&D by SKI was initiated to address the unique problems in piping reliability analysis. Detailed evaluations of service data enabled development of recommendations for how to define piping component boundaries. This R&D also addressed the requirements to be place upon data-driven models of piping reliability. Sections 3 through 6 develop the basic techniques of piping reliability analysis from the perspective of service data.

3

SERVICE DATA ON PIPING

In Section 1 we presented basic elements of a framework for analyzing piping reliability, which is based on evaluations of operational data. In this section, we consider the basic principles of how to collect and analyze service data. Also considered is the relationship between past and current reporting practices and the coverage and completeness of service data. The purpose is to address practical considerations in pipe failure data collection. We explore the question whether robust and believable failure parameters can be derived from service data: *Does the SLAP database have sufficient depth and detail to support meaningful reliability estimation?*

SKI's R&D project has produced a large database on piping failures. The unique problems associated with operational data and piping reliability estimation were addressed over thirty years ago. Since that time (i.e., 1964-68), several organizations have pursued database development and data analysis. Despite these efforts, no widely recognized PSA-oriented database has emerged. When viewed against the past projects, the uniqueness of SKI's R&D lies in the depth of the data collection. Reports on incipient, degraded and complete failures have been collected from operating nuclear power plants worldwide. The analysis of these data builds on the concept of 'conditional factors of failure,' which emphasizes the relative differences in reliability. These conditional factors relate to design parameters and environmental influences.

3.1 Pipe Failure Data - Sources of Uncertainty

Probabilistic safety assessment (PSA) is a safety assessment tool for nuclear power plants (NPPs). An intrinsic element of PSA consists of the estimation of equipment reliability parameters from plant operating records. The validity of a PSA is a function of how this estimation is performed, and how well the system and plant models reflect an as-built and as-operated NPP. Translating plant records into reliability parameters requires detailed engineering knowledge as well as knowledge of the strengths and limitations of statistical analysis techniques and methods.

Data estimation is done in two steps: 1) Collection of data on occurrences of the events of interest; and 2) Parameter estimation with the aid of statistical analysis techniques and methods. The foundation for believable estimates is laid in step 1. A first consideration of this step involves a determination that sufficiently detailed information has been collected on 'all' relevant failure events.

The completeness of a data collection reflects the scope of an analysis effort as well as the extent of the exploration of different sources of operational data for the nominated failure events. Incomplete data sets could lead to an under-estimation of the data parameters. Step 2 of the data estimation is concerned with the selection of appropriate techniques and methods so that the important factors, which affect reliability, are addressed in sufficient detail.

Extensive use of judgment is made in both these steps. The most extensive use of judgment usually is made in step 1 of the estimation process. Sometimes the available information in the plant records is unclear and incomplete. A reasonable interpretation of such information is impossible without having a detailed knowledge about the specific equipment-related failure modes and failure mechanisms. It is equally important to understand the reporting practices and the bases for maintenance work orders, licensee event reports, etc. In the next sections we address key considerations in collecting data on pipe failure events, and the data coverage and completeness issues.

3.2 The SLAP Database Content & Coverage

Databases on equipment failures must be tailored according to specific objectives. The SLAP database builds on the principle of collecting data on an *event and exposure basis*. Incorrect or incomplete data interpretations would result from a data collection, which is limited to a fault-count basis. The analysis of conditional factors of piping failures requires access to data collections, which include information on the '*why-where-how*' failures occurred.

The SLAP database contains information on known (i.e., reported) pipe failures in nuclear power plants worldwide. It covers the period 1970 to the present. In developing the database the scope of the work has emphasized pipe failures in light water reactors (LWRs). Currently (October 1997), the database includes about 2,360 *qualified* failure reports; *c.f.* Table 4.

Table 4. The SLAP Database Content (Version 7, Revision 7)[11]

Plant Type[(a)]	Number of Plants Surveyed	Coverage[(b)] [Reactor-Years]	Failure Mode		
			Crack[(c)]	**Leak**	**Rupture**
BWR	71 (94)	1,398 (2,282)	114 (1183)	648 (969)	63 (72)
LWGR	13 (13)	208 (302)	3 (100)	41 (49)	14 (14)
PHWR	20 (40)	354 (753)	11 (11)	75 (77)	14 (14)
PWR	164 (318)	2,670 (5,748)	55 (431)	1206 (1697)	112 (148)
”Other”	(5)	(94)	(5)	(5)	(3)
Totals:	274 (421)	4,741 (9,179)	183 (1730)	1970 (2913)	203 (251)

Notes: (a) The material used in primary system piping differs among the plant types; e.g., industrial grade vs. 'nuclear grade' stainless steel. Also, as an example, in WWER-1000, the primary system piping material is ferritic steel with austenitic cladding as an anti-corrosion measure.

(b) As of 9/30/97; no adjustment made for time in maintenance/refueling outage.

(c) Significant events only: crack depth > 20% of wall thickness. The total number of flaws among the worldwide NPP population is estimated to be at least a factor of 10 larger.

(d) Catastrophic loss of structural integrity and/or leak rate > 5 kg/s (80 gpm), without advance warning; e.g., no drop leakage or leakage large enough to actuate a leak detection system to enable prevention.

In Table 4, the category 'rupture' includes two types of events: 1) Catastrophic rupture which resulted in complete separation of pipe ends, or major 'fish-mouth' opening; and 2) Major crack opening which resulted in leakage in excess of 5 kg/s (80 gpm). In both cases the failure occurs without advance warning to the control room operators. The failure reports included in SLAP were all classified according to leak rates. For the majority of the reports, the leak rates were estimated based on event narratives.

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[11] Information in parentheses corresponds to database status as of 12-31-2004.

Except for the Swedish, U.S. and selected European plants, for which licensee event reports and special failure reports were available, the primary reference used was the IAEA/NEA Incident Reporting System (IRS)[3-1]. By design, the IRS database includes nominated or significant events as submitted by participating organizations. That is, an event report is submitted to IRS when the event is considered by a national coordinator to be of international interest. Approximately 10% of all pipe failure event records were extracted from the IRS database.

Summaries of the SLAP database content by pipe diameter, mode of plant operation when a failure was detected, and type of degradation or failure mechanisms are given in Figure 4 and Table 5. To date, all large-diameter, complete failures (i.e., ruptures) have occurred in balance-of-plant (BOP) systems, support systems or fire protection system; i.e., LOCA-insensitive piping. Complete failures affecting LOCA-sensitive piping (i.e., piping within the RCPB) have been restricted to small-diameter piping of DN ≤ 25. That is, instrument lines, vent/drain lines, bypass lines and test/sample lines. Finally, the SLAP database content is compared with a recent, independent data collection effort in Table 6.

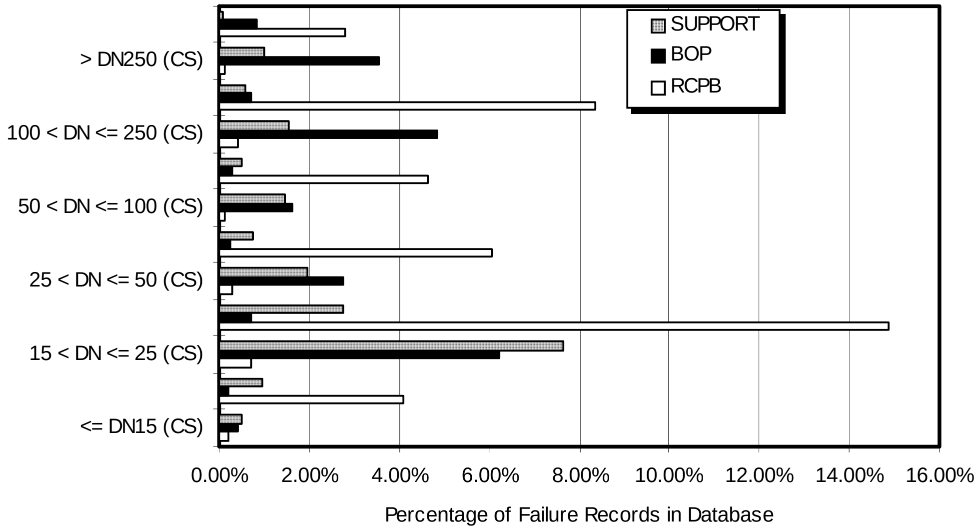

Figure 4. Overview of Database Content by System Category[12]

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[12] SUPPORT = Support System (e.g., component cooling water, service water, instrument air); BOP = Balance of Plant System (e.g., moisture separator reheater lines, condensate piping); RCPB = Reactor Coolant Pressure Boundary (systems within containment, see Appendix C for definition).

Table 5. The SLAP Database Content Organized by Pipe Size, Plant Operational State & Apparent Cause of Failure (SLAP Version 7, Revision 7)

Attribute / Influence	Number of Failure Records		
	Crack	Leak	Rupture
Nominal Pipe Diameter			
≤ DN15	6	138	19
15 < DN ≤ 25	13	732	55
25 < DN ≤ 50	15	261	25
50 < DN ≤ 100	25	178	16
100 < DN ≤ 250	49	312	43
> DN250	61	129	33
Unknown	14	220	12
TOTAL:	183	1970	203
Operational Mode[(a)]			
Startup	3	190	24
Normal operation	34	1600	157
Shutdown	146	180	22
TOTAL:	183	1970	203
Apparent Degradation / Failure Mechanism			
Corrosion+Erosion	14	490	50
Fatigue	40	656	64
IGSCC / SCC / TGSCC	102[(b)]	295	--
Severe Overloading (e.g., water hammer)	18	74	52
Human error	5	248	13
Other[(c)]	4	207	24
Totals:	183	1970	203

Notes: (a). Operational mode at the time when a piping failure was detected.
(b). Rejectable cracks (crack depth > 20% of pipe wall thickness).
(c). No explicit statement about cause of failure in LER, or results from ongoing investigation not yet available.

Table 6. Comparison of the Database Contents in SLAP & SKI Report 96:20

Pipe Size	SLAP Version 7.7 [Number of Records]	SKI Report 96:20 [Number of Records]
DN ≤ 25	963 (41%)	574 (38%)
25 < DN ≤ 100	521 (22%)	252 (17%)
100 < DN ≤ 300	446 (19%)	155 (10%)
> DN300	180 (8%)	74 (5%)
Unknown / Assumed Size[(a)]	246 (10%)	456 (30%)
Totals:	2356	1511

Note: (a). Failure report contains no explicit information on diameter.

3.3 The Reporting of Piping Failures

The piping systems in nuclear power plants are designed to high standards, and major failures are rare events. The rare failures have a low frequency of occurrence (e.g., less than, or much less than one failure per plant and year). Not only are the major, catastrophic failures rare events when viewed against a frequency-scale, they are also rare when viewed against a passive component 'population-scale.' Nuclear power plants contain a large volume of piping components (e.g., many thousands of welds, and several km of length of piping). Therefore, for any given plant, the ratio of major failures by the total piping component population is small (<< 0.1). Most piping failure incidents are incipient or degraded failures with minor or no immediate impact on plant operation and safety. The incipient or degraded failures have a relatively high frequency of occurrence; e.g., equal to or greater than one event per plant and year.

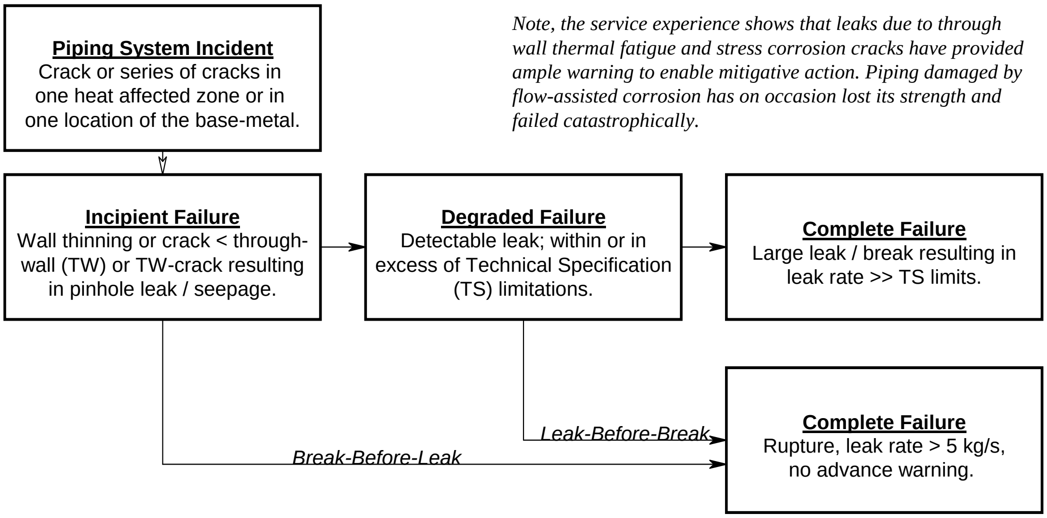
While the volume of technical information on operating experience with piping systems is considerable, the quality of this information varies immensely. Some reports present detailed root cause analysis insights and results (*c.f.* U.S. NRC, 1997[3-3]), while the majority of the reports contains cursory (and sometimes conflicting) information on the causes and consequences. The determination of root cause involves interpretation of results from visual examinations and, sometimes, detailed metallurgical evaluations of damaged or fractured piping components. In general, failure analyses and reliability analyses of incidents involving piping systems are complex and uncertain.

For the work documented in this report, the main source of information on piping failures was licensee event reports (LERs). The LERs are mainly prepared upon failure conditions, which place the plant operations outside the technical specifications. Rather than evaluations of the root causes, these reports concentrate on the apparent causes of failure. Uniform regulatory reporting requirements do not yet exist, and no industry standards have been developed for the reporting and dissemination of information on piping failures. This lack of detailed reporting protocols reflects the complex nature of piping reliability.

It is the opinion of the authors of this report that the lack of consistent reporting follows on not having a recognized model for analyzing piping reliability. Substantial interpretation of the available failure information is needed to determine the *where-why-how* a particular piping system failed. The interpretation should reflect the purpose of an analysis and the database design. It is not uncommon that the failure reports include detailed narratives of the circumstances of a given event (e.g., plant status and plant response). Reporting of the specifics of a piping failure (e.g., exact description of fault location, mode of failure, type and diameter of the failed piping component, trends and failure patterns) is beyond the scope of most LER systems, however. Therefore, and accurate and consistent failure classification often requires an 'interrogation' of several, independent information sources.

3.3.1 Reporting Practices and the Quality & Completeness of Data

Typically, piping failures are reported as 'cracks/crack indications', 'leaks' or 'ruptures', corresponding to incipient, degraded and complete failure, respectively; *c.f.* Figure 5. In this project, a 'rupture' is interpreted as a catastrophic loss of mechanical integrity, which occurs *without advance warning*. Ruptures potentially result in very large leak rates >> 5 kg/s (80 gpm).



Note, the service experience shows that leaks due to through wall thermal fatigue and stress corrosion cracks have provided ample warning to enable mitigative action. Piping damaged by flow-assisted corrosion has on occasion lost its strength and failed catastrophically.

Figure 5. Pipe Failure Mode Definitions Used in Developing the SLAP Database

The classification of events and the analysis of data build on a consistent application of clear definitions of failure. In the context of PSA, inadvertent or improper classification of a piping failure event as rupture could result in significant over-estimation of the true rupture frequency or probability. From the point of parameter estimation, there are several inherent limitations of LERs. By design, LERs document the effects of failure on system and safety functions. They do not go into the details about the specific degradation or failure mechanisms, contributing causes, and required repair actions, however. Therefore, events identified as candidates for inclusion in the SLAP database were processed according to the flowchart in Figure 6 and by augmenting the LER information with other relevant information sources.

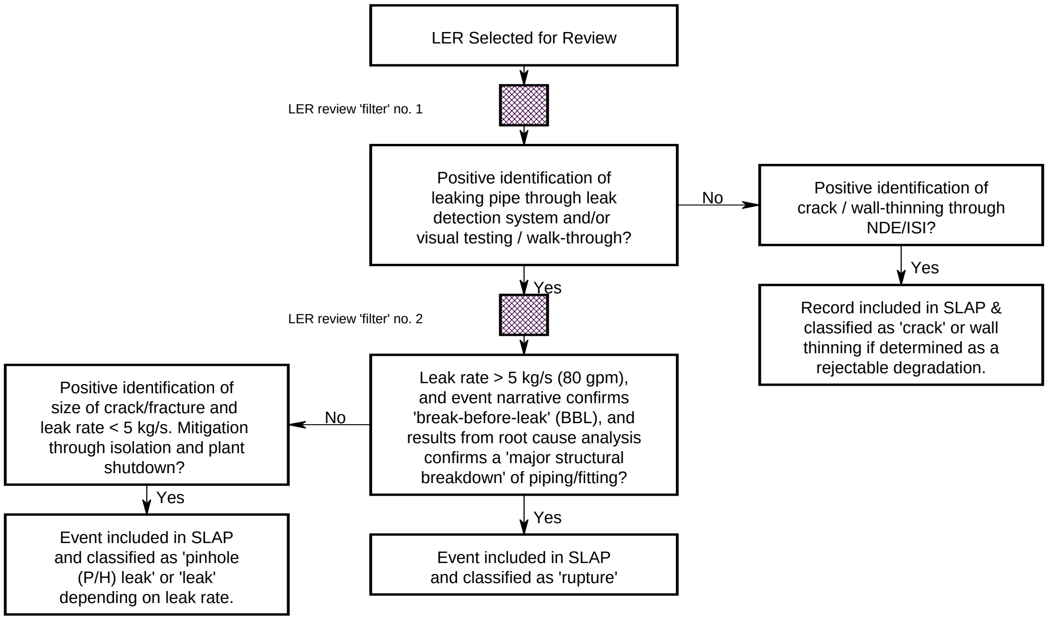


Figure 6. Development of the SLAP Database - The Event Review Process

Functional and structural interpretations of the potential or actual consequences of a given failure determine whether a formal, written report is prepared by a licensee for internal use or dispositioning with a regulatory agency. As an example, the probable consequences of small cracks due to stress corrosion cracking in piping within the Reactor Coolant Pressure Boundary (RCPB) are crack propagation in the through-wall direction and minor leakage of primary coolant. When small but detectable leaks occur, leak monitoring systems detect the change of leak rate, and a plant shutdown is required if allowable leak rate limits are exceeded. Such events are reportable according to technical specification reporting requirements. These reporting requirements do not cover degradation or failures in steam or feedwater piping that are outside of the RCPB boundary, however. Furthermore, the reporting of piping failures is a function of the approach to replacement of degraded piping. The replacement of degraded piping prior to developing a gross leakage would normally not be a reportable event. With the exception for significant degradation and complete failures occurring within the RCPB, *ad hoc* reporting of piping failures is the norm rather than the exception.

These observations would not be of any concern to PSA practitioners, were it not for the fact that piping failures are rare events. The believable reliability estimation based on the operational data requires full consideration of the entire body of operating experience, and a consistent interpretation of the diverse failure information. There needs to be assurance about the completeness and relevance of the operational data to be considered in piping reliability analysis.

A range of different reporting criteria is in current use. These criteria mostly follow structural reliability considerations and RCPB leak rate criteria as defined by the technical specifications for plant operation, and applicable piping codes and standards.

The piping codes define minimum requirements for design, materials, fabrication, installation, test and inspection. The standards contain design and construction rules and requirements for individual piping components such as elbows, tees, flanges and other in-line items. Compliance to Code is mandated by regulations imposed by regulatory agencies. The codes and standards encompass consideration of metallurgical degradation mechanisms. There are mandatory and non-mandatory requirements for nondestructive examination (NDE), including, as an example, inservice inspection (ISI) of Class 1, 2 and 3 component and structures per the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (ASME BPVC) Section XI[3-4].

The purpose of NDE is to determine the suitability for continued use of a given piping system after a predetermined in-service time. Depending on the extent of degradation, the findings of NDE could result in formal or informal reporting to regulatory agencies. Some examples of typical NDE-based reporting criteria are summarized in Table 7. While there are regional differences among the criteria, most of them are adaptations of the ASME BPVC Section XI and the applicable American National Standards Institute (ANSI) standards. In Sweden, SKIFS 1994:1[3-5] documents regulatory requirements for the mechanical integrity of piping system components.

Table 7. Examples of NDE-Based Reporting Criteria

ISI Acceptance Standards & Reporting Criteria - Some Examples
▪ Formal dispositioning with regulatory agency for pipe wall thickness < 50% of nominal wall thickness (NWT). ▪ Increased inspection frequency for wall thickness < 75% NWT; discretionary reporting may be acceptable. ▪ Using radiography, any elongated indication with a length greater than 1/3 T for T (= thickness of weld being examined) from 6 mm to 57 mm inclusive is unacceptable.

In addition to the structural reliability considerations, functional requirements (e.g., acceptable leak rates) also determine the reporting of piping failures. The definition of failure criteria based on leak rates is difficult and must, as a minimum, acknowledge the design criteria as defined in Final Safety Analysis Reports; e.g., leak detection capability and reliability, and make-up capacity of engineered safety systems. *The majority of documents surveyed during the database development and data collection did not include explicit leak rate or leak duration information.*

A large portion of reported incipient and degraded failures within the RCPB are detected by in-service inspection (ISI) during annual refueling and maintenance outages. Relaxations in the plant technical specifications (TS) and reporting requirements during outages result in discretionary reporting of the ISI-findings, however. This means that while formal licensee event reports (LERs) would not be filed based on the NDE/IS findings, other means of reporting could be prepared as part of summaries of the performance of outage activities (i.e., outage inspection reports). If a 'significant' ISI-finding by one licensee is believed to have potential generic, industry-wide implications, then that finding would be reported and result in formal dispositioning. Not only would the 'discovering' licensee provide a report, but also the other licensees which are affected by the original ISI results. The NDE-based reporting criteria are interpreted and implemented on a case-by-case basis, and a lack of functional considerations could impose restrictions on the dissemination of reports within and outside an organization. Examples of reporting *practices* include:

- Significant incipient or degraded failures discovered during refueling or extended maintenance outages normally are reported to regulatory agencies.

- Some degraded failures during routine power operation are reported; especially those with assumed generic implications.

- Most degraded failures within the RCPB are reported, especially where there is an external leakage which is detected by the leak detection system(s). The reporting is almost guaranteed whenever the plant-specific TS defines leak rate criteria with limiting conditions for operation (LCO).

- There are many exceptions to the above practices, however. As an example, to effect repairs, a RCPB leak could result in a planned shutdown of the unit. While progressing with the manual shutdown, an equipment failure occurs which is unrelated to the leak but possibly triggered by the change of plant status and causes an automatic reactor trip, say, from 50% power. In this case a LER may be filed for the equipment failure which caused the trip directly, but none filed for the piping failure. Therefore, a search for failure data on piping often must include more than one information source (*c.f.* Appendix A).

- Complete failures (e.g., ruptures) which result in manual or automatic reactor trip are reported most of the time, especially if they occur within the RCPB. Discretionary reporting applies to failures outside the RCPB.

There is no all-encompassing definition of pipe failure modes. Different interpretations based on functional and/or structural interpretations lead to inconsistent reporting of failures, and complicates data analysis. Insights from the data collection effort in this project seem to imply that ruptures and major leaks are reported at all time, while the incipient and degraded failures (e.g., leaks near or well below the TS limitations) at best are reported on an *ad hoc* basis. In simple terms, a rupture is a major loss of mechanical integrity without advance warning. Such an event is not foregone by precursors such as drop leakage, or leakage large enough to activate a leak detection system that would enable mitigation by plant personnel. Using a functional definition, a rupture is a piping failure which causes a loss of coolant (or process medium) inventory in excess of the make-up capability of an engineered safety system (or non-safety-related make-up system). The different interpretations of failure potentially influence the formal reporting of events involving piping degradation.

The reliability of reactor pressure vessels and primary system piping is an important topic for nuclear safety R&D as well as plant operations. The earliest nuclear safety debates kept addressing this complex reliability issue; sometimes in a highly unbalanced way. With this debate followed a ‘sensitized’ awareness about the potential implications of including too detailed accounts of the evaluations of results from NDE/ISI in the licensee event reports. Non-stringent use of technical terms could be misinterpreted. The historical developments within the nuclear safety have influenced the way piping failures are documented and reported today.

Since piping reliability and reporting of failures are so difficult, is there a way of determining the coverage and completeness of failure reports? A philosophy adopted by this project is the notion that piping failures of varying severity have occurred at each operating plant worldwide. Failure reports qualified for entry into the database came from the plants subjected to a detailed survey of its operating history. Plants not yet covered by the database were those plants for which operational data were unavailable to the project. In developing the SLAP database the emphasis of the detailed surveys of operational data was on Swedish and U.S. plants. According to the SLAP database, the annual frequency of a piping degradation is on the order of 0.5 event per year and plant (*c.f.* Table 3-1, page 16), which should be compared with the following published estimates:

- According to Rodabaugh (1985)[3-6], a “…reasonable pipe failure rate…” is about 1 event per year and plant;

- Recent information on flaws/cracks, leaks and ruptures in German reactor and feedwater-condensate piping systems indicates a failure rate of about 0.2 event per year and plant; *c.f.* Reck and Bieniussa (1995)[3-7].

We will return to the estimation of piping failure 'initiating' event frequencies in Sections 4 and 5. For reasons discussed below, the uncertainties in the pipe failure frequency estimation are considerable.

3.3.2 Assessing Coverage & Completeness

Databases on equipment failures must be tailored according to specific objectives. These objectives should be reflected in the database coverage and the efforts to achieve completeness. The coverage and completeness are concerned with fault-counts and the conditional factors of failure. Both these factors have an important impact on the data quality.

Determination of uncertainties in input data parameters and results is an important analytical activity in PSA. Therefore, each stage of PSA model development includes stating the assumptions and the reason(s) for selecting certain data parameters. The effects of assumptions and data selections on results and insights are determined through sensitivity analyses and engineering evaluations. An underlying premise of PSA is that analysts fully understand the range of operating experience covered by the data, and how the input data parameters were derived. In reliability data analysis the estimators for failure rates and demand failure probabilities must relate to a statistical model as well as data collection approach. As an example, for maximum likelihood estimators the necessary data to be collected are:

X = number of failures of the particular failure mode;
T = total exposure time of the items during the period of event data surveillance;
N = total number of item demands during the period of event data surveillance.

Quality PSA is a function of the technical knowledge embedded in judgments, data selections, parameter estimation and model development. Verification and validation of data parameters are important considerations in quality PSA. The performance of verification and validation includes the assessment of the coverage and completeness of data. The numerators and denominators of the maximum likelihood estimators must be consistently developed. *Coverage* is defined as a ratio of the number of occurrences reported in a database versus all occurrences reported in that database and elsewhere. For SLAP the coverage is expressed by:

$$QN = F_{SLAP} / (F_{SLAP} + F_{MISS}) \qquad (3\text{-}1)$$

where QN = Coverage of the SLAP database. QN varies from a value greater than 0 to a maximum of 1, where 1 indicates full coverage.
F_{SLAP} = Number of occurrences reported in the SLAP database.
F_{MISS} = Number of occurrences reported elsewhere (e.g., proprietary data not available to this project), but not in SLAP. Possible omissions are included by this category; i.e., piping failure reports that should have been captured in SLAP but were not due to omissions by the database developers.

How many reports are missing from SLAP? An accurate assessment is difficult or impossible to achieve. The coverage varies according to the type of piping system and type of plant, and the reporting practices. Beyond the proprietary data submitted to the project by five European utilities, one could say that the Swedish and U.S. data on significant piping failures within the RCPB has 'reasonable coverage.' Between 80 to 90% of all *major* leaks and ruptures are believed to be included in SLAP; *c.f.* Appendix A for further discussions on the database coverage.

Completeness is defined by the reliability attributes and reliability influences (*c.f.* Section 4*),* which that are addressed by the reports in a given database. In other words, do the failure records include sufficient information to support a definite classification of a failure event? The accurate interpretation and classification of failure build on the technical information contained by the reports. Where information is missing, inferences will have to be made from event narratives or similarities with other events for which more details are available. Obviously, errors in the interpretation of incomplete failure reports represent one source of uncertainty in the statistical estimation of failure parameters.

During the development of the SLAP database, the coverage and completeness issues were addressed by using calibration data, and diverse and complementary information sources. Comparisons against data summaries in the public domain were made to test the coverage of SLAP. As an example, for stress corrosion cracking (SCC) problems, several literature sources were utilized, including the following:

- Summary by the Pipe Crack Study Group which addressed intergranular SCC (IGSCC) in U.S. and foreign BWRs for the period 1965 through January 1979; *c.f.* U.S.NRC (1979)[3-8] and Shao and Burns (1980)[3-9]. For the stated period, the total incidents numbered 133 for pipe diameters in the range DN75 to DN300. No statements presented about crack depths or crack geometry.

- Summary by the Electric Power Research Institute which addresses IGSCC in nuclear power plants worldwide for the period 1974 through June 1, 1982; *c.f.* Danko (1983)[3-10]. For the stated period, the worldwide incidents numbered 287 for pipe diameters of DN50 through DN710. No statements presented about crack depth.

- Summary by the U.S. Nuclear Regulatory Commission addressing IGSCC observations as of March 1984; *c.f.* U.S. NRC (1984)[3-11]. According to this summary there were a total of 312 cracking incidents in piping of DN300 - DN700. For the stated period, a total of 1924 welds in BWR primary system piping had been inspected in response to the Inspection and Enforcement (IE) Bulletin 82-03; *c.f.* U.S. NRC (1982)[3-12].

- Swedish study on IGSCC problems in the domestic BWR plants covering the period 1972 - 1988; *c.f.* Skånberg (1988)[3-13]. This study summarizes information from 43 occurrences of IGSCC. No information presented on the crack depth and crack geometry.

These information sources enabled determination of piping *incident* frequencies. An absolute assessment of database coverage is not feasible without a combination of functional and structural interpretations of raw data, however. Only reports addressing crack indications with *explicit* statements on crack depth > 20% of the pipe wall were nominated for entry into SLAP. These were events with a potential for further crack propagation in the through-wall direction. Additional tests were performed by comparing the content in SLAP against other, independent database development efforts; e.g., Bush et al (1996)[3-2]. For many database entries, the completeness was systematically addressed by using diverse information sources. As examples, many reports nominated for entry into the database were based on information from at least two references. In some cases, as many as five different sources were used to corroborate the information contained by a primary source such as a licensee event report or significant event report. A summary of primary and secondary information sources is given in Table 8 and in Appendix A.

Table 8. Examples of Primary & Secondary Information Sources of SLAP Database

Primary Sources	Secondary Sources
Preliminary Notifications of Unusual Occurrence or Event (PNO) - U.S. NRC	Special reports; e.g., U.S. NRC Special Study Reports prepared by AEOD[(b)] and the U.S. NRC Pipe Crack Study Group
Licensee Event Reports (Germany, U.S, Sweden)	NRC Weekly Reports (NRR) for 1986-1996.
Power Reactor Events - bimonthly newsletter issued by the U.S. NRC.	U.S. NRC Generic Letters, Information Bulletins and Information Notices
NEA/IAEA Incident Reporting System - Worldwide Coverage (1970 - to date)	NUREG-0020: Licensed Operating Reactors Status Summary Report
Proprietary piping failure event reports made available to project by five European utilities	Summary of Operating Experience at Swedish Nuclear Power Plants, Annual Reports by RKS / KSU
INPO/SER Reports (Nuclear Network) up to 1989 made available to project via KSU in Sweden[(a)]	Übersicht über besondere Vorkommnisse in Kernkraftwerken der Bundesrepublik Deutschland
Nuclear Power Experience by Stoller Corporation (BWR & PWR event reports)	Auszug aus dem Bericht des ABE-Ausschusses (atomwirtschaft)
Swedish scram reports	Nuclear Safety, Volumes 12 - 33
SKI / STAGBAS - Event database maintained by SKI/RA (Dept. of Plant Safety Assessment)	IAEA: Operating Experience With Nuclear Power Stations in Members States, 1982-1993.

Note: (a). Reports less than five years old are proprietary to the member utilities of the Institute of Nuclear Power Operations (INPO).
(b). AEOD = Office for Analysis and Evaluation of Operational Data, U.S. NRC.

The actual reporting of failures depend not only on regulatory reporting requirements. Based on root cause analyses of significant events with potential generic implications, an operator may decide to submit a report to a regulator or industry organization. Additionally, a regulator may decide to request focused NDE/ISI efforts by licensees to determine existence of degradation that could substantiate or refute an earlier evaluation of the potential for a generic trend. Such requests could lead to increased coverage of the reporting for as long as a safety concern exists. The average number of piping failures per plant in the database and calendar year is shown in Figure 7. From that plot it is possible to distinguish relationships between data coverage and regulatory initiatives addressing degradation or failure mechanisms such as SCC, erosion/corrosion, and thermal fatigue:

- As the knowledge about stress corrosion cracking problems improved during the early 1970s, changes to the piping designs, welding techniques, NDE/ISI, etc. were implemented. Also, several utilities performed piping replacement programs involving the use of different materials. Results of these improvements were realized during the 1980s. Mostly, the peaks displayed by the plot are caused by incipient and degraded failures that were reported in response to the many NRC Inspection and Enforcement Bulletins.

- During the mid-1980s numerous, significant failures induced by erosion/ corrosion occurred. Again, initiatives by industry and regulators improved the knowledge about this particular degradation mechanism and design changes together with improved NDE/ISI have resulted in reliability growth.

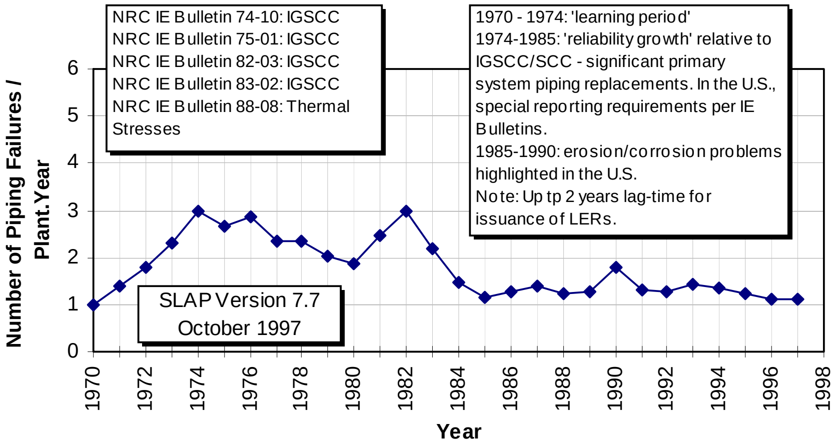


Figure 7. The SLAP Database Content (Number of Failures per Plant and Year)

3.4 Conditional Factors of Pipe Failure

In Section 2 of this report we identified some unique differences between passive and active components. As a consequence of these reliability features, which characterize piping, the development of a database must distinguish between ‘events’ and ‘exposures.’ The *event cells* of a database on piping failures identify the failure mode, and degradation or failure mechanism that led to failure. The *exposure cells* of a database identify the pipe size and material, process medium and pressure/temperature of the process medium. The event cells include information on reliability *influence* factors, whereas the exposure cells include information on reliability *attributes*. We distinguish between influence and attribute as follows: 1) an influence indicates a cause of failure that relates to environmental or operational conditions of or in the piping system; 2) an attribute indicates a cause of failure that relates to the inherent piping system design. Together, attributes and influences represent the ‘conditional factors’ which must be considered in data reduction and analysis. Reliability attributes are assigned piping systems on a global basis, while influence factors are assigned on a plant-specific basis.

Pipe failure modes and failure mechanisms differ according to metallurgy, process medium, operating time, plant and system transient history, operating environment (e.g., temperature, pressure, chemistry/composition of process medium, design, ISI-strategy, etc.). Relative to pipe diameter, the failure records could be grouped according to the following diameter classes:

- Instrument piping/tubing/thimble; ≤ DN25
- Test/sample/vent/drain/bypass/temporary lines; 25 < DN ≤ 50;
- Small-diameter process piping; 50 < DN ≤ 100;
- Intermediate-diameter process piping; 100 < DN ≤ 250
- Large-diameter process piping; > DN250.

This grouping is chosen for two reasons: 1) to enable comparisons with recent data published by GRS; and 2) the failure modes and mechanisms in piping of DN < 50 tend to be quite different from the other piping sizes. In general, the grouping of failure records should reflect intended application. Other groupings could be developed according to the make-up capability (i.e., thermal-hydraulic considerations) of safety injection system. A typical, PSA-oriented grouping is to use three classes; i.e., equal-to-or-below DN50, above DN50 and below DN250, and above DN250, respectively. In summary, any grouping by size should reflect an intended application.

The failure records are sorted according to failure mode; i.e., crack, leak and rupture, corresponding to incipient, degraded and complete failure, respectively. For now, the terms pinhole leakage, leakage and rupture are based on structural interpretations of piping failures. From a PSA-perspective and based on their impact on plant operations, some leaks should be re-classified as ruptures; i.e., the leaks are large enough (e.g., >> 0.3 kg/s) to incapacitate system functions and/or result in forced plant shutdown. The majority of failure records in the SLAP database do not have explicit information on leak rates, however. Based on event narratives, TS requirements and capabilities of leak detection systems, leak rates can be inferred from available information to assist with further event classification.

The conditional factors of pipe degradation and failure are numerous and of varying importance. Data analysis always should reflect an intended PSA application, which means that for LOCA frequency assessment one unique set of conditional factors should be considered and for internal flooding another set of factors. Regarding the dependence of pipe failure on plant operational status, it is difficult to establish such correlations. The issue of *latency* of pipe failures needs to be considered in the interpretation of operational data. Its relevance for data analysis is less clear, however. Some latent pipe failures develop during cold shutdown. Once a system is commissioned and pressurized, the latent failure could evolve into a degraded or complete failure. Taken from the SLAP database, three examples on ‘latency’ are given below:

(1) The use of induction heat stress improvement (IHSI) is commonly used on piping susceptible to IGSCC to avoid through-wall cracking of welds. If there already is a crack in the through-wall direction, the IHSI would enhance crack growth and eventually lead to a leak. The database includes several events where leaks have been revealed after IHSI, and power operation has resumed.

(2) Numerous small-diameter piping systems are used to enable functional testing of components, such as fast-closing isolation valves. Such test lines could include temporary connections. The database includes events where the leak tightness of a test connection (e.g., flange on a fixed spool piece) deteriorates over time. Because of transients involving, say, MSIV closure, it is no longer possible to line up flanges. This would be a combination of piping system design problem, and, possibly, procedural problem that does not sufficiently address the importance of exact flange lineup.

(3) During maintenance activities, wrong type of spare parts could be utilized and later affect piping reliability. A recent event points to the complex nature of piping system failures. In the particular case, simulating a pipe break to test the Reactor Protection System, caused two high-head safety injection (HHSI) system pumps to run against not fully closed medium-operated check valves. This created pressure waves and a DN15 drain line close to one of the HHSI pumps broke off, and another drain line ruptured causing a significant loss of primary system water (i.e., a small-LOCA precursor event). The check valves were unable to close fully because the wrong packing material was used during the most recent annual maintenance outage.

The three examples represent piping failures for which the root causes relate to plant shutdown operations and maintenance activities. The failures were revealed upon returning to routine power operation. Maintenance or testing during shutdown could affect component or system performance such that given a demand on active components (pumps, valves), pipe failure occurs due to an unusual or severe pressure transient. A general observation is that low system pressure during shutdown operations reduces the frequency of pipe failure, however. This brings up the topic of the correlation between failure mechanism and mode of plant operation. Some failure mechanisms are independent of operating mode. Others are clearly correlated with the plant transient history (i.e., number of shutdown-startup cycles) and reveal themselves during normal, steady state power operation.

Pipe failures generally are the result of coincident or dependent failure mechanisms. An example of a failure event which results from combined effects of degradation and damage mechanisms would be erosion/corrosion damaged piping and water hammer; e.g., a piping system subjected to wall thinning splits open at its weakest point when subjected to severe water hammer. An example of a failure event which results from dependent (or synergistic) degradation mechanisms would be where pipe cracking originates in a transgranular mode and progresses in the intergranular mode. Without the transgranular effect it could be feasible that the intergranular would effect would have been delayed or prevented. In this example the TGSCC effect could be viewed as the crack initiator 'catalyst.' The fact that the piping consisted of cold bent segments of IGSCC susceptible material contributed to the failure.

The SLAP database distinguishes between ‘apparent cause of failure’ and ‘root cause.’ While beyond the scope of the current work, a detailed data reduction should acknowledge the potential correlation of different degradation and failure mechanisms. Where supported by data, such distinction was selectively considered during the project while analyzing influence factors; *c.f.* Section 4.

Detectability of leaks is a function of the capability and reliability of leak detection systems, and mode of plant operation and the plant operating procedures. Also, the operating practices impact the response to leaks; e.g., some plants operate with persisting primary system leaks for long periods of time, while others are shutdown for repairs. Obviously such differences affect the reporting of pipe failures. During low power and shutdown operations the Technical Specification (TS) requirements are relaxed. Therefore, it is feasible that a leak developing during cold shutdown would not be detected until the plant is back at full power. Some leaks are so small (i.e., << TS-limits) that they would not be easily detected during normal plant operation. There are many examples in the database where operations personnel are sensitized to ever-present leaks via pump seals, valves, etc. without taking any remedial action. Some plants may have been operated for extended periods (perhaps, years) with small primary system leaks, and corrective action is taken while the plant is in unrelated maintenance outage. This raises a question about interpretation of operational data; i.e., during what mode of operation did a pipe failure actually occur? Should data reduction be performed on the basis of plant system in which the piping failure occurred, type of process medium, or mode of piping system operation (e.g., standby with stagnant medium, or operating with pressurized, flowing medium)? For the following (incomplete set of) reasons, there is no single, simple answer:

(1) *Where* do pipe failures occur? The plant system where the failure occurred could be a reasonable discriminator. Many systems perform dual functions; e.g., a normal process function and a safety function. As an example, in BWRs the residual heat removal system performs a containment heat removal function during normal plant operation by cooling the containment pressure suppression pool water. During cold shutdown, the system performs a residual heat removal function, and during LOCA the system would perform a low-pressure safety injection function. The extent, by which the system is used during normal, routine power operation is a function of safety relief valve actuations or leaks. Hence, there is extensive plant-to-plant variability in how the RHRS is being operated. In PWRs, the chemical and volume control system (CVCS) performs a triple function. During, normal routine power operation the system maintains primary system purity, injects boric acid for long-term reactivity control, and provides a storage location for excess primary water. The system also performs a high-head safety injection function on demand.

Obviously, the pipe failure discriminators are dynamic in the sense that the pooling of data cannot be structured by rigid rules. Depending on the intended application, there could be several influences to consider. The reliability influence factors are highly plant-specific. Moreover, at any given plant the effect an influence has on the reliability changes over time due to plant modifications or variability in maintenance practices. Data reduction must be based on knowledge of plant system design and operation. An advantage of using plant system as discriminator is that it encompasses implicit information about process medium, mode of operation, and design (e.g., pipe diameter and metallurgy). The disadvantage is the stated one, namely a ‘fixed’ system discriminator is not feasible.

(2) The data could be evaluated on the basis of *mode* of piping system operation. For the reasons stated under (1), this is not a trivial issue because of the ways some of the plant systems are operated, however. While it is known that the mode of operation is a conditional factor, an unambiguous discrimination of the database content is difficult to perform. An added complication is that within a given piping system, and for a specified mode of operation, there could be medium phase

transitions; i.e., portions of the piping system could have single-phase flow, and other portions could have a two-phase flow condition. Is the particular piping system designed to withstand two-phase flow conditions? Some failure mechanisms are manifestations of process media as a conditional factor. As examples, erosion/corrosion is a problem where there is turbulent steam flow, or wet steam flow. Furthermore, thermal fatigue could be a problem where there is thermal stratification in stagnant medium or cyclic injection of media at different temperatures. Yet another example, boric-acid corrosion in PWR environments is a problem where there is stagnant boric acid diluted water such as in safety injection system and residual heat removal system piping.

(3) In addition, data could be evaluated based on type of process medium. It is known that type of medium is a conditional factor. The triplet 〈 *process medium - plant system - mode of operation*〉 is a far stronger conditional factor than 'medium' alone, however. Rather than an attribute of piping reliability, it should be interpreted as an influence factor. Within any given category of process medium, the chemical composition could have significant impact on reliability; e.g., hydrogen injection in BWR feedwater to condition the reactor water.

3.5 Time-Dependent vs. Demand-Dependent Failures

On what basis should pipe data be analyzed? Intuitively, piping failures develop over time due to aging effects. In the earlier phases of the project the raw data were analyzed by means of hazard plots[3-14]. The primary outcome of these evaluations was recognition of the difficulties in developing reasonable groupings of the data. In general, no clear correlation could be found between operating time and the extent of piping degradation and failures. This observation pointed to the difficulty in defining exposure times of the piping failures during the period of event data surveillance.

A detailed discussion on the definition of exposure times is included in Section 4 of this report. In principle, the exposure time is a function of the type of piping system and the environmental conditions that exist in piping systems. As an example, small-diameter piping tend to be vulnerable to vibration-fatigue, and failures tend to develop over short periods of time. Here, the run time of a vibration-source (e.g., positive displacement pump) could determine the exposure time on which to base a statistical evaluation.

As an example of additional complications, the database includes events attributed to thermal fatigue and stress corrosion cracking which have occurred in systems that are operated for a few minutes per fuel cycle. In such cases the determination of the exposure time or number of demands on which failure rate estimation is to be based need to include evaluation of connecting systems and how they are operated. Although it is quite feasible that some pipe failures are demand-dependent, current service data included in the SLAP database do not support such evaluations. Therefore, the data evaluations in this study are based on time-exposures only. Some work on the relationship between crack propagation due to IGSCC and a plant's transient history points to a correlation between the two, however; *c.f.*, Aaltonen, Saarinen and Simola (1993)[3-15].

Estimation of piping reliability using available operating experience is complex, and for the following reasons: 1) Several reliability attributes impact the reliability; 2) several reliability influences impact the reliability; and 3) the available operating experience data are in-homogenous. There is no one way of approaching the problem. From the mathematical statistics perspective, the problem is that of multivariate statistics; i.e., several variables control the reliability of a piping system. In the proposed approach the leading idea builds on understanding the major causes of variation using reliability attributes. In this work, the reliability attributes are characterized by the *conditional probability of rupture given degradation*. The chosen approach reflects the completeness and coverage of the database, and the project scope limitations. Once we understand what the attributes are and how they impact the reliability, the analysis framework suggests that we choose a dominant or key attribute as a basis for developing informed generic failure distributions that reflect intended applications.

3.6 Random and Systematic Piping Failures

An underlying assumption in the statistical analysis of reliability data is that of the randomness of failure occurrences. The raw data in the SLAP database are a mixture of systematic and random failures, however. Often the systematic failures reveal themselves as recurring failures. These are the failures, which are repeated within one piping system at or near one location, and which show evidence of similarities in the degradation or failure mechanisms and therefore could be classified as recurring failures. Based on the information in the database, in some cases (e.g., for a specific plant system, during a limited time period) the systematic failures have dominated over the random failures. Overall, about 10% of the records in the database were classified as systematic failures; *c.f.* Figure 8.

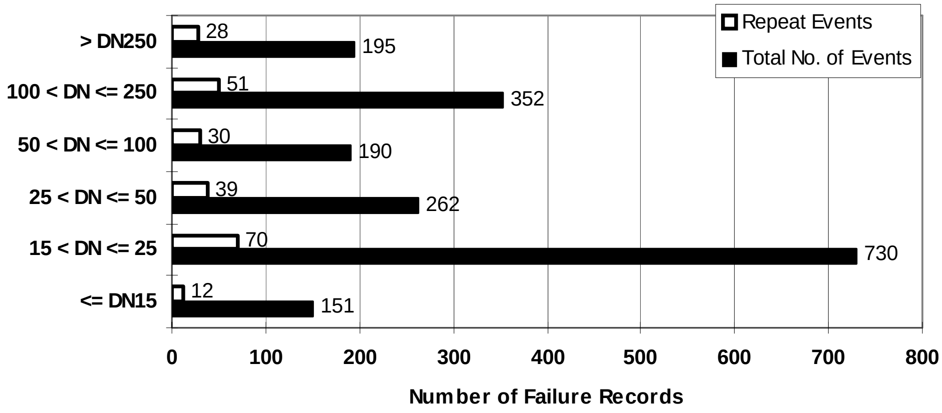


Figure 8. Overview of Systematic Failures in the SLAP Database

The systematic failures could be symptoms of ineffective or lack of root cause analysis efforts to prevent recurrence. For evolving technologies, they could also reflect a lack of knowledge of highly complicated degradation mechanisms due to ineffective feedback of operating experience. Examples of systematic failures include (e.g., Moieni and Apostolakis, 1981[3-16]):

- Design errors (wrong material selection, design specification errors, unforeseen dependencies, etc.).

- Manufacturing and fabrication errors. An example would be cold bending of austenitic stainless steel piping where crack initiation has been known to result from inside surface scratches caused by the bending tool, and surface contamination by pipe collars or via bending tool lubricants containing sulphides or chlorides.

- Construction and installation errors such as improper welding techniques, insufficient piping support, poor routing / 'low points' resulting in stagnant process medium, etc.;

- Unknown phenomena or conditions at the time of the design work (e.g., errors that could have been avoided assuming consideration of service data).

Within the database, random and systematic failures are intertwined in the conditional factors of failure. There is always the question whether the obvious systematic failures should be culled from the database. Furthermore, there may be questions about the division between random and systematic failures. In the current version of the database the event classification is based on the following criteria:

- Explicit statement by a failure report on recurring failures and with references to the previous failures at that or another plant.

- Evaluation of failure reports for one plant pointed to similitude with failure(s) at other plants.

Recurring failures could be indicative of a generic problem potentially affecting an entire NPP design generation. The term 'generic failure' is not synonymous with 'repeat failure', however. It could be argued that obvious systematic failures (applicable to a single plant) should be culled from a raw database from which generic failure parameters are estimated. Such culling should be performed on the basis of influence factors in combination with evaluations of plant-specific operational data. In developing the raw data files, which are summarized in Appendix B, no distinction was made between the two basic forms of piping failures. Additional discussions are found in Sections 4 and 5.

3.7 'Old' vs. 'New' Service Data

The service data on which this study is based cover the period 1970-1997. Many significant improvements to design, operating environments, and inspection practices have been implemented during the study period. Therefore, the value and applicability of the early service data to present conditions could be questioned.

Within the scope of this R&D-project it has not been possible to discard any service data solely on the basis of date-of-occurrence. In general, the degradation mechanisms that were revealed in the early 1970's remain relevant. It is questionable whether the full insights from reviews of the available service data yet have been exploited by the efforts to improve piping reliability, however. Service data should not be screened out from a parameter estimation effort unless sufficient justification is provided regarding an assumed ineligibility of certain operating experience.

3.8 Discussion

Section 3 summarized technical and plant safety management considerations affecting the development of a database on pipe failure events. The format for the reporting of pipe failures varies immensely from detailed root cause analysis reports, which address the conditional factors of failure to brief summary reports, which require further interpretation and analysis. For SLAP, numerous primary and secondary information sources are utilized to ensure reasonable database coverage and completeness. It is the opinion of the authors of this report that the estimation of piping reliability parameters is feasible as long as the estimation process is supported by a comprehensive and validated pipe failure database.

Aside from applications related to PSA, a database such as SLAP supports different types of qualitative assessments including trends and patterns. The database content points to the recurring nature of many failure types. The recurrences could be symptoms of insufficiently implemented experience feedback loops, but they also are symptoms of the complex nature of the degradation and failure mechanisms; i.e., mitigation programs continue to evolve. In the opinion of the authors of this report, a cost-effective approach to piping reliability management is achieved through improved reporting of degradation and failures.

3.9 References

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4

DATA REDUCTION

Piping reliability is a function of size, metallurgy, process medium, operating time, NDE/ISI practice, plant transient history, and operating environment (for example, temperature, pressure, flow rate, chemistry/composition of process medium). Section 4 presents basic considerations in data reduction and data analysis that are based on the conditional factors of piping reliability.

Section 2 presented the basic equation for calculating the frequency of pipe rupture (*c.f.*, Equation 2-2, page 14). This frequency was represented by the product of two terms: 1) The frequency of a pipe failure (flaw/crack, leak or rupture); and 2) The conditional probability of rupture given a failure, $p_{\mathrm{RUPTURE}\,|\,\mathrm{FAILURE}}$. The objective of Section 4 is to present the basis for deriving this conditional rupture probability from service data.

4.1 Models for Estimating Piping Failure Rates

The estimation of equipment failure rates must acknowledge the system-to-system, plant-to-plant and environment-to-environment variability. If all factors that influence the equipment failure rates were to be used to develop a mathematical model or correlation, the following expression would result:

$$\lambda = f(\phi_1, \phi_2, \phi_3, \ldots, \phi_n) \tag{4-1}$$

where λ = time- or demand-related failure rate;
ϕ_i = conditional factor (i = 1 to n).

Many of these conditional factors are addressed to different degrees in design, fabrication, installation, commissioning, operation, and maintenance so that their influences are controlled if not eliminated. A standard practice in reliability engineering is to apply ‘adjustment factors’ to those conditional factors that are not explicitly accounted for by the design or operations. One way of determining the actual failure rate that will be exhibited by a component is to first obtain a generic, or base failure rate and multiply it by the appropriate application and operation stress factors:

$$\lambda_{Actual} = \lambda_{Generic} \cdot k_{Ap} \cdot k_{Op} \tag{4-2}$$

where $\lambda_{\mathrm{Actual}}$ = actual (e.g., plant-specific) failure rate;
$\lambda_{\mathrm{Generic}}$= generic, or base failure rate which reflects the intended application as well as a specific component type;
k_{Ap} = application stress factor (or environmental application factor), a multiplying factor which considers the effect of environment such as water chemistry, steam quality, or high-cycle fatigue on $\lambda_{\mathrm{Generic}}$;
k_{Op} = operation stress factor, a multiplying factor which considers the effect of operations (e.g., standby, load-following, base load) on $\lambda_{\mathrm{Generic}}$.

While simple in concept, Equation (4-2) requires numerical values on the two 'k-factors.' It is less than clear how to derive such parameter estimates from service data, however. A specialization of Equation (4-2) was suggested by Thomas (1981)[4-1] for pressure vessels and piping system components:

$$\lambda_{Actual} = \lambda_{Generic} \cdot [(Q_P + A \cdot Q_W) \cdot E] \cdot F \cdot B \tag{4-3}$$

where $Q_P = D \cdot L/T^2$;
D = pipe diameter;
L = length of piping section;
T = wall thickness of piping;
A = weld penalty factor;
$Q_W = 1.75 \cdot NC \cdot D/T + 1.75 \cdot NL \cdot L/(3.14 \cdot T)$;
NC = number of circular welds;
NL = number of longitudinal welds;
E = quality factor;
F = age factor;
B = learning factor.

The 'Thomas correlation' estimates the actual failure rate from empirical data scaled by a geometric proportionality measure of size, shape and welds, and other factors such as plant age and 'learning factors.' In the remainder of Section 4 we shall define and quantify the conditional factors of piping failure by exploring the SLAP database. The objective is not to prove or disprove the 'Thomas correlation,' instead the objective is to demonstrate the application of a database developed especially for piping reliability analysis. We start by accepting the basic premise of correlations like those described by Equations (4-1), (4-2) and (4-3), next we define the constituent elements of an PSA-oriented correlation that builds on Eq. (4-2).

4.2 Reliability Attributes and Influence Factors

The conditional factors of piping reliability are numerous, and of varying importance. In this report we consider conditional factors that reflect generic reliability, and those that reflect plant-specific reliability. This R&D focused on the estimation of failure rates and failure probabilities of 'complete failures' as addressed by PSA studies. Using functional and structural definitions of piping failure, a complete failure could be the classical 'direct double-ended guillotine break' (DEGB) or a major leakage, via an extensive through-wall crack or split, in excess of the make-up capability of an engineered safety system. A 'rupture' is interpreted as a piping failure, which meets the PSA requirements of functional and structural definitions of complete failure.

We distinguish between two types of conditional factors: a) *attribute*; and b) *influence*; *c.f.* Figure 9. The attributes represent conditional factors of piping system reliability prior to installation and commissioning. In other words, the attributes relate to the design and the application of codes and standards in view of specific service requirements and safety considerations (i.e., the predicted reliability). An attribute cannot be modified without changing the design of the system. As an example, pipe diameter and the corresponding wall thickness (e.g., Schedule Number[13] to use U.S. nomenclature) reflect specific service requirements. Any piping system can be evaluated on the basis of its material, heat treatment history, stress level, number of weldments, and geometrical factors. For a given application, the reliability of a DN100, Schedule 40 piping system could be quite different from a DN100, Schedule 160 piping system. Similarly, DN25 piping is expected to differ from DN250 piping, etc. Piping material is another example of an attribute. The selection of material for piping applications requires consideration of material characteristics appropriate for the required service. There is a difference in reliability characteristics of stainless steel piping versus carbon steel piping. This difference is caused by the different susceptibilities to degradation and failure mechanisms. Depending on the metallurgy, within the group of stainless steels there are IGSCC-resistant and IGSCC-susceptible steels.

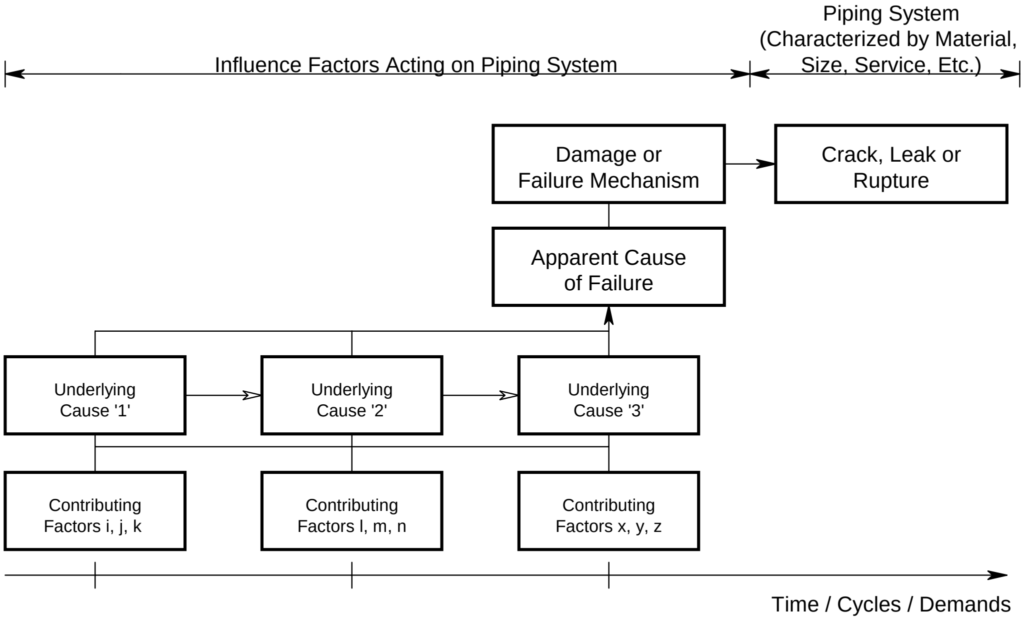

Figure 9. Simplified Root Cause Perspective on Attributes & Influences

An influence relates to a cause of failure, which is due to environmental or operational conditions of a piping system. Another term is ‘environmental application factor.’ For a given piping system design, the reliability influence factors represent the maintenance, inspection (e.g., NDE/ISI) and operational conditions ‘imposed’ on the piping as-installed and operated. A practical way of defining primary influence factors is to ask: *In view of an actual failure, what is the best (e.g., most cost-effective), remedial action to prevent recurrence?* This is the root cause analysis perspective on reliability influences. The definition implies that: a) influence factors can be inferred from operational data by differentiating between the apparent and underlying causes of failure; and b) short-term, and possibly long-term, reliability growth is accomplished by changing one or more influences, and not necessarily by changing the design.

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[13] Pipe schedules refer to predetermined nominal wall thicknesses according to dimensional criteria specified in ANSI Standards; e.g. B36.10 (Welded and Seamless Wrought Steel Pipe).

4.3 Determining Attributes from Service Data

The objective of determining attributes from service data includes development of application-specific, baseline conditional probabilities of pipe rupture. That is, probabilities that represent unique groups of piping systems according to design parameters (for example, material and size) and intended service. A piping reliability attribute is characterized by the conditional probability of pipe rupture given that a certain type of system has been exposed to degradation or failures requiring repair or replacement actions. Together, crack indications, leaks and ruptures are the manifestations of various degradation and failure mechanisms. The effect and magnitude of these mechanisms differ according to reliability attributes. For example, an austenitic stainless steel is immune to erosion-corrosion damage while a carbon steel could be highly susceptible, and small-diameter piping could be more susceptible to vibratory fatigue than large-diameter piping, etc.

Service data cannot be grouped according to pre-determined, rigid attributes. Instead, the grouping should be a function of the PSA requirements. For LOCA frequency estimation, the analysis could be a function of equivalent leak rates through holes (break size) in the reactor coolant pressure boundary (RCPB) and the proportionality between pipe size and break size. So far we have alluded to diameter/wall thickness and material as being attributes of piping reliability. We will start by describing a simple approach to calculating conditional probabilities of rupture for different attributes. Next we present some preliminary insights from analyzing service data included in the SLAP database, and, finally, we present some conclusions about the grouping of service data by attribute.

4.3.1 Conditional Probability of Failure

In this study, attributes are characterized on the basis of the conditional probability of pipe rupture. A conditional probability of rupture may be calculated using classical or Bayesian statistics.

Ultimately, the selected approach is a matter of analyst's preference and experience; both approaches have advantages[14] and disadvantages. We use a Bayesian approach together with the following assumption: Each exposure to a degradation or failure mechanism which results in detectable damage to the piping is viewed as a demand on the structural integrity. As an example, if we observe 300 flaws in one type of piping system, then that type of system (i.e., attribute) has been exposed to 300 demands. Next we determine how many of these demands actually led to complete failure (i.e., rupture). Hence, the reliability problem is treated as a failure-on-demand problem. The binomial distribution is the distribution of the number of ruptures, R, out of 'DP' independent demands where DP is the number of events leading to degraded piping. The binomial likelihood function, L (E | p), is:

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[14] Given sufficient service data the classical approach and the Bayesian approach produce numerically compatible results. Due to difference of interpretation, propagation of uncertainty measures in the Bayesian approach is easier than in the classical approach.

$$L(E|p) = (DP! / [R! (DP - R)!]) \times p^R \times (1 - p)^{DP-R} \qquad (4\text{-}4)$$

Where E = Evidence in the form of specific service data;
R = Number of ruptures;
DP = Number of 'demands' on the piping system;.
p = Probability of rupture.

In the Bayesian approach, the parameter p is regarded as a random variable with a specified prior distribution. There are different ways of generating a prior distribution, including: 1) A noninformative prior; or 2) empirical prior. Arguments can be made to support the choice of each of these priors. Ultimately the choice should be a function of the form and extent of available service data. For now, this report will use a noninformative prior, as discussed below.

A noninformative prior is valid if no consensus failure distribution exists. This would seem appropriate for piping failures. As stated by Atwood (1996)[4-2]: "*... When prior knowledge is vague, it is often not worth the effort of defending an assumed prior distribution against challengers who have various agendas ...*" For a detailed discussion on the choice of prior distribution, see Chapter 6 in the text by Martz and Waller (1982)[4-3]. A noninformative prior is calculated from:

$$f(p) \propto [p (1 - p)]^{-1/2} \qquad (4\text{-}5)$$

Using the likelihood function (Eq. 4-4) and the noninformative prior (Eq. 4-5) it can be shown (*c.f.* Ref. 4-3, pp 255-258) that the posterior mean and variance are as follows:

$$P_{R/DP} = (2R + 1) / (2DP + 2) \qquad (4\text{-}6)$$

$$Var\ (P_{R/DP}) = [(2R + 1)(2DP - 2R + 1)] / [2(DP + 1)^2 (2DP + 4)] \qquad (4\text{-}7)$$

where $P_{R|DP}$ = mean probability of rupture given a degraded piping ('DP') system;
R = number of rupture events (i.e., complete failures);
DP = number of occurrences of degraded piping of a certain kind. Includes consideration of flaws/crack indications, leaks or ruptures.

This approach yields a simple format for analyzing attributes of piping reliability, which enables estimation of reliability parameters when the evidence is 0 ruptures. But more importantly, the format encompasses a procedure for quantifying and expressing uncertainties that relate to the interpretations of the operational data. Assuming that any given attribute is applicable to all failure modes (e.g., material is equally strong attribute for crack indication as for leak), this approach (i.e. Eq. 4-6) enables consideration of all relevant service data. It is also sensitive to the coverage of the SLAP database and the classification of failure events. Without differentiating between different types of systems, Table 9 presents a summary of conditional rupture probabilities for the attributes 'diameter' and 'material.'

Table 9. Conditional Probability of ‘Rupture’ by Attribute (SLAP Version 7.7)

Reliability Attribute		**$P_{R\mid DP}$**	
Material	**Diameter**[a]	**Mean**	**Variance**
Carbon Steel	≤ DN25[b]	5.8E-2	1.9E-4
	25 < DN ≤ 50	1.5E-1	1.1E-3
	50 < DN ≤ 100	1.0E-1	1.5E-3
	100 < DN ≤ 250	1.8E-1	9.8E-4
	DN > 250	2.3E-1	1.7E-3
Stainless Steel	≤ DN25[b]	5.8E-2	1.0E-4
	25 < DN ≤ 50	4.1E-2	2.2E-4
	50 < DN ≤ 100	2.7E-2	2.6E-4
	100 < DN ≤ 250	1.5E-2	6.8E-5
	DN > 250	5.1E-3	5.1E-5

Notes: (a). Excludes bellows and expansion joints. The latter are forbidden by ASME Section III on Class 1 safety systems; however, they are used in Class 2 and 3 systems and the balance of plant at low pressures and temperatures. See Appendix C for definitions of ASME Class 1, 2 and 3 piping.
(b). Vibration-fatigue is a predominant failure mechanism affecting small-diameter piping/tubing (≤ DN25). The small-diameter piping also is susceptible to human factors deficiencies and human errors; e.g., maintenance worker inadvertently stepping on or bumping unsupported piping.

According to Table 9, in which it is assumed that ‘diameter’ is the key reliability attribute, there is no clear pattern in the ratios for carbon steels and stainless steels for intermediate- and large-diameter piping. The results for carbon steel piping are strongly biased by an under-reporting of failures in balance-of-plant (BOP) systems. Mostly the reporting has been limited to catastrophic failures of BOP piping such as steam extraction piping.

4.3.2 Comparison and Validation of Attributes

As defined above, given presence of a degradation mechanism, a reliability attribute is a measure of the ‘propensity’ of piping to fail completely. Some correlations and hypotheses describing the relationship between pipe diameter and the conditional probability of failure given degradation have been proposed. These proposed relationships have been developed from results and insights from structural mechanics models, experimental data and operating experience. Beliczey and Schulz (1987)[4-4] and Beliczey (1995)[4-5] have proposed the following semi-empirical (first-approximation) correlations, which assume the pipe size to be a primary reliability attribute:

$$P_{R/DP} = [(9.6 \cdot DN / 2.5) + (0.4 \cdot DN^2/25)]^{-1} \qquad (4\text{-}8)$$

$$P_{R/DP} = 2.5 / DN \qquad (4\text{-}9)$$

A comparison of these correlations with the results in Table 9 is shown in Figure 10. For stainless steel piping, there is agreement between the correlation by Beliczey and Schulz and the conditional rupture probabilities derived from service data in the SLAP database.

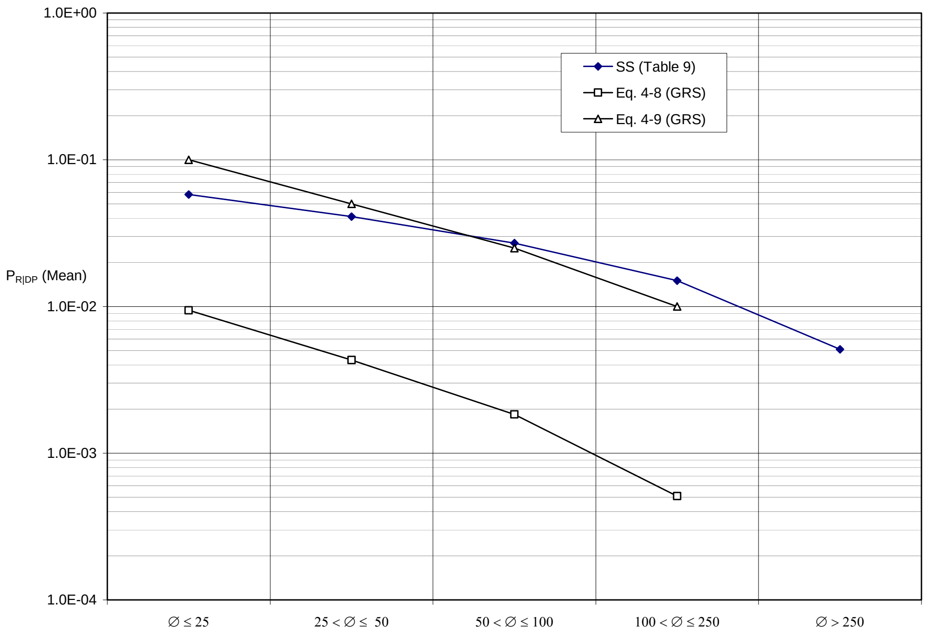

Figure 10. Conditional Rupture Probability as a Function of Diameter & Material

According to Figure 10, diameter is a relatively strong attribute of stainless steel piping. The uncertainties in the estimates are dictated by database coverage and the interpretations and classifications of the experience data. The entire SLAP database is represented in the above graph and the service data were not differentiated according to specific types of piping system types. By contrast, Figure 11 compares the 'first-approximation' correlation given by Equation (4-9) with conditional rupture probabilities derived from service data for IGSCC-susceptible stainless steel piping.

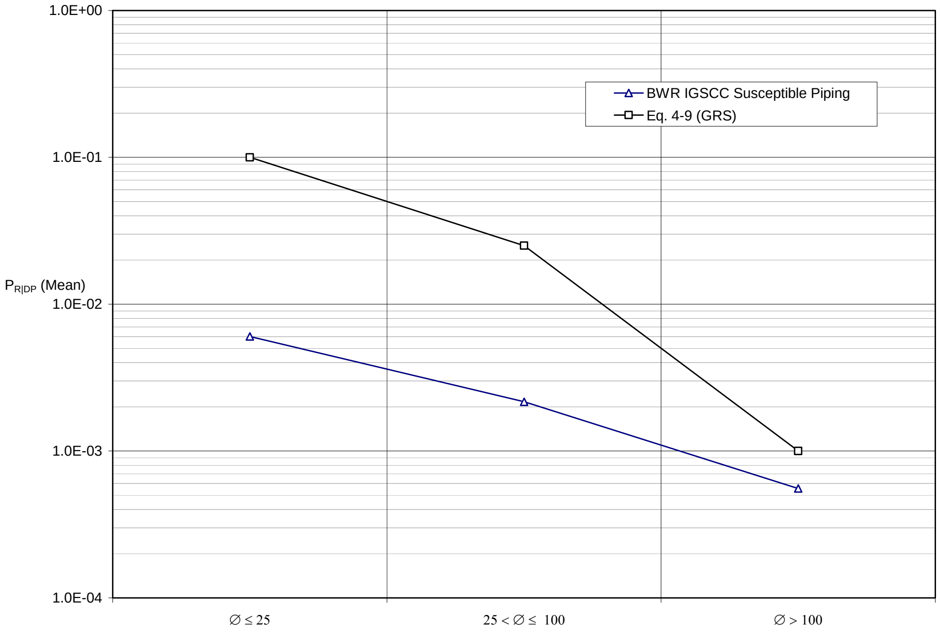

Figure 11. Conditional Rupture Probability of IGSCC-Susceptible Stainless Steel Pipe

For the IGSCC-susceptible piping a question arises as to the bias in the estimation by the coverage/completeness of the SLAP database. The scope of the present work was limited to significant events as documented in public domain information sources. There have been thousands of IGSCC crack indications and confirmed cracks in BWR plants worldwide. While some of the more significant events are reported as LERs or reportable occurrences (ROs), most of the events are documented in special inspection or outage reports, however.

As examples on the IGSCC incidence rate, for the period up to March 1984, of 1924 examined welds in U.S. BWRs, 312 were found to be defective; *c.f.* U.S. NRC (1984)[4-6]. At a German plant, examinations in the early 1990s found approximately 30 cracks out of 1300 welds which were inspected; *c.f.* IAEA (1993)[4-7]. Finally, Wachter and Brümmer (1997)[4-8] and Bieniussa and Reck (1997)[4-9] report that as a result of an extensive non-destructive testing program involving almost 3000 welds in stainless steel piping greater that DN50 in German BWRs, about 90 cracks were detected. Most of these extended less than 30% in the through-wall direction. In the current version of the SLAP database, only cracks extending more than 20% in the through-wall direction have been included. The potential biases in parameter estimates due to different data interpretations are addressed further in Section 5.

As an additional proof-of-the-SLAP-principle, we turn to a set of relatively recent probabilistic fracture mechanics evaluations. In the May 1973 the U.S. NRC published the Regulatory Guide 1.45, "Reactor Coolant Pressure Boundary Leakage Detection Systems." This document provides guidance on leak detection methods and system requirements. Furthermore, leak detection limits are specified in plant Technical Specifications and are different for BWRs and PWRs. These leak detection limits are also used in leak-before-break evaluations performed according to the Standard Review Plan (SRP), Section 3.6.3[4-10]. In this SRP, for each position of the highest stress or with the least advantageous material properties, a through-wall crack of a length corresponding to a 3.8 kg/min (1 gpm) leak under normal operating condition multiplied by a safety factor of 10 is postulated. This crack length is called l_{leak} and is used in determining the crack size considered in subsequent fracture analyses. In a study by Battelle, the conditional rupture probability for piping (base metal and weld metal) of DN100 to DN800 leaking at the allowable leak detection limit is calculated; *c.f.* Rahman et al (1995)[4-11]. Depending on the degree of piping degradation, the rupture probability ranged from 1.0E-4 to about 1.0E-1 in the most unfavorable cases. This evaluation by Battelle concluded that:

- The conditional failure probability of wrought stainless steel is much lower than for carbon steel, particularly when the crack is located in the base metal.

- Due to a significant reduction in the toughness properties of the weld metal compared with the base metal of wrought stainless steel pipes, the conditional failure probability for cracks in weld metal was much larger (by about two orders of magnitude) than for cracks in base metal.

- The conditional failure probability for both BWR and PWR piping systems is decreasing with increasing pipe diameter.

- The conditional probability of complex-cracked[15] pipes was higher than that for through-wall-cracked pipes. Also, the conditional failure probability was found to increase with increasing depth of the surface crack. If the depth of the surface crack is large enough, then failure could occur even under normal operating loads, which is the principal reason that piping susceptible to IGSCC type mechanisms is not permitted for LBB.

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The conditional failure probability strongly depends on the chosen attribute; i.e, the grouping of the operational data. Since an attribute reflects specific design considerations, the operational data should be grouped according to the PSA requirements. Different reliability attributes are summarized in Table 10.

Table 10. Examples of Different Piping Reliability Attributes

Attribute	**Comment**
Pipe diameter	A strong attribute. The grouping of the operational data should reflect the intended application. Note that the database coverage differs according to pipe size.
Piping system type	Insights from the review of the operational data show considerable system-to-system variability. Note that this variability could be a function of process medium, mode of operation and/or pressure and temperature.
Piping material	A strong attribute. The effect of degradation and failure mechanisms differ with the material. Within a given class of material (e.g., industrial grade stainless steel) extensive plant-to-plant variability could arise depending on the influence factors.
Location of piping failure (e.g., base metal vs. weld metal)	A strong attribute. The location of failure depends on material, diameter/wall thickness, type of system and the susceptibility to specific damage/failure mechanism(s).
Pipe wall thickness	See 'pipe diameter' above. The wall thickness implicitly is accounted for via 'pipe diameter' and 'piping system type.'
Failure location	A strong attribute; depends on the susceptibility(ies) to degradation/failure mechanism(s).
Leak rate / failure mode	Highly dependent on 'piping system type', 'material' and the prevalent degradation/failure mechanism.
Process medium	Implicitly accounted for via 'piping system type.' Extensive plant-to-plant variability exists. The BWR primary system environment differs from the corresponding PWR environment.
NSSS vendor / plant type	Weak attribute. The failure 'propensity' is determined by other factors as explained above.

Reviews of the operational data yield insights about the many correlations between failure occurrences and piping system designs. In addition to the ones listed in Table 10, some general, qualitative reliability correlations are:

(1) Erosion and erosion/corrosion damage typically occurs in base metal of carbon steel piping; stainless steels are virtually immune to these failure mechanisms. Primary fault locations are elbows (e.g., outside radius), tees, straight-sections

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[15] As defined by Rahman et al (1995), a complex crack is a long circumferential surface crack that penetrates the thickness over a short length.

downstream of welds or valves (flow disturbances). Erosion and erosion/ corrosion damage is not a major problem of LOCA-sensitive piping, and stainless steels are virtually immune to these failure mechanisms. In some plant designs, safety system, such as safety injection systems and auxiliary feedwater system, rely on steam-driven pumps. The steam supply piping systems use carbon steels, and, hence, are susceptible to erosion/corrosion damage.

(2) Failure due to stress corrosion cracking invariably occurs in weld metal or weld heat affected zones (HAZ). An exception would be TGSCC where cracking has been experienced in the base metal. It is a stainless steel problem which occurs due to environmental influences. Some stainless steels are more susceptible than others. Steels with low carbon-content are more resilient than high carbon-content steels. Recent experience with primary system piping in German BWRs indicates stress corrosion cracking to be a problem in Ti-stabilized and Nb-stabilized stainless steels under certain conditions; *c.f.* Wachter et al (1996)[4-12].

(3) Fatigue failures (e.g., vibration-induced, or acoustically induced) tend to develop at the weakest portions of a piping system; at or near over-stressed joints, reducers, bends. Often, failures occur in weld metals, at or near HAZ.

4.4 Reliability Influence Factors

An explicit consideration of all environmental and mechanical influence factors is difficult. The influences are many, tend to be highly plant-specific, and they change over time. Complications result from competing degradation mechanisms and inter-acting degradation mechanisms. With the improved knowledge of environmental stress factors follows changes to operational strategies. Subtle changes at one plant could significantly impact the reliability, while the same changes at another plant could have a modest impact only. The design and operating practices evolve with the improved knowledge and historical data may not apply to all analytical situations. The objective of determining influence factors includes assessing how NDE/ISI-practices and operational conditions could improve or degrade piping reliability.

Different data interpretations may lead to different conclusions about an ‘inherent’ reliability characteristic (i.e., attribute, a characteristic which cannot be altered/ eliminated without changing a design) versus an achieved reliability (i.e., influence, a characteristic which can be controlled through operational strategy, ISI, chemistry, etc.). Conceptual relationships between attributes and influence factors are shown in Figure 12. According to this figure, an influence could have different effect on different types of piping. Influence factors should be determined on the basis of the underlying causes of predominant degradation and failure mechanisms; i.e., insights and results from root cause analyses.

The dependency between attributes and influence factors is complex. Subtle changes to an attribute could drastically change the effect of an influence factor on the reliability, and vice versa.

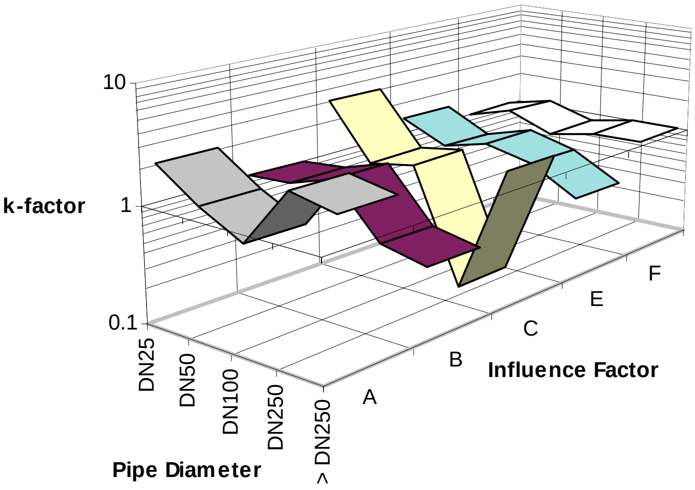

Figure 12. Conceptual Relationships between Attributes and Influence Factors

4.4.1 Determining Influence Factors from Operational Data

Each predominant degradation or failure mechanism reflects different piping system applications. Results from root cause analyses[16] give information on the influence factors and the ways by which a piping system component failed. An example of influence factors for piping susceptible to IGSCC is included in Table 11; *c.f.* Danko (1983)[4-13]. According to this table, the influence factors include welding techniques, fabrication and installation practices, and water chemistry.

Piping normally or intermittently containing stagnant water has exhibited accelerated IGSCC in the presence of high oxygen level as well as contaminants of chlorides, fluorides, caustics, and sulphur compounds. The environment chemistries could involve several independent or competitive processes that affect the cracking; *c.f.* Cullen, Gabetta and Hänninen (1985)[4-14].

As an example of the impact of water chemistry, according to the U.S. NRC Generic Letter 88-01[4-15] the use of hydrogen water chemistry (HWC), together with stringent controls on conductivity, will inhibit the initiation and growth of IGSCC. However, the response to hydrogen injection differs from plant to plant. There is no generic HWC specification, and the reduction in piping inspection frequency based on the use of HWC has been considered on individual case bases. The effect of water chemistry on reliability has been known to differ depending on whether piping is fabricated from stabilized or unstabilized austenitic stainless steels.

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[16] A degradation or failure mechanism is a symptom of underlying causes. The analysis of influence factors should be done on the basis of the contributing and causal factors of degradation and failure mechanisms.

Table 11. Some Remedies for Mitigation of IGSCC (Adapted from Danko (1983)

Influence Factor / Remedial Activity	Objective
1. <u>Sensitization Related</u>	
1.1 Solution heat treatment	(1.1) Eliminate weld sensitization and residual stresses
1.2 Corrosion-resistant clad	(1.2) Provide protection of weld-heat-affected zone. Welds are considered resistant to IGSCC if the weld HAZ on the inside of the pipe is protected by a cladding of resistant weld metal (CRC - corrosion resistant cladding)
(1.3) Alternate material	(1.3) Prevent weld sensitization. Materials considered resistant to sensitization and IGSCC in BWR piping systems are low carbon wrought stainless steel (maximum carbon content of 0.035%).
2. <u>Stress Related</u>	
2.1 Heat sink welding	2.1 Alter the internal surface and through-wall residual stress distribution.
2.2 Last pass heat sink welding	2.2 Same as (2.1)
2.3 Induction heating stress improvement	2.3 Same as (2.1)
3. <u>Environmental Related</u>	
3.1 Startup deaeration	3.1 Reduce dissolved oxygen content during startup
3.2 Hydrogen water chemistry (HWC)	3.2 Reduce steady-state oxygen content

Research on erosion-corrosion mechanisms suggests a wide range of operational and environmental influences. Most of the failures have occurred in wet-steam systems, but there is evidence of failures in single-phase systems. Based on historical data, the pipe rupture at Trojan Power Station in March 1985 was caused by single-phase erosion-corrosion phenomenon. According to a study by Cragnolino, Czajkowski and Shack (1988)[4-16], the most promising approach to mitigating erosion-corrosion in the short term would be to modify environmental factors such as:

- Effect of temperature. Laboratory studies generally have found that erosion-corrosion rates drop off markedly at high and low temperatures with a strong peak at intermediate temperatures. Failures in single-phase flow systems have occurred within a temperature range of 80 - 260 C; and for two-phase flow systems in the range 140 - 260 C.

- Effect of pH. Erosion-corrosion rates are strongly dependent on pH over the range of interest in secondary side water systems. The data (as quoted by Ref. 4-16) consistently show a decrease of more than an order of magnitude in erosion-corrosion rates over the pH-range 8.5 - 9.5.

- Effect of Oxygen. Dissolved oxygen and oxide reaction products can have severely damaging effect on steam generator materials. Modern practice seeks to keep air ingress and dissolved oxygen levels as low as possible in PWR secondary systems. For BWRs, industry guidelines suggest that dissolved oxygen levels in the feedwater be maintained at ≥ 20 ppb, even under hydrogen water chemistry conditions (see above).

- Effect of Material Composition. Alloying can greatly reduce susceptibility to erosion-corrosion; chromium being the most important alloying element for improving resistance. Austenitic stainless steels are considered virtually immune to erosion-corrosion. Plant-to-plant variations in susceptibility (or even heat-to-heat variations within a plant) could be strongly influenced by variations in the levels of chromium present as a trace element in a nominally carbon steel. The specifications for the commonly used carbon steels do not include chromium; however, experience suggests that chromium could be present as an 'impurity' at levels ranging from 0.005 - 0.07 wt%.

The system-to-system variability in reliability is a function of influence factors such as those listed above. Typical influence patterns are determined from the historical data, and insights from root cause analyses and failure analyses. While some influence factors apply in the generic sense, others are highly plant-specific. Depending on the specific implementation strategy, a factor that improves reliability at one plant may give negative side effects at another plant.

The manifestations of influence factors include the location of a crack indication, the shape and orientation of cracks, and ultimately the effect on plant operations. Some results from a top-level review of event narratives, including failure analysis results in the SLAP database, are included in Tables 12 and 13. It is recommended that an evaluation of the significance of influence factors on average piping reliability be done in four steps:

(1) For a given attribute (e.g., ⟨*diameter - material*⟩), identify the prevalent degradation and failure mechanisms; *c.f.* Tables 12 and 13. The evaluation should go beyond the 'apparent' mechanism.

(2) Identify the causal and contributing factors and determine the remedial actions to prevent recurrence of a specific degradation or failure mechanism.

(3) Identify physics-of-failure concepts/models to verify the insights from historical data and failure analyses.

(4) Calculate the overall range of effect an influence factor has on the average piping reliability, or global failure propensity. For the chosen attribute, calculate the ratio:

$$r_{Ap\text{-}I} = max\ p_{R/DP\text{-}I} / min\ p_{R/DP\text{-}I} \qquad (4\text{-}10)$$

This ratio measures the range of effect (or relative importance) of an influence on average piping reliability. It establishes a basis (or checklist) for plant-specific evaluations of operating experience.

The effects of influence factors on different size stainless steel piping are summarized in Table 14 and Table 15; additional examples are included in Appendix B. The influence matrix (Table 13) should be used as checklist of influences for small-diameter, stainless steel piping inside the containment.

Table 12. Examples of Influence Factors and Piping Damage/ Failure Locations

Damage / Failure Mechanism		Location of Piping System Flaw		
Mechanism	**Influence**[a]	**Inside→Out**[b]	**Outside→In**[c]	**Description**
Erosion or erosion-corrosion	Environmental	x		Erosion or erosion/corrosion damage occurs where there is turbulent flow; e.g., downstream of valves, elbows, tees. Typically the damage occurs in base metal. Limited to carbon steels. Stainless steels are almost immune to this damage mechanism. Reliability improvements are introduced by changing geometry of piping, and through NDE/ISI.
TGSCC	Environmental / Stress / Sensitization	x	x	Typically occurs in base metal, and where the surface of the pipe wall microstructure has been damaged during initial fabrication/ installation. As an example, cold bending of piping has been known to cause damage to the microstructure (inside and/or outside pipe wall). The TGSCC is induced by presence of sulphides, chlorides or phosphates. Pipe collars, valve packings containing these chemicals could be the source of the environmental stress.
Vibration-fatigue	Process / Mechanical	N/A	N/A	Low- or high-cycle vibrations, acoustic vibrations. Primarily a small-diameter piping problem affecting the weakest part of a system. Where there is insufficient pipe support, welds/joints tend to fail first. Seldom causing damage to base metal.
Thermal-fatigue	Process / thermal cycling	x		Caused by temperature fluctuations causing repeated contraction / expansion of piping component. Damage to base metal and weld metal has been observed.
Thermal-fatigue	Process / thermal stratification	x		Hot water floats on top of cold water. Hot water mixes with the cold water causing abrupt cooling of the hot water, and abrupt heating of cold water. Cyclic temperature changes lead to fatigue of mixing zones. A base metal problem.

Notes: (a). Distinction made between environmental & influence related to process environment or design.
(b). Cracking of pipe wall from the inside in the through-wall (TW) direction.
(c). Cracking of pipe wall from the outside in the TW-direction.

Table 13. An Example of Influence Matrix

INFLUENCE FACTOR	**Attributes: Stainless steel, TGSCC-susceptible Piping**			
	Industrial Grade		**Nuclear Grade**	
	≤ DN25	**25 < DN ≤ 50**	**≤ DN25**	**25 < DN ≤ 50**
Method of fabrication:				
- Cold bending - lubricant contains fluorides.	++ (a)	++	+	+
- Warm/hot bending tools and coatings contain zinc.	(+)	(+)	(+)	(+)
- Cutting lubricant contains chlorides.	+	+	(+)	(+)
Installation:				
- Pipe collar containing chlorides.	+	+	(+)	(+)
- Flange gasket material of asbestos with traces of chlorides.	+	+	(+)	(+)
- Proximity to piping carrying waste water (chlorides); environmental stress from external impact	(+)	(+)	(-)	(-)
Operation / Maintenance:				
- Flushing of system to keep inside pipe surface free from chlorides / irregular or no flushing.	+	+	(+)	(+)
- Leak-tightness of isolation valves not verified / chlorides in test/sample lines during long periods.	+	+	(+)	(+)

Legends: '++' = based on operational data, the specific influence could be strong (e.g., reducing time to failure), '+' = the SLAP database contains at least 10 reports indicating a recurring problem, '(+)' = probably a plant-specific issue - SLAP database does not indicate a recurring problem, '(-)' = plant-specific issue, only a problem if one or more failures in adjacent systems occur (e.g., leaking valve coincident with failure of piping insulation).

As an example, a susceptibility to TGSCC should be assumed to exist given certain environmental influences as listed in the left column of Table 13. Many different environmental conditions could, individually or together, cause the degradation mechanism to act on the piping material. In the example it has been assumed that TGSCC is the *apparent* cause of failure. The SLAP database includes reports where TGSCC has been a *contributing* degradation mechanism. That is, it has either coexisted with other degradation mechanisms or has triggered another 'faster-acting' mechanism. After crack initiation through TGSCC, cracks have been known to propagate intergranularly.

In Table 14 the operating experience indicates that small-diameter piping mainly is vulnerable to 'human factors' and vibration fatigue. This implies that that 'internal' factors such as process medium, flow rate, chemistry have less influence on the reliability than the external influences. A recurring problem could be prevented by enhancing existing maintenance procedures or by improving the design practice. The range of effect of influence factors depends on the pooling of the experience data. An evaluation of small-diameter instrument lines in emergency diesel generator systems would reveal vibration-fatigue due to improper material selection combined with lack of support as a stronger influence than human factors.

Table 14. Overall Range of Effect of Influence on Pipe Reliability - Example #1

≤ DN25 Stainless Steel Piping **Application:** Instrument Line / Sample Line - Stagnant or Intermittently Stagnant Fluid				
Level of Influence	**Factor**	**Level**	**Description**	**Range of Effect $[r_{Ap-I}]$**
1	Human Factors	1	Construction defect / QA deficiency	9.3 [17]
		2	Design error - lack of verification	
		3	Fabrication error	
		4	Human error	
		5	Installation error	
		6	Maintenance error	
		7	Repair error	
		8	Welding error	
2	Fatigue	1	Vibratory fatigue	4.6
		2	Thermal fatigue	
		3	Fatigue - 'default'	
3	Corrosion	1	Flow-assisted corrosion	3.1
		2	Boric acid corrosion and cracking	
		3	Chloride induced corrosion	
4	Stress corrosion cracking	1	IGSCC - BWR environment	2.0
		2	SCC - PWR environment	
		3	TGSCC - LWR environment	

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[17] Using the service data, for each of the eight (in this case) contributors to pipe failures induced by human factors problems/deficiencies compute the conditional probability of pipe rupture, then calculate the ratio of the largest to smallest value.

Table 15. Overall Range of Effect of Influence on Pipe Reliability - Example #2

100 < DN ≤ 250 Stainless Steel Piping
Application: Process Line - Stagnant or Intermittently Stagnant Fluid

Level of Influence	Factor	Level	Description	Range of Effect [r_{Ap-I}]
1	Stress Corrosion Cracking	1 2 3	IGSCC - BWR environment SCC - PWR environment TGSCC - LWR environment	20.1
2	Human Factors	1 2 3 4	Construction defect / QA deficiency Design error - lack of verification Fabrication error Welding error	7.0
3	Fatigue	1 2 3	Vibratory fatigue Thermal fatigue Fatigue - ‘default’	4.8
4	Corrosion	1 2 3	Flow-assisted corrosion Boric acid corrosion and cracking Chloride induced corrosion	3.8

The insights about the effect of influence factors on reliability change with different reliability attributes. The insights also change depending on how the contributing and causal factors of degradation and failure are defined. That is, the depth of an evaluation of root causes determines the quality of the insights about influence factors. Yet other insights are developed by pooling of the operational data according to type of plant system, mode of operation.

4.4.2 Evaluating Plant-Specific Service Data

A measure of the actual or potential effects of plant-specific influences is established by comparing them against the global data; e.g., influence matrices (*c.f.* Table 13) and range of effects of influences (*c.f.* Tables 14 and 15). Consistent definitions of causal factors and contributing factors must be developed to enable a comparison. A simple quantitative measure of the effect of influence ‘i’ on attribute ‘X’ is given by:

$$k_i/_X = [(\phi_{SPECIFIC} /_{‘i’} / T) / (\phi_{GENERIC} /_{‘i’} / T_{GENERIC})] \qquad (4\text{-}11)$$

where $\phi_{SPECIFIC}|_{‘i’}$ = Number of failures according to the plant-specific experience given an influence ‘i’;
$\phi_{GENERIC}|_{‘X’}$ = Number of failures according to industry-wide service data for piping systems affected by an influence ‘i’;
T = Plant-specific exposure time;
$T_{GENERIC}$ = Total exposure time according to the industry-wide service data.

As an example of how (Eq. 4-11) could be applied, assume that for the influence of ‘vibration’ the industry-wide experience is 20 failures in 250 reactor-years (e.g., service data from 5 plants with a total operating time of 50 years). Furthermore, assume that the plant-specific experience is 1 failure in 20 reactor-years. The corresponding k-factor = 1.25. This means that the plant-specific susceptibility could be 25% higher than the industry average. In case the single failure was a systematic error addressed through a minor design change (e.g., improved piping support), the analysis should also consider the case of zero failures. Assuming that instead of 1 failure in 20 years, the plant-specific operating experience is 0 failures in 20 years. A simple approach to this problem could be to perform a 1-stage Bayesian updating using 20 failure in 250 reactor-years as the prior. The mean-failure rate of the posterior distribution, assuming lognormal distributions, is 1.57E-6/reactor.hour. In this case the k-factor becomes 0.17; i.e., the plant-specific experience indicates the reliability to be about 6 times better than the industry-wide data indicates.

Based on the operational data alone, the evaluation of an influence such as primary water chemistry is difficult. Some examples of possible approaches to the analysis are summarized in Table 16. Failure records in SLAP represent the full range of water chemistry strategies. While theoretically possible, it would not be practical to determine the water chemistry strategy for each of the surveyed plants in the database, however. We therefore make the assumption that the global data represent an average water chemistry strategy. This 'average strategy' reflects the state-of-knowledge ten to twenty years ago. How should today's state-of-knowledge about the physics of degradation mechanisms-be accounted for in the parameter estimation? A decision to derive plant-specific failure parameters, which takes into account specific influence factors, should be based on detailed consideration of industrywide and plant-specific operating experience. The conditions under which some damage or failure mechanisms evolve are complex. It therefore is difficult to base a decision to use a small or negligible k-factor on a single factor. Additional details are addressed in Section 5.

Table 16. Evaluation of Plant-Specific Influence Factors - An Interim Proposal

Operating Experience	Analysis Strategy
(1) No evidence of degradation or failure	(a) No action - generic data applies; i.e., no reason to believe the plant-specific experience to be better than the 'average' plant. (b) If degradation and failure mechanisms have been explicitly accounted for, use k = 0.1, 0.5 or 0.8. Justifications essential; the demand for justification increases for low 'multipliers'. (c) Assume zero failures
(2) Degradation / failure has been experienced	Perform quantitative evaluation as indicated above and substantiate with reviews of NDE/ISI results. The evaluation must address the question: "*In what way(s) does (do) the plant-specific operating experience differ from the industry-wide experience?*"

4.4.3 'Bounding' of Influence Factors

The 'range factor' (*c.f.* Eq. 4-10) is an indirect measure of the reliability growth which can be achieved by eliminating or minimizing the effects of a certain influence factor. As an example, according to Table 17 an improvement by a factor of about 20 could be realized by eliminating piping material susceptible to IGSCC. The Electric Power Research Institute (EPRI) has studied the potential improvements by implementing remedies for mitigating IGSCC; *c.f.* Danko (1983)[4-13] and Table 17 (based on Danko's paper).

Table 17. Factor of Improvement for Piping Failure Remedies (IGSCC in DN100 Piping)

Piping Failure Remedy	**Factor of Improvement (Increase in 'Time to Failure')**
1. <u>Sensitization Related</u>	
(a) Solution heat treatment	> 20
(b) Corrosion resistant clad	> 20
(c) 316 nuclear grade (NG) stainless steel	> 20
(d) 304 NG stainless steel	> 20
2. <u>Stress Related</u>	
(a) Heat sink welding	15.1
(b) Induction heating stress improvement (IHSI)	> 10

Another way of determining the range factor is by developing hazard plots for groups of failure data. In theory, the spread in values of time to failure (TTF) could help determine the effects of different remedies. Figure 13 is a hazard plot[18], which shows the TTF for cold worked medium-diameter stainless steel piping.

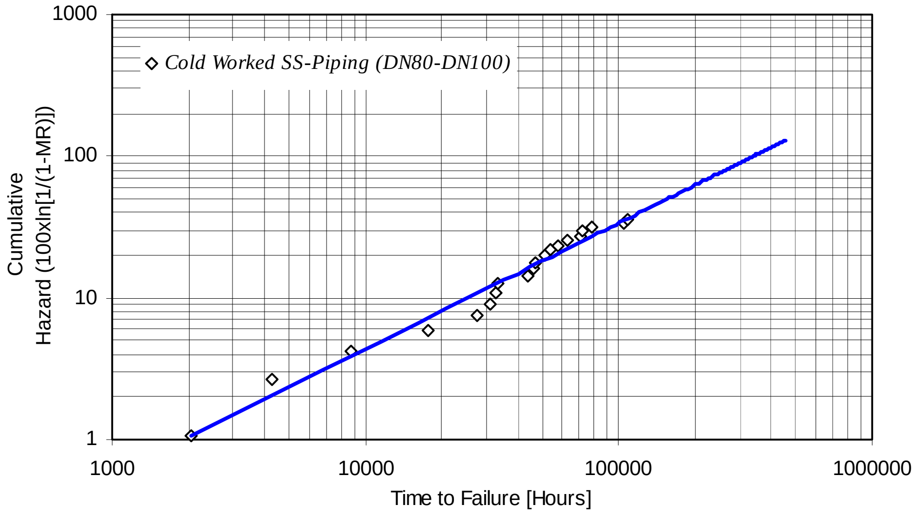

Figure 13. Example of Hazard Plot of Time to Small Leaks in Stainless Steel Piping

Only failed piping system components are included in this hazard plot. It is seen that for small-diameter piping systems the time to failure has ranged from about 10,000 hours to about 130,000 hours (i.e., difference is a factor of 13). Different attributes and environmental influence factors explain this difference.

4.5 An Interim 'SLAP Reliability Correlation'

Data analysis should be based on a model of failure. That model should portray pertinent aspects of failure as extracted from service data. The model should discriminate between general reliability attributes and plant-specific influence factors. Translating operating experience data into a parameter data set for PSA requires a multi-step approach.

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[18] For an introduction to hazard plotting techniques, see: O'Connor, P.D.T. (1991): *Practical Reliability Engineering*, Third Edition, John Wiley & Sons, Chichester (UK), ISBN 0-471-92696-5, pp 82-85.

Consistent with the discussion in Section 4.1, for the purpose of interpreting and applying the industry-wide data in the SLAP database, the following 'symbolic' piping reliability concept is chosen:

$$p_{R\text{✉}DP\text{-'}X\text{'}} = \Sigma_{n\,=\,\alpha,\,\beta\ldots\eta}\,(k_{i\text{-'}X\text{'}}\ \text{✌}\, p_{R\text{✉}DP\text{ - }GENERIC}) \qquad (4\text{-}12)$$

where $p_{R\text{✉}\,DP\text{-'}X\text{'}}$ = plant-specific conditional probability of pipe rupture and 'X' refers to a specific attribute such as type of system;

$k_{i\text{-'}X\text{'}}$ = influence factor 'i' applicable to attribute 'X';

α, β …. η refer to different, independent degradation or failure mechanisms affecting the piping system under consideration.

$p_{R\text{✉}\,DP\text{-}GENERIC}$ = generic conditional probability of pipe rupture derived from industry-wide service data.

Therefore, the plant-specific conditional rupture probability is the conditional probability resulting from the reliability influence factors that act upon an attribute, which is considered on the basis of the industry-wide data. Each of the elements in Equation (4-12) is addressed by the data reduction and data analysis steps described in Sections 4.3 and 4.4. So far we have only discussed the relative contributions to piping failure. Ultimately the goal is to derive an absolute rupture frequency for which a 'nominated' (i.e., consensus) frequency of pipe failure is required. A 'nomination' implies that the raw data meet acceptable levels of completeness and coverage. Exactly how a nominated frequency of failure is generated could be controversial. The approach to deriving an absolute pipe rupture frequency is a function of the PSA application requirements as described in Section 5 of this report.

An approach to estimating the k-factor was discussed in Section 4.4.2. In practical applications, the determination of k-factors is quite complex, and a rigorous statistical analysis of influence factors would require the design and analysis of statistical experiments. A more straightforward approach could be to perform further pooling of the service data according to specific 'exposure cells.' As an example, if we were interested in, say, the influence of hydrogen water chemistry (HWC) on IGSCC-susceptible piping, the service data should be organized according to the different HWC-strategies that have been implemented. Next, by evaluating the impact on piping reliability by HWC would enable an assessment of the conditional rupture probability with and without HWC. Such parametric studies could be supported by probabilistic fracture mechanics.

4.6 Discussion

The conditional factors of piping reliability were defined in terms of 'attributes' and 'influence factors.' An attribute relates to piping system design features as addressed by codes and standards and functional requirements. An influence factor relates to the operating environment once a system has been commissioned. An analysis format building on these conditional factors provides the framework for deriving plant-specific piping reliability parameters.

The selection of a statistical analysis approach must reflect intended application(s). In Section 4 we used Bayesian statistics to infer *some* insights about reliability attributes. It must be understood that in the context of PSA the Bayesian approach works quite well for the purpose of deriving point estimates with consideration of uncertainties. A drawback of this approach is that it is insensitive to changes in the operational data. That is, the approach is not very useful for performing trend analysis or other reliability-oriented applications. At this stage of the R&D there is no need for more advanced Bayesian statistics, however. The techniques and tools of classical statistics should be exploited when performing detailed evaluations of the operational data. Piping reliability is a complex topic. Section 4 outlines some key analysis considerations that are included in the analysis framework, which is presented in Section 5. This framework constitutes minimum analytical requirements to be acknowledged in modern PSA.

4.7 References

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5

THE ‘PFCA’ ANALYSIS FRAMEWORK

As stated in Section 1, the ‘*Pipe Failure Cause and Attribute*’ (PFCA) Framework consists of five steps. The details of this analysis framework for piping reliability are discussed and illustrated in this section. Each step in PFCA consists of inputs, analytical activities, special considerations (i.e., caveats), and outputs. Completing an analysis probably requires several iterations within and between steps; especially between Steps 2, 3 and 4.

A given level of analytical ambition determines the particular implementation of this Framework. That is, the analytical implementation might be part of a detailed, plant-specific LOCA frequency estimation requiring an effort of several person-months. At the other end of the range of possible applications could be a limited scope validation of an old, judgmental piping reliability estimate requiring no more than a few hours of effort.

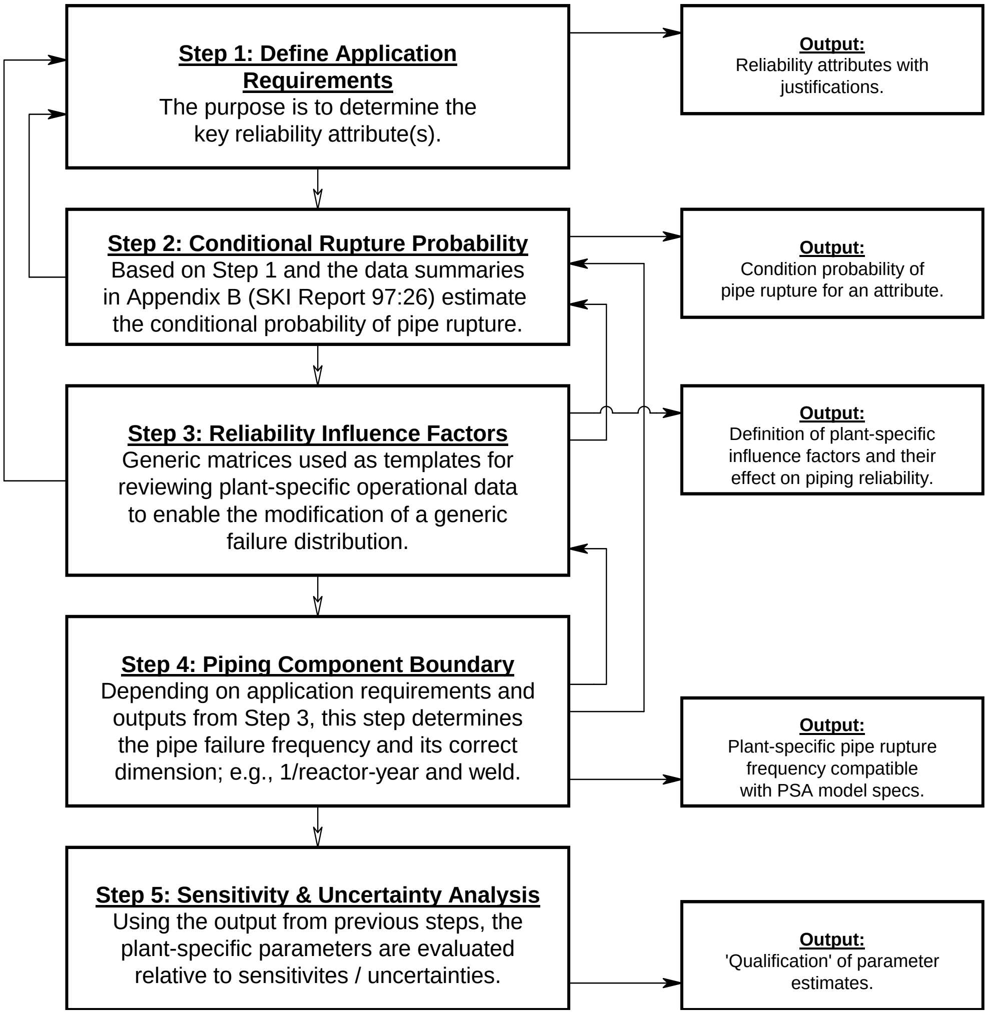
5.1 An Overview of the ‘PFCA’ Framework

The ‘PFCA’ Framework (*c.f.* Figure 14) is not a prescriptive, or ‘cook book style’ analysis framework. It represents a menu of steps, activities, and rules or recommendations. This ‘menu’ enables an assessment of piping reliability to be tailored to meet work scope definitions and analysis objectives in the context of PSA applications. Users of the framework are encouraged to explore the failure data beyond what was done in Section 4. To refine the analysis framework, further analyses of the data together with pilot applications should be pursued. Ultimate objective of the framework is to support development of plant-specific failure parameters for piping system components based on the broadest possible database, while recognizing the inherent large statistical uncertainties. A philosophy is presented for how to derive piping reliability parameters. The framework is data-driven and builds on qualitative and quantitative insights from reviews and evaluations of operational data from nuclear power plants worldwide.

For reasons cited in Sections 2, 3 and 4, the derived failure parameters will have large statistical uncertainties. Parameter estimation based exclusively on service data is not advisable, nor is it feasible for all intended applications. The completeness and coverage of the reporting on piping failures are well below the standards established by the modern equipment reliability databases for active components. Therefore, the framework develops and explains the many caveats to be considered in piping reliability estimation. The user of this framework should be aware of the statistical uncertainties associated with parameter estimation based on operational data. Throughout an estimation process, expert judgment by structural expertise is recommended. The analyst should always assess the reasonableness of estimated parameters, however.

The analysis framework favors decomposition of a given piping reliability problem. Upon identification of key design features of a piping system, the analyst proceeds by addressing the questions about the *why-where-how*. An analysis should acknowledge the full operational experience database together with the specifics of the requirements for application. The framework consists of five steps with required inputs, analytical activities or deliberations, rules and outputs:

Figure 14. The Five-Step 'PFCA Framework' for Piping Reliability Analysis



(1) <u>Application Requirements</u>. The input to this step consists of descriptions of a piping system (e.g., isometric drawings, material specifications) and service history. The output is a concise description of the planned application; e.g., estimation of LOCA or main steam line break (MSLB) frequency. The intended application determines how to select generic piping reliability parameters. It also determines how reliability attributes and influence factors are evaluated and used. Finally, the application requirements determine how the piping system component boundaries are defined; e.g., piping section/segment definitions.

(2) <u>Raw Data, Piping Population Data & Generic Reliability Parameters</u>. The framework includes the necessary analysis techniques and raw data for calculating plant-specific parameters. Examples of generic parameters are given. The framework comes with tabulations of raw data (Appendix B) and piping

population data. Development of application-specific generic data parameters is followed by detailed evaluations of plant-specific operating experience (including inspection records and other relevant information) to estimate the plant-specific parameters. Ask the question: *Does the available raw data support the application requirements?*

(3) Reliability Influences & Review of Plant-Specific Experience. The step from application- to plant-specific parameter estimation is taken via the implementation of reliability influence matrices (or 'check-lists') and evaluations of the observed effects on reliability by specific influences. Extracted from the SLAP database, the framework provides information on the influence factors affecting piping reliability. Information is also provided on the potential reliability improvements that can be achieved by different remedies. A decision to develop plant-specific parameters is a major step, and to be meaningful it requires substantial resources (budget, personnel). Consideration should be given the potential additive or cumulative effects of two or more influence factors on piping reliability.

(4) Piping Boundary Definition. The review in Step 3 should be done on the basis of isometric drawings, and the output could be in the form of pipe section/ segment definitions, and a quantitative basis for modifying generic reliability parameters, with proper justifications. *The purpose of Step 4 is to define the dimension of the parameter estimates and the PSA model representation of piping failures*. The dimension (e.g., failure/system-year, failure/'length-of-piping' and year) is a function of the predominant degradation or failure mechanisms, material, system layout, etc. For example, in IGSCC-susceptible piping the cracks or leaks typically develop in weld and weld heat affected zones. For such systems the rupture frequency should be derived on a per-weld-basis.

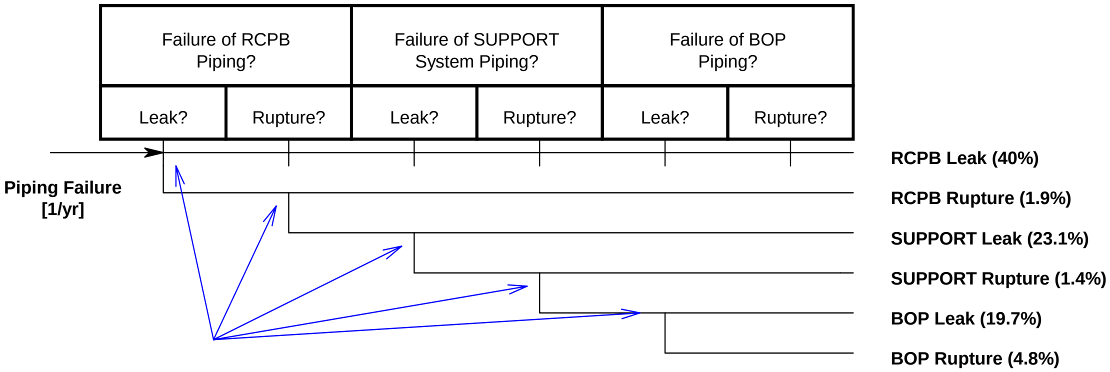
(5) Statistical Analysis & Uncertainty Analysis. The framework recognizes the importance of analyzing uncertainties, and identifies the sources of uncertainty and how they should be addressed. In the final derivation of plant-specific parameters expert judgment elicitation and discussions will be combined with estimates that are based purely on operational data. The ultimate goal of uncertainty analysis is to qualify the conclusions about piping reliability based on point estimate evaluations. Uncertainty analysis should also be used to identify where improvements in the state of knowledge can lead to maximum benefit with respect to an accurate assessment of piping reliability.

Typical applications are illustrated in Figure 15. The LOCA frequency assessment is concerned with piping system failures within the RCPB. Similarly, the systems analysis or the analysis of internal flooding events could be could be concerned with failures in support system piping, etc. In the PFCA Framework we divide the parameter estimation into the following activities, as indicated in Figure 15:

(1) Assessment of the piping failure frequency (i.e., initiator) by asking how often does a plant experience piping degradation. As indicated in Sections 2, 3 and 4, there are different estimation strategies; e.g., a) direct estimation using the service data in the SLAP database, b) conservative assumption of 1 event per year, or c) data specialization using a combination of '1' or '2' and plant-specific data.

(2) Determination of an attribute of piping reliability which yields the conditional probability of rupture given a degradation.

(3) Consideration of influence factors to generate application-specific parameter estimates.



Split fractions are characterized as a 'conditional probability of a leak or rupture given an occurrence of degraded piping.

Note: Numbers in ( ) represent the percentage of the total SLAP database content (per Version 7.7, a total of 2,356 events).

Figure 15. Illustration of the Data Needs - The Frequency of Pipe Failure

5.2 The ‘PFCA’ Steps

The ‘PFCA’ Framework was developed for PSA practitioners, and it is strongly influenced by interpretations of operational data. Each step of the framework consists of inputs, activities, rules, and outputs.

The *inputs* are derived from prior steps, from the main PSA study tasks, or from other information sources (e.g., incident reports, root cause analysis reports, published PSA studies, probabilistic fracture mechanics (PFM) evaluations). The activities are what are basically undertaken by the analysts within each step to achieve the objectives of that step. Recommendations and rules guide the activities of the analysts. The output is the product of the activities carried out by the analysts and is determined by the information required in the other steps or by the PSA study itself. It is envisioned that a team of system analysts (i.e., PSA practitioners) and structural expertise would be intimately involved in all steps of the analysis.

Data analysis should be based on a model of failure. That model should portray pertinent aspects of failure as extracted from operational data. The model should also discriminate between reliability attributes and influence factors. Translating operating experience data into a PSA parameter data set requires a multi-step approach. For the purpose of interpreting and analyzing service data the following model of piping reliability is chosen; *c.f.*, Section 2.3 and Section 4.5:

$$f_R = f_{FAILURE} \times p_{RUPTURE\,|\,FAILURE} \tag{5-1}$$

where f_R = frequency of a pipe rupture;
$f_{FAILURE}$ = frequency of a pipe failure (e.g., flaw/crack, leakage);
$p_{RUPTURE\,|\,FAILURE}$ = conditional probability of rupture given a flaw/crack or leakage.

$$p_{R|FAILURE} = \Sigma_{n\,=\,\alpha,\beta\,..\,\eta}\,(k_{i\text{-}‘X’} \times p_{R|DP\text{ - }GENERIC}) \tag{5-2}$$

where $p_{R|DP\text{-}‘X’}$ = plant-specific conditional probability of pipe rupture and ‘X’ refers to a specific attribute such as type of system;
$k_{i\text{-}‘X’}$ = influence factor ‘i’ applicable to attribute ‘X’;
α, β … η refer to different, independent degradation or failure mechanisms affecting the piping system under consideration.
$p_{R|DP\text{-}GENERIC}$ = generic conditional probability of pipe rupture derived from industry-wide service data.

Equation (5-2) acknowledges that within a given type of piping system, different, independent degradation or failure mechanisms (denoted by α, β ... η) could be acting upon the piping system components. The right-hand side of Equation (5-1) consists of two terms which are addressed by Steps 1 through 5 of the ‘PFCA’ Framework:

- Step 1 defines the attribute(s) of interest (e.g., ⟨*material* - *diameter*⟩, ⟨*material* - *plant system* - *diameter*⟩) and how they relate to the PSA (e.g., static versus dynamic PSA, full power versus low power or shutdown PSA) and the definition of population data;

- Step 2 quantifies the attribute(s), provides a basis for nominating a base failure rate, and produces an application-specific generic failure rate. The output is a conditional rupture probability ($p_{R|DP}$);

- Step 3 identifies the key influence factors and develops a basis for converting an application-specific generic failure rate into a plant-specific failure rate.

- Step 4 defines the PSA model requirements including the parameter database. The output is the pipe failure frequency, $f_{FAILURE}$;

- Step 5, finally, should be seen as a validation of assumptions made in previous steps. The sensitivities and uncertainties in parameter estimates are evaluated in this step.

The combination of activities in Steps 1 and 2 establishes a basis for application-specific but generic pipe failure rates. The term ‘generic’ should not imply an ad hoc selection of data parameters. Instead, the selection of generic data should be done with the same care and attention to operating environments and plant design features as the data specializations themselves. In Steps 3 and 4, the generic information is specialized to reflect the unique features of a given piping system as defined by Steps 1 and 2. We can say that Steps 1 and 2 are concerned with *a priori* analysis, while Steps 3 and 4 consider the *a posteriori* analysis. The details of the steps are discussed in the next five sections.

5.2.1 Step 1: Definition of Application Requirements

The parameter estimation should be performed against clearly defined application requirements. The ‘top-level’ requirements come from the PSA model specifications (e.g., computer code requirements and data input formats), assessments of consequences of potential piping system failures, and the motivations behind the PSA project. Before presenting the intents of Step 1, the data parameter content of the PFCA are discussed below. PFCA includes ‘modules’ to carry out plant-specific piping reliability analysis in the context of PSA projects, including base-line full power, low power and shutdown PSAs and ‘living’ or ‘online’ PSAs. The latter type of application could be concerned with the risk-impact of different ISI strategies. For any given analytical context, combinations of modules may be developed by the analyst using the data contained in Appendix B. The data is organized according to the conditional factors of failure. Included with the data presentations in Appendix B are the following items, which represent the generic data:

- Reliability attributes (e.g., type of piping system, type of plant system, material). Using the raw data in Appendix B, the user of this framework may develop new, application-specific attributes;

- Population data (e.g., type and number of piping system components). Embedded within this ‘block’ is the question about what kinds of operational data should be considered (i.e., data from all plants worldwide, or a subset of all data). Some examples of population data are included in Appendix B;

- Raw data; e.g., number and types of failure events corresponding to a given attribute or set of attributes;

- Summaries of reliability influence factors, and checklists containing global influences extracted from the SLAP database.

Step 1 of the PFCA Framework is represented by a flow chart; *c.f.* Figure 16. With emphasis on purpose, inputs and outputs, and expected analysis activity, the application of this flow chart is discussed below. A chosen attribute, or set of attributes, must have relevance to the specific piping system(s). The approach to data analysis and identification of the most appropriate piping reliability attributes are functions of study scope and objectives.

As an example, should an attribute be selected on the basis of ⟨*material* - *diameter*⟩ or ⟨*plant system* - *material* - *diameter*⟩? The answer should reflect the desired analytical discrimination. The purpose of defining attributes is to support development of a generic failure rate distribution based on operational data, which correspond to the chosen attribute(s). The selection of an attribute should reflect our knowledge about piping reliability and its conditional factors.

The user of the Framework should develop justifications for selecting a certain set of attributes among the extensive set of attributes included in Appendix B. As an example, if the study objective is to develop new LOCA frequencies, the operational data of interest could be limited to piping failures in LOCA-sensitive piping. A systems review enables the identification of those systems of concern (e.g., primary system piping and unisolateable connecting piping inside containment). The review would provide the attributes to be considered for further analysis. These user- or application-defined attributes most likely would be limited to piping systems of certain metallurgy, diameter, mode of operation, safety significance, systems addressed by existing PSA model structures, etc.

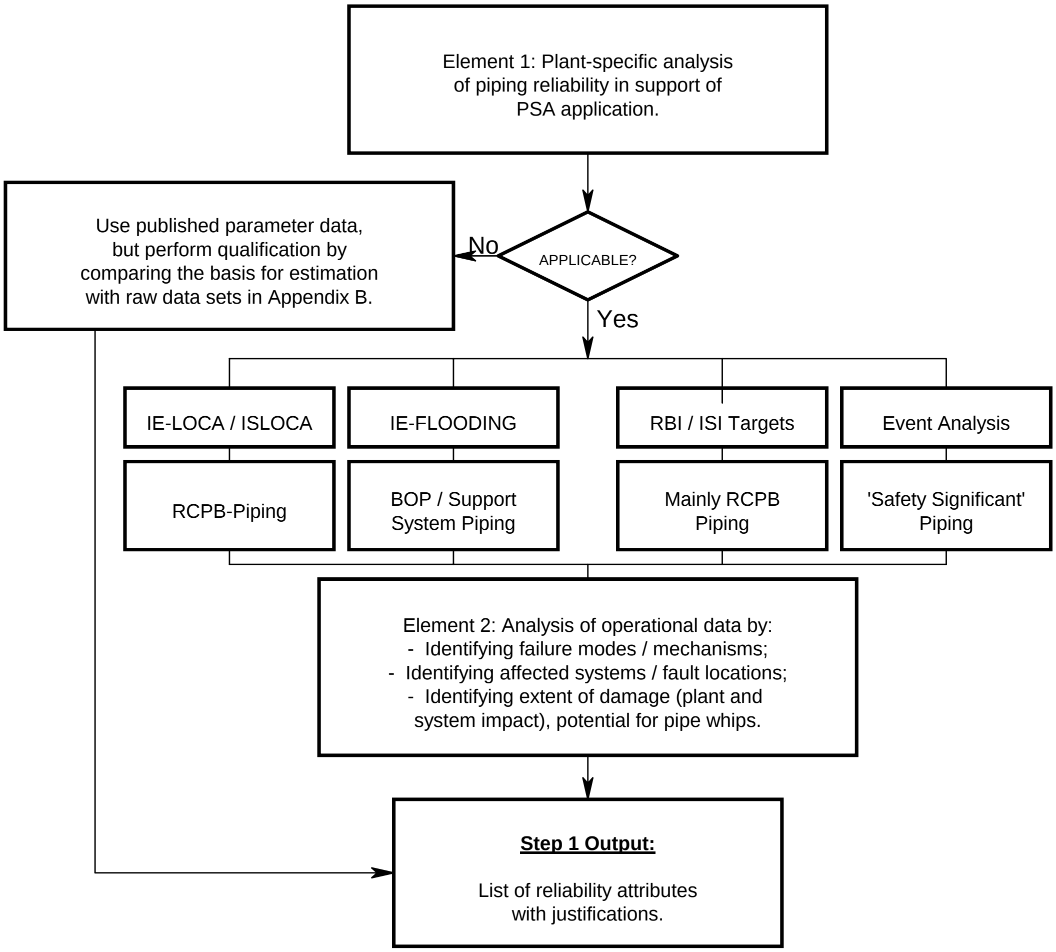


Figure 16. Step 1 of the 'PFCA' Framework - Application Requirements

The applications are differentiated according to ‘black-box approach’ (which is equivalent to direct use of already published data; e.g., WASH-1400), ‘opaque-with-constraints’ and estimation by ‘decomposition.’ The problems associated with the direct use of published data are well documented; e.g., SKI Report 95:59[5-1]. Therefore, this report does not present any tabulations of recommended or nominated failure frequencies or conditional rupture probabilities. Instead, the analyst has to derive parameter estimates that best fit an application. The analysis framework provides all the main elements for developing failure parameters that reflect interpretations of the selected service data, however. The focus of this analysis framework is on the opaque-with-constraints and decomposition approaches. It is expected that an application is performed as a team effort, which involves PSA expertise, structural expertise, and NDE/ISI expertise.

THE ‘PFCA’ STEP 1

The Analysis Inputs (*c.f.* Figure 5-3): Description of the scope and objective of the PSA / PSA application, definition of resources.

Intent of Step 1: To decide whether implicit or explicit modeling of piping reliability is required. Also, to determine the specific safety issues / regulatory issues to be considered by PSA. To establish the level of analytical discrimination which is required.

Rules: Compatibility with PSA model structures and data requirements.

Outputs: Itemized list of piping systems to be considered by the analysis.

In the context of piping reliability analysis, ‘opaque-with-constraints’ means that while an analysis is concerned with the details of piping failures (i.e., causes, attributes and influence factors, industry-wide and plant-specific operating experience), it does not include explicit modeling of an entire piping system with its components such as welds, nozzles, bends, elbows, etc. The opaque approach looks at a piping system as a whole; i.e., without explicit recognition of geometry or individual welds, elbows, etc. In other words, the analysis ‘blocks out’ the individual features of a piping system design deemed unimportant to plant safety/PSA results, analytical discrimination, etc.

THE PFCA STEP 1 / ELEMENT 2

Inputs to Element 2 of Flowchart in Figure 5-3: Information on piping system design (e.g., isometric drawings), material specifications, NDE/ISI experience/insights and service data.

Activity: *Review* of the conditional factors (e.g., attributes and influence factors), including the relevant raw data tabulations in Appendix B of this report. *Determine* whether the data analysis should be done according to type of system, operating mode, material, or other attribute.

Outputs: List of reliability attributes to consider, with guidance on how to proceed with the estimation of failure parameters.

Validation of an estimate solely on the basis of referencing published data is not recommended. In the past, most PSA studies have used the WASH-1400 estimates. For the reasons stated in SKI Report 95:58 (*c.f.* Nyman et al (1996)[5-2]), these estimates could lead to over-conservatism in the parameter estimation. The purpose of Step 1 of the analysis framework is to ensure that the available service data are considered in sufficient detail.

The decomposition approach is equivalent to a section-by-section or component-by component evaluation of piping system reliability. A detailed review of a piping system should be done on the basis of reviews isometric drawings and system walkdowns. Such review would reveal any discrepancies between the as-designed and as-built/operated system. Next, spreadsheets are developed with details on piping system design issues, operating experience, reliability attributes and influence factors for each piping system section or component as identified by the analysis team. An example of a spreadsheet is given in Figure 17.

Node No.	P&ID NO.	Isometric No.	Material Spec.	Weld spec.	DN	Medium	Service history

Notes: - Node No. refers to an individual component as identified on the isometric drawing.
- Under 'Medium' identify the type of medium, and whether the process medium is (could be) stagnant during normal operation.

Figure 17. Blank Sample Spreadsheet for Collecting Piping System Information

Proceeding to 'Element 2' of the flowchart in Figure 16 implies a detailed consideration of the applicable industry-wide operational data, including the plant-specific experience. The SLAP database includes mainly significant failures as documented in LERs and equivalent reports. The coverage and completeness of the SLAP database are discussed in Section 3 and Appendix A.

While most major piping failure events have been included in the database, SLAP *does not* contain the plant-specific service data normally available to a PSA project (e.g., the reports on NDE/ISI results, primary and secondary side incipient and degraded failures not determined to require formal dispositioning with regulatory agency). Objective of 'Element 2' is to ensure that all the relevant plant-specific operating experience is being accessed, and to prepare for detailed evaluation of plant-specific data against industry-wide data. The formation of an analysis team should include consideration of involving structural expertise NDE/ISI expertise. That expertise should be consulted when reviewing isometric drawings and the service data.

5.2.2 Step 2: Derivation of Application-Specific Rupture Probabilities

There is no one way of developing an application-specific rupture probability. From the SLAP database (*c.f.* Appendix B) we get the conditional probabilities of pipe rupture, $p_{R|DP}$, for various attributes. The way we elect to define the attribute(s) of concern affects the derivation of *absolute* pipe rupture frequencies. Note that each attribute category may incorporate (i.e., subsume) several specific reliability attributes.

A simple way of characterizing reliability attributes is via direct estimation of conditional rupture probabilities using the Bayesian approach (*c.f.* Section 4). An alternative approach would be to use probabilistic fracture mechanics (PFM). PFM techniques have gained increased acceptance as a method of generating piping failure probabilities. Mostly, these studies have analyzed the probability of a double-ended guillotine break (DEGB) of the reactor coolant loop piping. An overview of the methodology is given in Simola and Koski (1997)[5-3], and a summary of typical results is given in Bush and Chockie (1996)[5-4]. PFM evaluations are labor intensive and may not fit into a PSA project schedule. In the past, PFM has been used to calculate large and medium LOCA frequencies.

An example addresses the potential problems of converting PFM results into PSA parameters. As part of its reevaluation of the DEGB of reactor coolant loop piping as a design basis event, the Lawrence Livermore National Laboratory, under a contract with the U.S. Nuclear Regulatory Commission, estimated the probability of occurrence of DEGB by using the PRAISE computer code[5-5]. Results from an evaluation of Westinghouse PWRs are reproduced in Table 18.

Table 18. Probability of DEGB and Leak in RCS Piping[5-6] *- An Example*

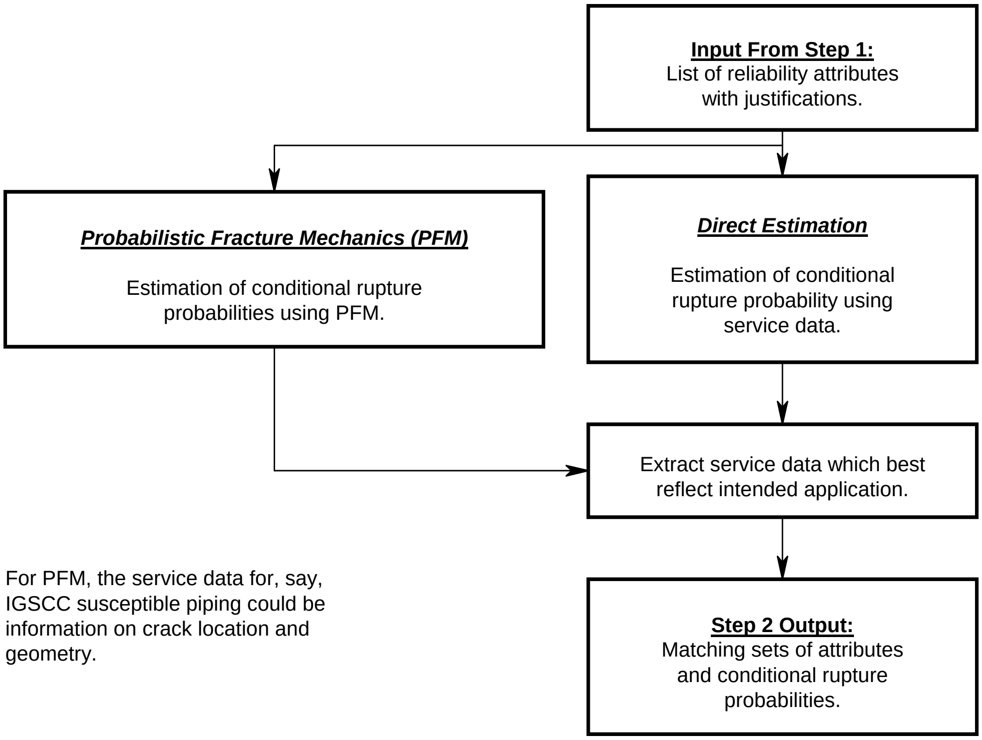
Failure	**Probability of Failure / Yea**		
Mode	**10%**	**50%**	**90%**
DEGB	5.0E-17	4.4E-12	7.5E-10
Leak	5.6E-10	1.1E-7	2.4E-7

These results relate to the hot leg, cold leg and crossover leg of a four-loop PWR plant. Additional information on material, dimensions, degradation mechanisms, and crack size must be derived from the input data used to run the PRAISE computer code. Prior to a PSA application, information as presented in Table 18 should be evaluated relative to the computer code input parameters. That is, do the tabulated results represent the conditional rupture probability of the entire system or a specific piping system component such as a weld? Performing a parameter conversion, or specifying the PFM input parameters could be done within the PFCA Framework.

The limitations of service data should always be considered when performing direct estimation of conditional rupture probabilities using service data. The SLAP database is limited to failures for which a requirement has existed to file a licensee event report. This means that failures, which result in an entry into a Technical Specification Action Statement are included in the database. Statistical uncertainties due to data coverage and completeness impact applications in different ways. Events involving support system and BOP system are typically under-reported.

The PFCA Framework stresses the importance of surveying existing plant-specific maintenance work order records, NDE/ISI records, etc. to ensure full consideration of all relevant operating experience. SLAP provides a general overview of the types of failures that have been experienced to date. Based on the coverage and completeness of the SLAP database, the users of the Framework should pursue further explorations and evaluations of operational experience, however.

Depending on intended application, operational data can be interpreted and pooled in any number of ways. The analysis must be supported by proper justifications, however. The objective of Step 2 (Figure 18) is to ensure the derivation of *relevant* application-specific generic failure rates. That is, the failure rates should be relevant to the specific piping systems.



For PFM, the service data for, say, IGSCC susceptible piping could be information on crack location and geometry.

Figure 18. Step 2 of the 'PFCA' Framework - Estimation of the Conditional Pipe Rupture Probability

Step 2 Analysis Inputs (*c.f.* Figure 18):
Piping reliability attribute(s) together with application specifications; e.g., detailed pipe-section-by-pipe-section LOCA frequency estimation, or define PFM evaluation requirements.

Intent of Activity:
Estimation of the conditional probability of pipe rupture to support the calculation of pipe rupture frequency per Equation (5-1).

Rules:
There must be consistency between the Step 1 output and the selection of service data. When performing direct estimation, the pooling of service data must be consistent with the defined attributes; e.g., service data for carbon steel and stainless steel should not be mixed.

Outputs:
Conditional pipe rupture probability for a specific attribute or sets of attributes.

5.2.3 Step 3: Reliability Influence Factors

Step 3 (Figure 19) could be the most time-consuming and challenging part of a plant-specific analysis of piping reliability. It includes detailed engineering evaluations of a given piping system to determine where vulnerable areas exist. Such an evaluation should be done against the service data, including the NDE/ISI experience relevant to the specific piping system. Ultimately, Step 3 is concerned with the question whether the industry-wide service data applies or not. There should be well formulated, compelling reasons for modifying a conditional rupture probability as derived in Step 2.

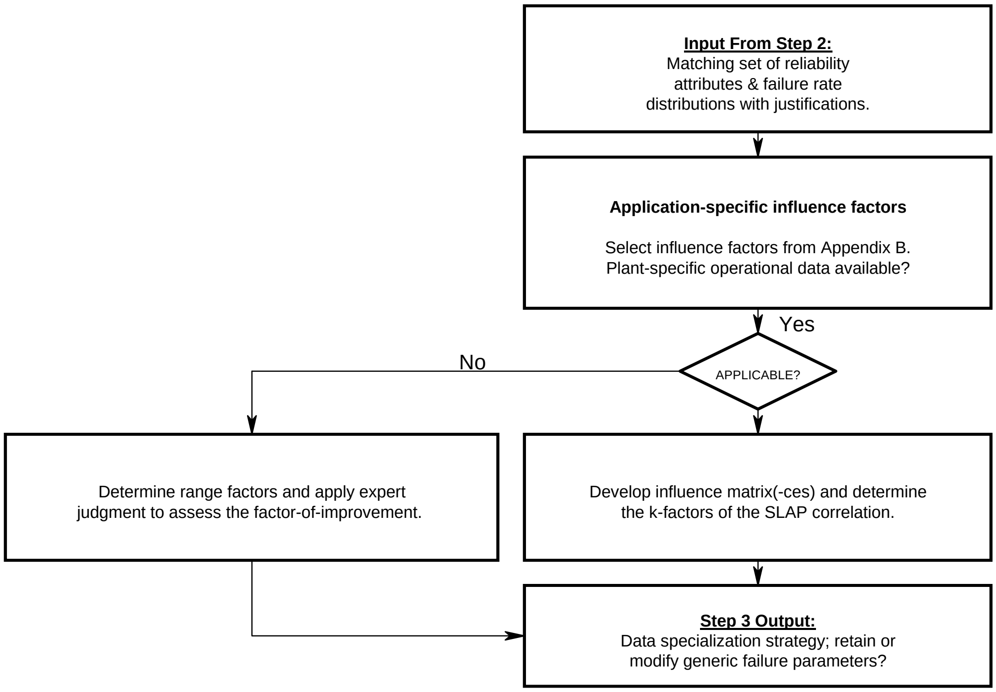


Figure 19. Step 3 of the 'PFCA' Guidelines - Evaluation of Influence Factors

Step 3 Analysis Inputs (*c.f.* Figure 19):
Application specific conditional pipe rupture probability)-ies). Reliability influence matrix(ces) that apply to the specific system(s); Appendix B.

Activity:
Performance of the 4 tasks of Step 3: Team effort, with input from PSA expertise, piping design engineers, structural engineers, and NDE/ISI expertise.

Rules:
Derived 'k-factors' should be consistent with observed ranges of variability. A 'k-factor' is a measure of how plant-specific service data differ from the industry-wide data.

Outputs:
A determination of how plant-specific service data differs from the industry-wide data, and (possibly) k-factor values.

The objective of Step 3 is to develop justifications of sufficient depth for modifying or not modifying the conditional rupture probability as developed in Step 2 of the framework. The output of Step 3 could include the 'k-factors' of the interim SLAP Reliability Correlation (*c.f.* Sections 4.4 and 4.5) for modifying an application-specific conditional rupture probability, including justifications. Equally plausible could be the decision not to pursue further data specialization. Four tasks are included by this step:

- Task 1. Review of an influence matrix (*c.f.* Section 4.4 and Appendix B) relevant to a specific attribute. The matrix represents a checklist that identifies typical degradation and failure mechanisms with their influence factors. A multi-discipline analysis team determines which of the given influences apply to the system under review, and to what extent the influence applies relative to the industry-wide service data.

- Task 2. Based on the root cause analysis approach, identify the causal and contributing factors and determine the remedial actions to prevent recurrence of a specific degradation or failure mechanism. The evaluation must go beyond the apparent cause of failure. Of particular interest is to note the effectiveness of remedial actions at other plants; e.g., effectiveness of HWC, the extent by which IGSCC has been reduced or eliminated by changing the piping material from, say, Type 304 stainless steel to Type 304 NG stainless steel.

- Task 3. Identify physics-of-failure concepts/models to verify the insights from historical data and failure analysis.

- Task 4. Determine the overall range of effect an influence factor could have on average piping reliability. Appendix B includes examples of the range of effect of different influences on different attributes. The raw data files in Appendix B supports the calculation of range factors that are not explicitly covered in this appendix.

The output consists of justifications for keeping or modifying a generic failure rate. Assuming that sufficient plant-specific experience exists, Step 3 could provide k-factors per the interim SLAP reliability correlation (Equation 4-12). The evaluation and review of influence factors should be augmented by piping system isometric drawings and system walkdowns. The isometric drawings include details on:

- Layout and geometry, including welds, flanges, valves, pumps;
- Instrument and test line connections, sample points including locations of stagnant process medium;
- Supports and hangers;
- Accessibility for NDE/ISI;
- Type and extent of piping insulation, heat tracing;
- Diameter, wall thickness, metallurgy;
- Process medium and flow direction;
- Method of fabrication, which includes identification of shop- and field fabricated piping and welds;
- Test and inspection points;
- Physical proximity of fixed equipment (i.e., pipe whip vulnerabilities).

An implementation of Step 3 reflects the outputs from Steps 1 and 2. As an example, evaluations of test and inspection points, and NDE/ISI, become more important in the context of dynamic PSA than for the static PSA. In the former case we need to acknowledge the testing and inspection intervals and practices, and how they could influence piping reliability. The effectiveness of NDE/ISI would also be a consideration.

5.2.4 Step 4: Definition of Piping System Component Boundary

At this stage we have defined the application requirements with the reliability attributes and influence factors. The objective of Step 4 (Figure 20) is to estimate the absolute pipe rupture frequency. Before estimating the pipe rupture frequency we must define the type of modeling to be considered; e.g., pipe rupture frequency per length of piping, per weld.

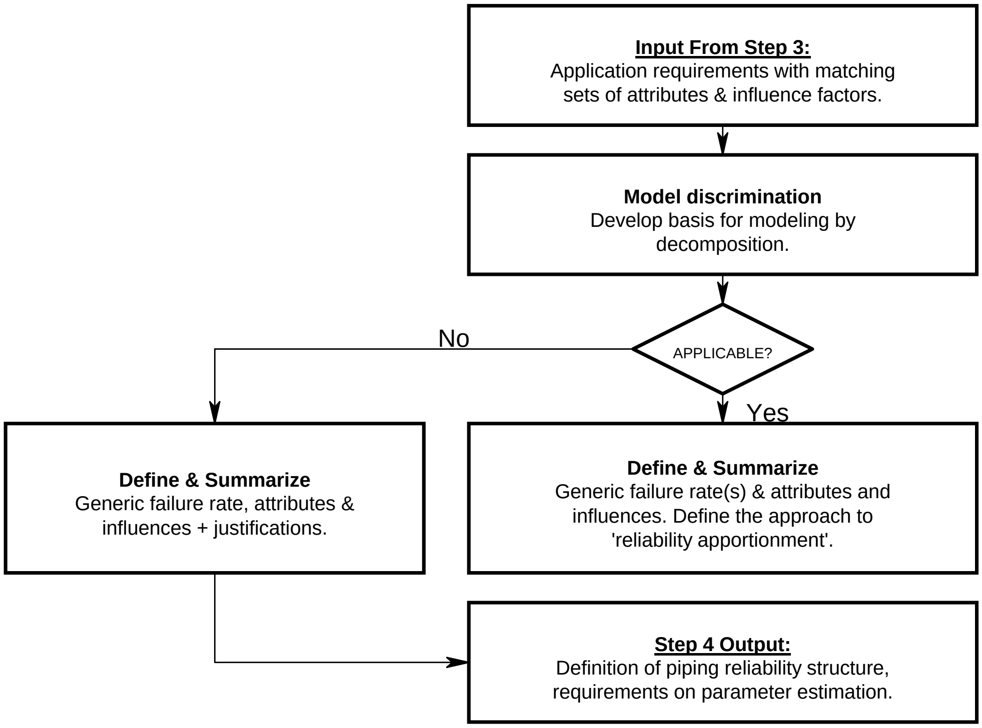


Figure 20. 'Step 4 of the PFCA' Framework - Estimation of Pipe Rupture Frequency

The purpose of a model determines its basic form and data needs. An engineering purpose could be to use the PSA as a basis for optimizing the system design and operation. In this form most attention is given to relative differences in reliability. A plant safety management purpose could be to use the PSA to monitor plant safety against some target value. The safety monitor approach could imply an interest in absolute rather than relative reliability. Typically, optimization requires a higher level of model discrimination than 'safety monitoring.' Step 4 essentially determines the completeness of the modeling that is necessary to meet the PSA application requirements.

Model discrimination is a function of the approach to establishing reliability models. Decomposition models are based on reliability methods such as the fault tree or the reliability block diagram, which includes the individual piping system components; e.g., bends, elbows, straight sections, tees and welds. Holistic models are established based on a proposed direct functional relationship between a quantitative measure of reliability performance and the variables affecting reliability. Holistic models of piping reliability consider an entire system rather than modeling of individual components.

Plant-specific operating experience could influence the modeling approach. Piping system component failures are location dependent, which means that leaks or ruptures occur in the weakest piping system component. A piping system model should reflect known or expected degradation and failure susceptibilities. Available operating experience points to the location dependency of failures. Examples include elbows or tees thinned to the point of failure due to erosion-corrosion mechanisms, or welds cracked by stress corrosion cracking or vibrational fatigue. A piping system model which is based on decomposition could be limited to the most vulnerable (i.e., most risk significant) piping system components. The objective of Step 4 includes ensuring that the piping reliability data are derived against an objective. Plant-specific experience could result in a decision to apply a mixed modeling approach; i.e., some piping systems are analyzed by decomposition while others are analyzed holistically.

A piping system boundary definition could be based on the global data to demonstrate the relative importance of environmental conditions such as water-in-steam, vibrations-by-poor-piping support, etc. There is a fine division between definitions of attribute and influence, however. Different data interpretations may lead to different insights or conclusions regarding what is considered an influence factor, a characteristic controlled through operational strategy, ISI, or chemistry). The component boundary definition determines the form of the piping failure rate estimators; e.g., failure per weld and hour of failure per piping section and hour.

In the decomposition approach, pipe sections as defined by isometric drawings are analyzed individually. Accurate piping component population counts is obtained via reviews of isometric drawings. Differentiated by their failure susceptibilities, failure frequencies are developed on a ‘per-section-basis.’ This means that different failure frequencies are derived for welds, fittings, bends, elbows, etc. The frequency of pipe failure is determined from:

$$f_{FAILURE} = (Number\ of\ failures) / (Time \times Extension) \tag{5-3}$$

where ‘Extension’ = Piping system component boundary; e.g., number of pipe segments, welds, elbows, or tees. Based on the attribute(s) defined in Step 1, population data on the piping system components must be derived from reviews of piping system design information.

Depending on the output from Step 1 of the PFCA Framework, different strategies could be applied to the definition of the numerators and denominators of Equation (5-3). Significant uncertainties are associated with the failure frequency estimates. The value of the numerator is a function of the coverage and completeness of service data. The denominator is a function of the completeness of design information. Some literature data on piping system component populations exist; *c.f.* Table 19 and Appendix B. There are considerable plant-to-plant differences in piping system designs; major differences between BWRs and PWRs, between external-pump and internal-pump BWRs, and major differences between the different reactor vendors. The development of realistic component counts could be *very* time consuming.

Table 19. Examples of Literature Data on Piping System Component Populations

Source	Type of Data	Comment
EPRI TR-100380 (1992) and EPRI TR-102266 (1993): Pipe Failures in U.S. Commercial Nuclear Power Plants	Pipe section counts for different systems or system combinations. A 'section' is defined as ".. a segment of piping, between major discontinuities such as valves, pumps, reducers, tees, etc. .." A pipe section typically contains between one or three elbows and four to eight welds. The information is differentiated by pipe diameter (three classes).	Proprietary report available to EPRI members only. According to this EPRI report, the reason for using the pipe section definition is that pipe section counts ".. can be readily counted on the P&IDs .." It is to be noted, that for some piping systems the P&IDs would not provide the level of detail needed for accurate pipe section counts - significant uncertainties could arise if a verification is not performed against isometric drawings.
NUREG/CR-4407 (1987): Pipe Break Frequency Estimation for Nuclear Power Plants.	Approximate number of welds and approximate length of piping for BWR and PWR systems. The information is differentiated by pipe diameter (two classes).	For reasons stated in Section 4, this type of information is of limited practical use. Piping reliability analysis must be performed on the basis of '*where-why-how*' a specific piping system fails. Pipe length is a weak measure of reliability.
PSA applications; Oskarshamn-1 (1995), Surry (1996) , Millstone-3 (1996, WCAP-14572), etc.	Detailed evaluations of individual piping systems; accurate counts of piping components with information on material, size, inspection histories.	The best sources of information. Note that the estimation of absolute rupture frequencies *must* include plant-specific assessments of piping component populations.

A problem with an estimator like Equation (5-3) is that it is largely controlled by the denominator. The uncertainty could be very large depending on how the denominator is defined. Not only is it difficult to develop realistic component counts, the definition of the exposure time also requires knowledge about plant operations and piping system design. In general, the exposure time is a function of the type of piping system and the dominant degradation mechanism. A few examples are given below:

- The exposure time is equal to the time between failure of a specific piping system component. Relative to active components, passive components such as piping are highly reliable. Therefore, the exposure time normally is equal to the age of the component 'socket' *if* the dominant degradation or failure mechanism can be attributed to corrosion, erosion/ corrosion or stress corrosion cracking.

- The mode of piping system operation determines the exposure time *if* the dominant degradation or failure mechanism can be attributed to vibrational fatigue. Usually the operating time of the vibration source (e.g., pump, compressor, fan) determines the exposure time. Reliable estimates are available via run time meters where available.

- The SLAP database tracks instances of piping system replacements as well as repeat failures. The estimation of exposure time should include adjustments that recognize replacements and time between repeat failures.

As for the estimation of the conditional pipe rupture probability in Step 2, the estimation of the numerator and denominator of Equation (5-3) must reflect a stated application. Detailed engineering evaluations of a piping system should always be considered in the parameter estimation process.

5.2.5 Step 5: Statistical Analysis & Uncertainty Analysis

There are many sources of uncertainties and the objective of Step 5 is to develop a qualitative discussion of these sources and how they could impact the results. The goal of uncertainty analysis is to qualify the conclusions made as a result of point estimate evaluations.

Given the sparseness of the piping failure data, the analyst is forced to merge the data from several plants together and to pool similar (but not identical) piping system components into generic classes. Engineering judgment is required to determine the applicability of data and to perform the aggregation of the different sources of data into generic groupings. Even in the case of the simplest type of data, true data in the sense of a set of measurements of the quantity in question (e.g., failure rate) does not exist. We have records of the number of components failing in a given span of years, and from this a failure rate is computed as the ratio of the number of failures over the exposure. The data are taken at different plants and on components in different systems having different operating environments, NDE/ISI-intervals and modes of operation.

Typically, the denomination is not known precisely and engineering judgment is used to determine reasonable average exposure times, demand histories, etc. Thus, in addition to a piping system component type's inherent variability in failure history due to randomness in, say, materials, we also have variability, which is due to data source differences:

- Plant-to-plant differences (type, age of plant, operating practices);

- In-plant differences (age of component, location in plant, mode of usage during routine plant operation, low power operation, or shutdown operation);
-
- Generic grouping;

- Mode of failure (*c.f.* discussion on failure modes in Section 3).

This type of variability is often termed *systematic* and becomes a source of uncertainty when data from several sources are applied to the analysis of a particular plant. In practice, one must use the existing data with its systematic variability and the question becomes:

- How to characterize the uncertainty to reflect the systematic variability;
- How to reconcile generic data from many sources with more limited plant-specific data (if available).

Some considerations in answering these questions have been addressed by Mosleh (1987)[5-7]. One resolution is to define a generic group (i.e., according to attribute) of components for which the times to failure are assumed to be fixed values. By plotting the cumulative distribution function against time an assessment is made of the plant-to-plant variability. When plant-specific data are available, the generic distributions can, in the Bayesian method, be modified, using it as a prior distribution, and utilizing the plant-specific data to specify the likelihood.

It may also be desirable to include other sources of variability in deriving a distribution. For example, the distribution may be chosen to reflect both plant-to-plant and system-to-system variability. This distribution should, however, be used to represent uncertainty in the failure characteristics of a piping system component only if there is no consistent system-to-system variability at all plants. If there is a significant consistent system-to-system variability, the piping components from different systems should not be grouped into the same population, but rather each system should be treated separately by constructing a plant-to-plant distribution for components of that system.

5.3 Guiding Principles

The proposed 'PFCA' framework evolved from reviews of service data on piping systems. It supports piping reliability analysis in the context of PSA applications. Although the framework supports direct estimation, alternative techniques to the estimation of the conditional rupture probability in Steps 1 and 2 should be considered. Probabilistic fracture mechanics (PFM) is an example of an alternative to direct estimation. Regardless of the chosen technical approach, PFCA is not a short-cut method to failure parameter estimation. In fact, whether direct estimation or PFM is used, the level of effort involved in parameter estimation could be considerable.

Based on the attribute and influence concepts, the service experience should be organized according to exposure and event fields (or 'bins'). Each record fits one unique exposure field, and each failure is the realization of one and only one degradation mechanism and one and only one failure mode. The pipe rupture frequency, f_R, associated with a particular attribute may be estimated from:

$$f_R = f_F \times p_{R|F} \tag{5-4}$$

Where $f_F = (2F + 1)/2T$ (5-5)

$p_{R|F} = (2R + 1)/(2F + 2)$ (5-6)

Index ‘R’ = rupture;
Index ‘F’ = failure, which could be a flaw/crack, leak or rupture (see below);
T = exposure time in reactor-years (i.e., the in-service time).

In Equation (5-4) the parameter estimation problem is separated into two steps. First, the occurrence rate of a ‘failure’, $f_{F,}$, resulting in a plant shutdown for repair or replacement is estimated from the service experience. Next, the conditional rupture probability given a failure, $p_{R\text{✉}F}$, is estimated. Equation (5-4) is useful for degradation mechanisms that progress from leakage to rupture if the leak is not detected and repaired. The estimates derived through Equations (5-5) and (5-6) are the *mean* values of aposteriori Γ- and β-distributions, respectively, using non-informative priors; *c.f.* Martz and Waller[5-8]. Some failure frequency and rupture frequency estimated by using the above set of equations and the service experience summarized in Section 3 and Appendix A are given in Table 20.

Table 20. Examples of Pipe Failure and Rupture Frequency Estimates

Degradation Mechanism	**Number of Failures**	**Number of Ruptures**	**Mean Failure Frequency [1/Reactor-Year]**	**Mean Conditional Rupture Probability**	**Mean Rupture Frequency [1/Reactor-Year]**
Boric Acid Corrosion (BAC)	19	0	4.1E-03	2.5E-02	1.0E-04
Corrosion (COR)	143	4	3.0E-02	3.2E-02	9.6E-04
Erosion-corrosion (E/C)	405	46	8.6E-02	1.1E-01	9.4E-03
Vibration-fatigue (VF)	618	57	1.3E-01	9.3E-02	1.2E-02
Thermal fatigue (TF)	84	4	1.8E-02	5.3E-02	9.5E-04
Stress corrosion cracking (SCC) - PWR environment	115	0	4.3E-02	4.3E-03	1.9E-04
Intergranular SCC (IGSCC) - BWR environment	230	0	1.6E-01	2.2E-03	3.6E-04
Transgranular SCC (TGSCC)	28	0	6.0E-03	1.7E-02	1.0E-04
TOTALS:	1642	111	3.5E-01	6.8E-02	2.4E-02

These tabulated values represent industry wide experience with piping subjected to respective degradation mechanism. Next the attribute of concern must be defined more precisely, and the dimension of exposure must also be determined. For PSA applications, an attribute could be <*diameter* - *type-of-system* - *process-medium*>. This leads to the necessity of organizing the service experience according to exposure fields by defining appropriate reliability attributes. Does it matter in what way the service data are disaggregated? The data dis-aggregation - and the establishment of raw data summaries, which reflect a specific attribute - should reflect a deep understanding of piping reliability, the service experience, and the role of the influence factors. Figure 21 shows comparison of conditional rupture probabilities for a selection of attributes. This comparison demonstrates the importance of defining strategies for dis-aggregation of service data. Equally important is the *qualification* of the service data. That is, the relevance of a particular service data aggregation to a specific application must be validated relative to application requirements.

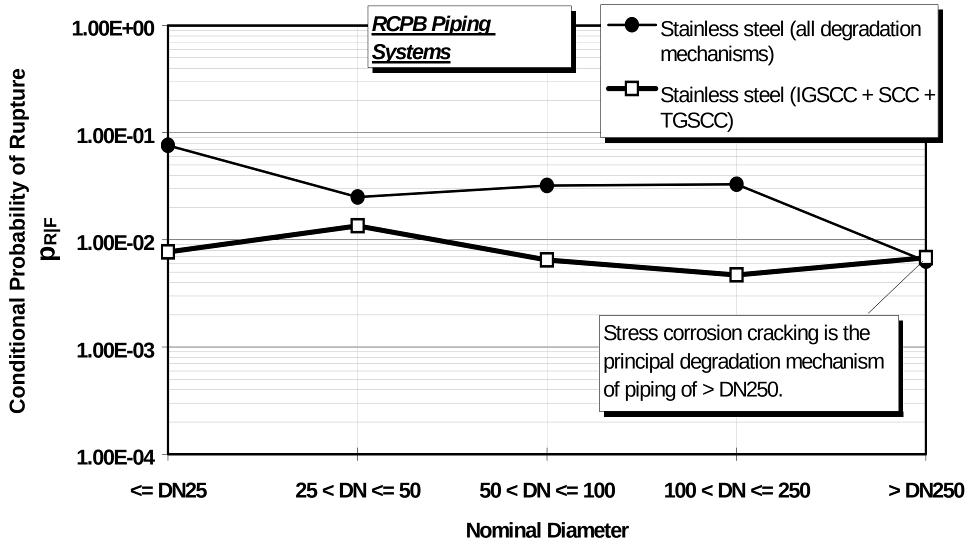


Figure 21. Conditional Rupture Probabilities for Different Attributes

Before inputting the parameter estimates in the PSA models, the proper failure parameter dimension must be applied. For piping system components the dimension of exposure is [*time* × *extension*]. Hence, the parameters given in Table 5-3 are incomplete estimates. The 'extension' cannot be universally defined, however. It is a function of the applicable reliability attributes and influence factors. For austenitic steels susceptible to IGSCC, the flaws/cracks or leaks develop in welds or weld-heat-affected zones (HAZ). Therefore, the 'extension' would be the number of welds/HAZ in the piping system(s) under consideration. The extent of erosion/corrosion (or flow-assisted corrosion) damage in ferritic steels is strongly influenced by flow velocity and geometry. Hence, for piping susceptible to erosion/corrosion (or flow-assisted corrosion) the 'extension' would be given by the number of elbows, tees, reducers and straight sections.

Assuming that the average number of welds in IGSCC-susceptible piping in an external-recirculation pump BWR is about 2000 per plant, the mean rupture frequency then becomes:

$$f_R = (f_F / 2000) \times p_{R|F} = (1.6 \cdot \text{E-01}/2000) \times 2.2\text{E-03} = 1.8\text{E-07} / \text{Weld. Reactor-yr}$$

The above parameter estimate is provided for illustrative purposes. It does not distinguish between IGSCC-susceptible piping of different diameter and different grades of austenitic stainless steels. Accurate piping component population counts should be extracted from design information (e.g., isometric drawings). At this stage the analysis should address the influence factors; e.g., water chemistry (normal water chemistry versus hydrogen water chemistry), welding method.

Step 4 of the PFCA framework addresses the estimation of application-specific pipe failure frequencies. That is, failure frequencies which relate to a specific degradation or failure mechanism. Pipe degradations and failures are location-dependent. As examples, in IGSCC-susceptible piping the cracking or leaks develop in welds and weld-HAZ, and in piping susceptible to erosion-corrosion the wall thinning, leak or ruptures develop in the base metal. Table 21 summarizes the failure frequency basis for some degradation and failure mechanisms.

Table 21. Some Pipe Failure Frequency Bases

Degradation / Failure Mechanism	Failure Frequency Basis	Comment
Corrosion (COR)	1/pipe-length.yr	
Boric acid corrosion cracking (B/A-CC)	1/# fittings.yr or 1/pipe-length.yr	B/A-CC could develop in base metal due to stagnant process medium. Therefore, the analysis should consider determination of the number of fittings, straight sections that contain stagnant process medium.
Erosion-corrosion (E/C)	1/# fittings.yr or 1/pipe-length.yr	E/C typically develops in base metal, and especially in elbows, tees
IGSCC / SCC	1/# welds.yr	
TGSCC	1/# welds.yr 1/# fittings.yr.	TGSCC could develop in the base metal; e.g., cold-bent pipe sections. Pipe sections with pipe collars (in pipe penetration areas) have been known to be susceptible to TGSCC
Thermal fatigue (TF)	1/# welds.yr	In PWRs, TF has occurred in FWS welds
Vibrational fatigue (VF) Water hammer (WH)	1/pipe-length.yr	

5.4 Discussion

A verification of the different analysis steps in the proposed analysis framework requires more extensive ‘numerical experimentation.’ Selection of reliability attributes and pipe failure frequencies, respectively, is critical to plant-specific applications. Data interpretations and data reductions should recognize the requirements of an intended application. Typically, operational data for small-diameter sample lines, drain lines, test lines do not apply to process piping, or vice versa.

Consistency in applications must be ensured through critical reviews of the operational data being considered. Equally important, any generic data included with the Framework must be qualified, and justifications or caveats clearly stated. The effects on parameter estimation by different data pooling strategies should be explored.

The service experience highlights the complex nature of piping reliability management. Despite the lessons from past incidents, new incidents occur with similar ‘failure signatures’ as events which occurred in the 1970s or 1980s. Anticipated applications of the ‘PFCA’ Framework include estimation of LOCA frequency and internal flooding initiating event frequency. Old experience data should not be dismissed simply because they are ‘old,’ however. The analysis framework encourages critical evaluations and applications of the *entire* database as long as statistical uncertainties are considered. The current database includes information on failures in LOCA-sensitive piping of ‘industrial grade’ (IG) and ‘nuclear grade’ (NG) stainless steels. The evaluation of IGSCC data is difficult. The quality of construction, installation, operations and inservice inspection together with the unique features of a given piping system design (e.g., number of welds, overall layout and accessibility) tend to be as important than an attribute such as material. Against this background, a rigorous application of the ‘PFCA’ Framework should be very useful in determining the relative merits of different piping system design solutions.

5.5 References

(5-1). Nyman, R. et al, 1996. *Reliability of Piping System Components. Volume 2: PSA LOCA Database - Review of Methods for LOCA Evaluation Since the WASH-1400,* SKI Report 95:59, Swedish Nuclear Power Inspectorate, Stockholm (Sweden).

(5-2). Nyman, R. et al, 1996. *Reliability of Piping System Components. Volume 1: Piping Reliability - A Resource Document for PSA Applications,* SKI Report 95:58, Swedish Nuclear Power Inspectorate, Stockholm (Sweden).

(5-3) Simola, K. And K. Koski, 1997. *A Survey of Probabilistic Methods for Evaluation of Structural Component Reliability,* TAU-7007/97, VTT Automation, Technical Research Centre of Finland, Espoo (Finland).

(5-4). Bush, S.H. and A.D. Chockie, 1996. *Failure Frequencies and Probabilities Applicable to BWR and PWR* Piping, SKI Report 96:39, Swedish Nuclear Power Inspectorate, Stockholm (Sweden).

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(5-7) Mosleh, A., 1986. “Hidden Sources of Uncertainty: Judgment in Collection and Analysis of Failure Data,” *Nuclear Engineering and Design*, **93**:187-198.

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6

SUMMARY & RECOMMENDATIONS

The R&D project by the Swedish Nuclear Power Inspectorate (SKI) was initiated in 1994 to establish a systematic approach to piping reliability analysis. This R&D emphasized two difficult areas in piping reliability analysis: 1) the coverage and completeness of the reporting of piping failures; and 2) parameter estimation in the absence of data on the 'sample size' of piping systems in NPPs. Results of SKI's R&D include a large database on piping failures in NPPs worldwide, and an analysis framework for interpreting failure data and estimating failure parameters. Further work is needed to fully exploit and explore the operational data, however. Similarly, pilot applications of the analysis framework should be pursued to develop a streamlined analysis procedure.

6.1 Overview of the Technical Approach

Central to the R&D was the development of an event-based, relational database on piping failures. Insights and results from exploring the operational data were used to develop a framework for estimating plant-specific failure parameters. There are major sources of uncertainties in the reliability parameter estimation. Therefore, the *ultimate objective of the analysis framework was to establish a structured approach to data qualification*.

An important aspect of data qualification consists of understanding the database content, including its coverage and completeness. Section 3 summarized technical and plant safety management considerations affecting the development of a database on pipe failure events. The reporting of pipe failures varies immensely from detailed root cause analysis reports, which address the conditional factors of failure, to brief summary reports, which require further interpretation and analysis.

The assessment of reliability of piping system components is difficult. Reasons for this difficulty include the inconsistent reporting of failures, and the lack of population data (e.g., sample size). The inconsistent reporting reflects the complex nature of piping reliability. Quality data on the sample size (measured in number of components times an appropriate time-unit) is lacking in a considerable way. Therefore, the R&D emphasized the value of analyzing the conditional factors of reliability. The effects of reliability attributes and influence factors must be evaluated before representative, absolute reliability parameter estimates can be produced.

The coverage and completeness of data are important to the development of a database on piping failures. For the SLAP database, numerous primary and secondary information sources were utilized to ensure reasonable coverage and completeness within the scope of the project. Spot-checks were performed to verify and validate the data nominated for entry into the database. Estimation of data parameters *is* feasible assuming that the database collection approach is clearly stated and that the data coverage is verified.

In addition to meeting the needs of PSA applications, there are many potential benefits of enhanced reporting practices. The content of the SLAP database points to the recurrence of piping failures. The recurrences could be symptoms of insufficient feedback of operating experience, but they also are symptoms of the complex nature of the degradation and failure mechanisms. In the opinion of the authors of this report, a cost-effective approach to piping reliability management is achieved through improved reporting of degradation and failures.

Realistic parameter estimation based exclusively on fault counts and exposure times is not feasible. Parameter estimation should be based on the thorough understanding of the *why-where-how* of piping failures. In Section 4 the conditional factors of piping reliability were defined in terms of attributes and influence factors. An attribute relates to piping system design features as addressed by codes and standards and functional requirements. An influence factor relates to the operating environment once a system has been commissioned. An analysis format building on these conditional factors provides the framework for deriving plant-specific piping reliability parameters.

The selection of a statistical analysis approach must reflect intended application(s). In Section 4 we used Bayesian statistics to infer *some* insights about reliability attributes. It must be understood that in the context of PSA the Bayesian approach works quite well for the purpose of deriving point estimates with consideration of uncertainties. A drawback of this approach is that it is insensitive to changes in the service data. That is, the approach is not very useful for performing trend analysis or other reliability-oriented applications. At this stage of the R&D there is no need for more advanced Bayesian statistics, however. The techniques and tools of classical statistics should be exploited when performing detailed evaluations of the service data. Piping reliability is a complex topic.

Section 4 outlined important analysis considerations, which were included in the analysis framework in Section 5. This framework constitutes the minimum analytical requirements to be considered by modern PSA. The framework defined five analysis steps. In this report the requirements for 'base-line' evaluations were presented. More comprehensive evaluations would have to be done on the basis of detailed service data collections like SLAP.

6.2 Recommendations for Further Work

Many operating nuclear power plants are undergoing renovation and modernization as part of the plant life extension projects. In some cases, the renovation activities are directed at improving the primary system piping reliability by incorporating detailed considerations of the current state-of-knowledge about degradation and failure mechanisms and structural reliability. Increasingly, PSA applications are performed (or are being considered) to evaluate the effects the modified primary system piping designs could have on plant risk. Also, PSA applications are performed to support the definition of enhanced strategies for in-service inspection (ISI) objectives or targets and with these applications follow unique parameter estimation considerations.

SKI's R&D project is one step in the development of a comprehensive database on the operating experience with piping systems. Further work is required to improve the database coverage and completeness. The R&D also demonstrated a simple approach to parameter estimation, and developed a framework for qualifying these parameter estimates. The project team strongly recommends that future efforts to improve the database and the statistical analysis should be pursued within the international cooperative nuclear safety research programs. Examples of areas to pursue further include:

(1) Pilot applications of the PFCA Framework. Improvements to the proposed analysis framework should be pursued through pilot applications in two phases: 1) limited-scope applications within the framework of current Swedish regulatory research, or Nordic research; and 2) broader scope applications within international cooperative research programs (e.g.; risk-based ISI).

(2) Detailed statistical analysis of the service data using techniques from design of experiments (DOE). Special consideration should be directed at the influence factors.

(3) Development of piping system component population data. While a time-consuming task, tabulations of population data for different plant design generations and plant systems would enable more streamlined parameter estimation.

APPENDIX A

SOURCES OF DATA ON PIPING FAILURES

Developed mainly from public domain data sources, SLAP is an event-based, relational data collection on piping failures in commercial nuclear power plants, worldwide. The primary data sources for developing the current version of the database included Swedish and U.S. licensee event reporting (LER) systems and the NEA/IAEA Incident Reporting System (IRS). Proprietary data on piping failures plus several secondary data sources enabled consideration of the completeness and coverage of the SLAP database. Summarized in this appendix are examples of data search strategies for the database development.

A.1 Data Search Strategies

No *dedicated* reporting system exists for piping failures. Therefore, failure rates based on operational data must be derived from counts of piping failures together with information on the conditional factors of failures as addressed by existing multi-purpose reporting and data management systems; *c.f.* Figure A-1. There is no one way of extracting relevant failure information from the public domain sources. The information that makes its way from plant work order requests, inspection reports, significant event reports, trip reports, etc. into central repositories for operational data is filtered according to different criteria.

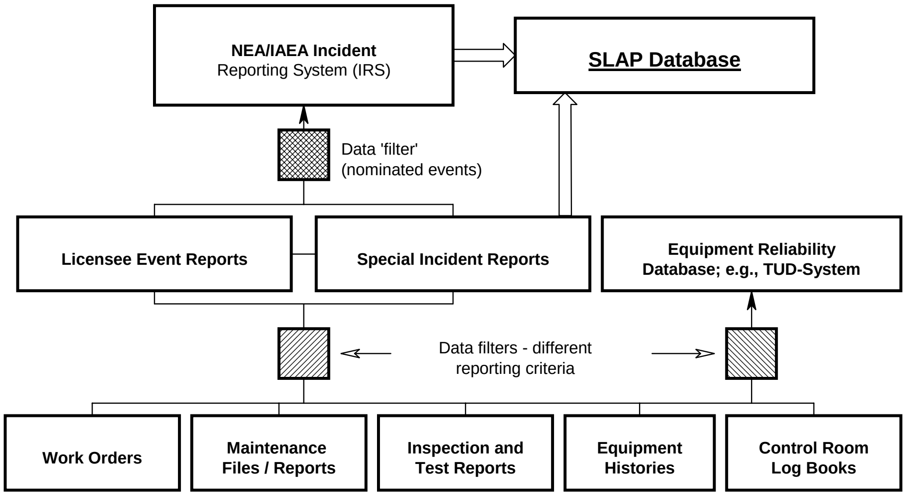

Figure A-1: The Sources of Piping Failure Information

The LER systems cover events deemed significant enough to require notification based on actual or implied safety impact. Technical specification limits for primary system leakage constitute examples of criteria for licensee event reporting. Equipment reliability data management systems, like the Swedish TUD-System[A-1] and the EPIX System in the U.S, include events that have been selected on the basis of functional definitions of failure. While there are overlaps between different national systems, there also are omissions and errors in recorded data. In deriving information on piping failures, a fundamental question relates to the completeness and coverage of the selected information sources. No individual information source provides full data coverage. The information sources identified in Figure A-1 are multipurpose reporting systems. Events that appear in LER systems may or may not appear in equipment reliability databases, and vice versa.

LER systems include significant reactor coolant pressure boundary leaks (RCPB), which occur during routine power operation; e.g., leak rates > 0.1 kg/s[A-2]. The reporting of RCPB leaks is a function of the detectability of leaks, and when and how leaks are detected. Should an RCPB leak be discovered during a plant outage and after removal of piping insulation, that information on degradation or failure may become embedded in outage inspection reports. Some piping failures are under-reported; e.g., piping failures in balance-of-plant (BOP) systems. Inconsistent reporting requirements and failure definitions for piping degradation and failures influence the reporting. While an objective assessment of database coverage and completeness is difficult or impossible, relative measures of coverage and completeness result from comparative, iterative, overlapping and complementary data search strategies.

As an example of a comparative search, for events in U.S. plants the primary data source was the LER abstracts[A-3] combined with full-text LERs requested via the U.S. NRC Public Document Room (PDR) and Preliminary Notifications of Unusual Occurrences or Events (PNOs). Key words for these three information resources were ‘pipe failure’, ‘leak’, ‘severance’, ‘rupture’ and ‘crack indication.’ Next, the Nuclear Power Experience (NPE) was searched manually using ‘piping’ as keyword for finding failures in BWR and PWR plant systems. A new, consolidated master data file resulted from comparisons of the results from the two data searches.

In addition to the U.S. LERs, piping failure event summaries appear in Information Bulletins and Information Notices (*c.f.*, Table A-1) issued by NRC’s Office of Nuclear Reactor Regulation (NRR), Special Study Reports (e.g., AEOD/E308[A-4], AEOD/E4 16[A-5] and AEOD/S902[A-6]) prepared by NRC’s Office for Analysis and Evaluation of Operational Data (AEOD), Power Reactor Events[A-7] by AEOD, and other special study reports published in the NUREG or NUREG/CR series (e.g., NUREG-0531[A-8], NUREG-0679[A-9], NUREG-0691[A-10], NUREG/CR-2781[A-11], NUREG/CR-5156[A-12]). Iterative surveys and searches of the four groups of NRC information sources verified the relative coverage of the initial comparative searches.

Examples of overlapping information sources include NRC’s monthly NUREG-0020 series[A-13] and IAEA’s annual Operating Experience With Nuclear Power Stations in Member States. The former includes monthly summaries of operating data (e.g., load reductions, manual and automatic reactor and turbine trips, equipment failures). Similarly, the IAEA-source includes operating data for plants worldwide. For U.S. plants, selected data from NUREG-0020 are entered into the IAEA data collection.

Table A-1. Selected U.S. NRC Information Notices / Bulletins on Piping Degradation & Failures (Sheet 1-of-3)

U.S. NRC INFORMATION NOTICE / BULLETIN NO.	DOCUMENT TITLE	SLAP Event IDs / NOTE(s)
74-10 (September 18, 1974)	Failures in 4-Inch Bypass Piping at Dresden-2	1736, 1758
75-01 (January 31, 1975)	Through-Wall Cracks in Core Spray Piping at Dresden-2	623, 2794
76-04 (March 30, 1976)	Cracks in Cold Worked Piping at BWRs	560, 566, 1342, 2061
76-06 (November 22, 1976)	Stress Corrosion Cracks in Stagnant, Low Pressure Stainless Piping Containing Boric Acid Solution at PWRs	1218, 1518
79-03 (March 12, 1979)	Longitudinal Weld Defects in ASME SA-312, Type 304 Stainless Steel	Generic communication
79-13 (June 25, 1979)	Cracking in Feedwater System Piping	466, 2123, 2795
79-19 (July 17, 1979)	Pipe Cracks in Stagnant Borated Water Systems at PWR Plants	Generic communication
81-04 (February 27, 1981)	Cracking in Main Steam Lines	Surry-1 (<20% TWC)
82-02 (June 2, 1982)	Degradation of Threaded Fasteners in the Reactor Coolant Pressure Boundary of PWR Plants	Generic communication
82-03 (October 14, 1982)	Stress Corrosion Cracking in Thick-Wall, Large-Diameter, Stainless Steel, Recirculation System Piping at BWR Plants	437
82-09 (March 31, 1982)	Cracking in Piping of Makeup Coolant Lines at B&W Plants	551, 2739
82-17 (June 11, 1982)	Overpressurization of Reactor Coolant System	Generic communication
82-22 (July 9, 1982)	Failures in Turbine Exhaust Lines	500
82-39 (September 21, 1982)	Service Degradation of Thick Wall Stainless Steel Recirculation System Piping at a BWR Plant	437
83-02 (March 4, 1983)	Stress Corrosion Cracking in Large-Diameter Stainless Steel Recirculation System Piping at BWR Plants	437
84-18 (March 7, 1984)	Stress Corrosion Cracking in Pressurized Water Reactors	2113
84-41 (June 1, 1984)	IGSCC in BWR Plants	2401
85-34 (April 30, 1985	Heat Tracing Contributes to Corrosion Failure of Stainless Steel Piping	1707
85-76 (September 19, 1985)	Recent Water Hammer Events	Generic communication
85-99 (December 31, 1985)	Cracking in Boiling-Water-Reactor Mark I and Mark II Containments Caused by Failure of the Inerting System	610
86-106 (December 16, 1986)	Feedwater Line Break	595

Table A-1. Selected U.S. NRC Information Notices / Bulletins on Piping Degradation & Failures (Sheet 2-of-3)

U.S. NRC INFORMATION NOTICE / BULLETIN NO.	DOCUMENT TITLE	SLAP Event IDs / NOTE(s)
86-108 (December 29, 1986	Degradation of Reactor Coolant System Pressure Boundary Resulting from Boric Acid Corrosion	949
87-36 (August 4, 1987)	Significant Unexpected Erosion of Feedwater Lines	Generic communication
88-01 (January 27, 1988)	Safety Injection Pipe Failure	616
88-08 (June 22, 1988)	Thermal Stresses in Piping Connected to Reactor Coolant Systems	14, 616
88-09 (July 26, 1988)	Thimble Tube Thinning in Westinghouse Reactors	Generic communication
88-11 (December 20, 1988)	Pressurizer Surge Line Thermal Stratification	Generic communication re. pipe movement
88-17 (April 22, 1988)	Summary of Responses to NRC Bulletin 87-01. Thinning of Pipe Walls in Nuclear Power Plants✍ (a)	595, 2410
89-07 (January 25, 1989)	Failures of Small-Diameter Tubing in Control Air, Fuel Oil, and Lube Oil Systems Which Render Emergency Diesel Generators Inoperable	405, 426, 972, 2315, 2819, 2820
89-53 (June 13, 1989)	Rupture of Extraction Steam Line on High Pressure Turbine	445
91-05 (January 30, 1991)	Intergranular Stress Corrosion Cracking in Pressurized Water Reactor Safety Injection Accumulator Nozzles	1734, 2116
91-38 (June 13, 1991)	Thermal Stratification in Feedwater System Piping	Beaver Valley-1; global stratification(b)
91-18 (March 12, 1991)	High-Energy Piping Failures Caused by Wall Thinning	498, 534
92-15 (February 24, 1992)	Failure of Primary System Compression Fitting	1373
92-35 (May 6, 1992)	Higher Than Predicted Erosion/Corrosion in Unisolable Reactor Coolant Pressure Boundary Piping Inside Containment at a Boiling Water Reactor	614
93-20 (March 24, 1993)	Thermal Fatigue Cracking of Feedwater Piping to Steam Generators	470, 615
94-38 (May 27, 1994)	Results of a Special NRC Inspection at Dresden Nuclear Power Station Unit 1 Following a Rupture of Service Water Inside Containment	Freeze damage to system in decommissioned unit.

Notes: (a). This Information Notice reports 34 events involving pipe wall thinning in feedwater-condensate systems during the period June 1967 - June 1986.
(b). No failure reported. Global stratification over a long stretch of horizontal feedwater system piping inside containment.

Table A-1. Selected U.S. NRC Information Notices / Bulletins on Piping Degradation & Failures (Sheet 3-of-3)

U.S. NRC INFORMATION NOTICE / BULLETIN NO.	DOCUMENT TITLE	SLAP Event IDs / NOTE(s)
95-11 (February 24, 1995)	Failure of Condensate Piping Because of Erosion/Corrosion at a Flow-Straightening Device	863
97-19 (April 18, 1997)	Safety Injection System Weld Flaw at Sequoyah Nuclear Power Plant, Unit 2	1226
97-46 (July 9, 1997)	Unisolable Crack in High-Pressure Injection Piping	2781

Examples of complementary information sources include the U.S. LER-system and the Institute of Nuclear Power Operations (INPO) Nuclear Network, which includes event-based summaries of operating experience (e.g., Significant Operating Experience Reports - SOERs). For SLAP, a search in Nuclear Network for piping failures was facilitated by Kärnkraftsäkerhet och Utbildning AB (KSU)[A-14,15]. This search yielded failure events for which no LERs existed.

A.2 Coverage and Completeness Issues

Throughout the SLAP database development, diverse information sources were used to verify the coverage, accuracy and completeness of data. In many cases at least two data sources were utilized to substantiate the accuracy and completeness of failure information, and in some cases up to five sources were used. The difficulty in assessing the coverage and completeness of piping failure data is compounded by factors such as:

- Some failures of the non-catastrophic kind are not reported at all. No forced plant shutdown; repairs are done with turbine-generator connected to grid.

- Isolateable failures in BOP-systems which do not impose safety hazards or affect plant operations negatively are repaired without delays. Beyond work order requests, and depending on the exact circumstances of the failures, formal written input may or may not be submitted to a LER system or equipment reliability database.

- Despite the regulatory reporting requirements, there exists discretionary reporting of incipient or degraded failures. Beyond specific requirements defined in plant-specific technical specifications, the exact circumstances and implications of a given failure ultimately determine the reporting.

- Many piping failures are revealed during refueling or maintenance outages, and the results of NDE/ISI may only be included in outage inspection reports.

- Licensee event report formats do not include data fields or key words specific to degradation and failure mechanisms affecting piping systems. As a consequence, computerized data searches may not identify flaws/cracks, leaks or ruptures involving piping systems.

In designing the SLAP database structure, the coverage and completeness were accounted for by including the following three basic types of database fields; *c.f.* SKI (1995)[A-16]:

(1) *Reliability Attribute Field*. Using a set of key words, each failure report was classified according to reliability attributes. In the context of piping reliability, an attribute represents the inherent reliability as determined and realized by applying recognized design codes and standards. This means that the inherent reliability cannot be changed without changing the original design; e.g., increasing the diameter and wall thickness, changing the metallurgy throughout the system from high carbon content stainless steel to low carbon content stainless steel, etc. Information entered into a reliability attribute field is used to facilitate data reduction and data analysis. Examples of attributes include metallurgy, diameter/wall thickness (piping schedule), geometry.

(2) *Reliability Influence Field*. An influence addresses the operating environment and how it affects (or could affect) the as-designed and installed piping system. Reliability management is directed at the influence factors and reliability improvement/growth can be accomplished through changes to the operating environment. Information entered into a reliability influence field is used to facilitate data reduction and analysis. Examples of reliability influences include water chemistry, steam quality, method of fabrication and installation, NDE/ISI.

(3) *Background Information Field*. The information in this field supports the identification and classification of attributes and influences. Some failure reports include explicit information on attributes and influences. In most cases, the attributes and influences are extracted or inferred from the background information, which mostly is in the form of event narratives and descriptions of corrective actions. The narrative describes the conditions prior to, at the time of, and immediately after failure, together with details on the plant response and the affected systems.

A.3 Piping System Component Exposures

Cumulative worldwide operating experience from nuclear power plants at the end of 1997 is well over 9,000 reactor-years. Based on data reported to the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS), a total of 442 nuclear power plants were operating around the world in 1997. The SLAP database currently includes service data from 274 plants representing approximately 4,700 reactor-years of operating experience. In the past, efforts to develop rupture frequencies from service data mostly have used the number of reactor years as a basis for estimating an exposure time.

An estimation of piping system exposure times solely based on reactor-years of operating experience would include a large uncertainty, however. For reasons stated above and in Section 3, the coverage and completeness of the data collection strongly influences the estimation of exposure times. Furthermore, the analysis steps of the PFCA Framework should assist in determining how an exposure time is assessed; Table A-2.

Table A-2. Examples of Piping System Exposure Times

Plant System / Degradation Mechanism	Piping System Exposure Time
Small-diameter piping / tubing susceptible to vibratory fatigue	Controlled by run-time of vibration source. As an example, instrument lines on emergency diesel generators have been known to fail during 24-hour endurance runs
Intermediate- and large-diameter steam extraction piping	Age of component socket, or better operating time of plant.
Primary system piping susceptible to stress corrosion cracking	Age of component socket or number of plant transients. Consider an evaluation of time- and demand-related failures

A.4 References & Notes

(A-1) Nyman, R. et al, 1995. *The T-Book Seminar 1995-01-27 in Stockholm,* SKI/RA-01/95, Swedish Nuclear Power Inspectorate, Stockholm (Sweden).

(A-2) Technical specification governing a facility operation requires that certain leak detection systems be functioning during operation and impose limits on the amount of leakage that may be permitted. When these conditions cannot be met, timely remedial measures are required. The exact limits vary depending on presence of IGSCC-susceptible piping materials. As an example, for older plants not designed to meet LBB criteria, plant shutdown should be initiated for inspection and corrective action when the leak detection system indicated, within a period of four hours or less, an increase in the rate of unidentified leakage in excess of 0.13 kg/s (2 gpm), or when the total unidentified leakage attains a rate of 0.32 kg/s (5 gpm), whichever occurs first.

(A-3) U.S. Nuclear Regulatory Commission. *Licensee Event Report (LER) Compilation*, NUREG/CR-2000, Washington (DC) [Monthly summaries of LER abstracts].

(A-4) Brown, E.J., 1983. *Engineering Evaluation Report on Cracks and Leaks in Small Diameter Piping*, AEOD/E308, Office for Analysis and Evaluation of Operational Data, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-5) Brown, E.J., 1984. *Erosion in Nuclear Power Plants*, AEOD/E4 16, Office for Analysis and Evaluation of Operational Data, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-6) Su, N.T., 1990. *Review of Thermal Stratification Operating Experience*, AEOD/S902, Office for Analysis and Evaluation of Operational Data, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-7) “Power Reactor Events” used to be a bimonthly newsletter that compiles operating experience information about commercial nuclear power plants. This includes summaries of noteworthy events and listings and/or abstracts of U.S. NRC and other documents that discuss safety-related or possible generic issues.

(A-8) Pipe Crack Study Group, 1979. *Investigation and Evaluation of Stress-Corrosion Cracking in Piping of Light Water Reactor Plants*, NUREG-0531, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-9) Frank, L. et al, 1980. *Pipe Cracking Experience in Light-Water Reactors*, NUREG-0679, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-10) PWR Pipe Crack Study Group, 1980. *Investigation and Evaluation of Cracking Incidents in Piping in Pressurized Water Reactors*, NUREG-0691, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-11) Uffer, R.A. et al, 1982. *Evaluation of Water Hammer Events in Light Water Reactor Plants*, NUREG/CR-2781, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-12) Cragnolino, G., C. Czajkowski and W.J. Shack, 1988. *Review of Erosion Corrosion in Single Phase Flows*, NUREG/CR-5136, U.S. Nuclear Regulatory Commission, Washington (DC).

(A-13) U.S. Nuclear Regulatory Commission. *Licensed Operating Reactors Status Summary Report*, NUREG-0020, Washington (DC) (Published monthy).

(A-14) Svensson, P., 1994. *Survey of NUCLEAR NETWORK for Failures in Nuclear Power Plant Piping Systems*, KSU-S 171, Kärnkraftsäkerhet och Utbildning AB, Studsvik (Sweden).

(A-15) KSU is the utility owned Nuclear Training and Safety Center in Sweden. The Swedish utilities are members of INPO via KSU. Regarding NUCLEAR NETWORK, the INPO SEE-IN Program Information less than 5 years old is proprietary to the INPO member organizations.

(A-16) Swedish Nuclear Power Inspectorate, 1996. *Reliability of Piping System Components. Volume 4: The Pipe Failure Event Database*, SKI Report 95:61, Stockholm (Sweden).

APPENDIX B

RAW DATA SUMMARIES: PIPING SYSTEM OPERATING EXPERIENCE IN NPPs WORLDWIDE

This appendix includes a summary of the SLAP database content as of October 1997. The database content is organized in five groups by nominal diameter (DN):

- $\leq$ DN25 ($\leq$ NPS1)
- $25 < DN \leq 50$ ($1 < NPS \leq 2$)
- $50 < DN \leq 100$ ($2 < NPS \leq 4$)
- $100 < DN \leq 250$ ($4 < NPS \leq 10$)
- $>$ DN250 ($>$ NPS10)

For each pipe size group, the experience data are summarized in three (3) tables addressing the effect and influence of different degradation and failure mechanisms, material and process media. The following broad groups of piping systems are addressed in the raw data summaries:

- Balance of Plant (BOP); e.g., main steam, feedwater, condensate and moisture separator reheat systems, steam extraction lines (mainly non-Code class systems). The systems in this group tend to be included in augmented inspection programs for flow accelerated corrosion (FAC; see Appendix C)

- Fire Protection System (FPS). Increasingly, this system is subject to volumetric inspection programs (e.g., ultrasonic testing).

- LOCA Sensitive Piping (LSP); the piping systems that contain the reactor coolant (ASME Code Class 1 piping). In the data summaries below, the 'RCPB' category also includes the ASME Code Class 2 piping systems located inside containment; i.e., piping systems connected to the reactor coolant system. The systems in this group are subject to ASME Section XI (or equivalent) ISI programs.

- Auxiliary Cooling Water Systems (AUXC); this group includes Code Class 3 and non-Code Class service water systems (raw water systems).

A given system can belong to more than one group, however. As noted in Sections 3 through 5 of this report, the grouping (i.e., pooling of data) should reflect a stated application. The data summaries in this appendix represent the SLAP database content as of October 1997 (SLAP Version 7.7).[19] Each database application includes unique data processing requirements. Note that the tabulations in this appendix excludes failures involving closed-loop cooling piping (e.g., Component Cooling Water System, Spent Fuel Pool Cooling Water System), and instrument air piping.

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[19] In this 3rd Edition of SKI 97:26, for the period 1972-1997 all tabulations have been updated with information from the current (12-31-2004), proprietary version of the database. In each table, the updated information is included in parentheses. Figure B-1 is a summary of the evolution of the PIPExp database.

Table B.1-1. Summary of Failures in ≤DN25 Piping

System Category	Failure Mode		
	Crack	Leak	Rupture
Balance of Plant	3 (24)	156 (220)	29 (16)
Fire Protection System	0 (0)	6 (11)	1 (2)
LOCA Sensitive Piping	13 (41)	500 (627)	21 (28)
Auxiliary Cooling Water Systems	0 (3)	98 (134)	2 (6)
Totals:	16 (68)	760 (992)	53 (52)

Table B.1-2. Summary of Failures in Piping of 25 < DN ≤50

System Group	Failure Mode		
	Crack	Leak	Rupture
Balance of Plant	2 (4)	64 (77)	14 (16)
Fire Protection System	0 (0)	9 (5)	4 (2)
LOCA Sensitive Piping	20 (65)	124 (163)	5 (4)
Auxiliary Cooling Water Systems	1 (1)	34 (88)	1 (0)
Totals:	23 (70)	231 (333)	24 (22)

Table B.1-3. Summary of Failures in Piping of 50 < DN ≤100

System Group	Failure Mode		
	Crack	Leak	Rupture
Balance of Plant	4 (9)	59 (67)	15 (12)
Fire Protection System	0 (0)	4 (8)	2 (1)
LOCA Sensitive Piping	23 (182)	101 (117)	4 (4)
Auxiliary Cooling Water Systems	2 (6)	62 (92)	1 (0)
Totals:	29 (197)	226 (284)	22 (17)

Table B.1-4. Summary of Failures in [100 < DN ≤250] Piping

System Group	Failure Mode		
	Crack	Leak	Rupture
Balance of Plant	12 (32)	101 (116)	32 (37)
Fire Protection System	0 (2)	8 (26)	3 (3)
LOCA Sensitive Piping	70 (344)	146 (130)	3 (3)
Auxiliary Cooling Water Systems	1 (19)	34 (77)	2 (1)
Totals:	83 (397)	289 (349)	40 (44)

Table B.1-5. Summary of Failures in Piping of DN > 250

System Group	Failure Mode		
	Crack	Leak	Rupture
Balance of Plant	34 (61)	63 (59)	29 (25)
Fire Protection System	0 (0)	0 (6)	3 (9)
LOCA Sensitive Piping	106 (600)	44 (82)	0 (0)
Auxiliary Cooling Water Systems	0 (16)	23 (85)	2 (0)
Totals:	140 (677)	130 (232)	34 (34)

Table B.2-1. Event Count by Calendar Year (≤DN25 Piping)

Failure Mode	**Calendar Year**													
(DB Version)	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**Σ**
Crack (as of 12-31-1997)	0	0	0	0	0	0	0	5	1	0	1	1	1	9
(as of 12-31-2004)	(0)	(0)	(0)	(0)	(0)	()	(2)	(6)	(2)	(0)	(4)	(4)	(3)	(21)
Leak (as of 12-31-1997)	3	16	32	53	45	40	37	36	30	48	63	54	27	484
(12-31-2004)	(2)	(10)	(21)	(38)	(46)	(40)	(42)	(52)	(50)	(55)	(73)	(60)	(32	(521)
Rupture (as of 12-31-1997)	2	0	2	3	3	3	0	2	3	1	1	2	1	23
(as of 12-31-2004)	(1)	(0)	(3)	(3)	(4)	(3)	(2)	(2)	(2)	(1)	(1)	(2)	(2)	(26)

Failure Mode	**Calendar Year**													
(DB Version)	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**Σ**
Crack (as of 12-31-1997)	0	0	1	0	0	3	0	0	4	0	0	0	0	8
(as of 12-31-2004)	(2)	(2)	(6)	(7)	(3)	(5)	(3)	(4)	(5)	(2)	(3)	(5)	(0)	(47)
Leak (as of 12-31-1997))	15	16	32	22	24	27	30	19	28	20	20	12	16	281
(as of 12-31-2004)	(33)	(27)	(52)	(42)	(30)	(45)	(40)	(32)	(41)	(23)	(37)	(31)	(32)	(465)
Rupture (as of 12-31-1997)	1	3	4	4	3	1	4	1	0	0	7	1	2	31
(as of 12-31-2004)	(3)	(8)	(6)	(7)	(2)	(2)	(3)	(2)	(0)	(0)	(7)	(5)	(3)	(49)

Table B.2-2. Event Count by Calendar Year (25 < DN ≤50 Piping)

Failure Mode	**Calendar Year**													
(DB Version)	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**Σ**
Crack (as of 12-31-1997)	0	0	1	1	0	2	0	1	0	3	1	2	1	12
(as of 12-31-2004)	(0)	(0)	(1)	(1)	(1)	(2)	(0)	(1)	(0)	(6)	(2)	(3)	(3)	(20)
Leak (as of 12-31-1997)	2	4	15	6	14	10	10	9	11	14	19	23	11	148
(12-31-2004)	(1)	(4)	(8)	(5)	(16)	(7)	(10)	(20)	(11)	(13)	(21)	(20)	(8)	(144)
Rupture (as of 12-31-1997)	0	1	1	0	0	1	1	0	2	0	0	2	2	11
(as of 12-31-2004)	(0)	(0)	(0)	(0)	(0)	(1)	(2)	(0)	(0)	(0)	(0)	(2)	(1)	(6)

Failure Mode	**Calendar Year**													
(DB Version)	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**Σ**
Crack (as of 12-31-1997)	0	0	0	0	0	0	0	0	4	2	4	0	1	11
(as of 12-31-2004)	(7)	(0)	(0)	(21)	(2)	(0)	(0)	(0)	(4)	(2)	(5)	(3)	(6)	(50)
Leak (as of 12-31-1997))	7	4	6	10	6	9	10	10	2	5	7	3	5	84
(as of 12-31-2004)	(6)	(5)	(5)	(13)	(11)	(14)	(18)	(16)	(20)	(14)	(42)	(9)	(16)	(189)
Rupture (as of 12-31-1997)	3	0	1	0	0	1	1	2	3	1	1	1	0	14
(as of 12-31-2004)	(2)	(0)	(2)	(0)	(0)	(0)	(1)	(1)	(4)	(1)	(2)	(2)	(0)	(15)

Table B.2-3. Event Count by Calendar Year (50 < DN ≤100 Piping)

Failure Mode (DB Version)	Calendar Year													
	1972	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**Σ**
Crack (as of 12-31-1997)	0	0	0	2	4	2	43	1	1	0	1	1	10	17
(as of 12-31-2004)	(0)	(0)	(3)	(3)	(4)	(2)	(12)	(1)	(5)	(0)	(8)	(14)	(6)	(58)
Leak (as of 12-31-1997)	3	1	22	17	6	6	10	15	9	13	11	12	9	134
(12-31-2004)	(2)	(0)	(12)	(15)	(7)	(5)	(11)	(16)	(10)	(11)	(10)	(13)	(13)	(125)
Rupture (as of 12-31-1997)	3	1	0	1	2	1	0	0	0	1	0	1	1	11
(as of 12-31-2004)	(3)	(1)	(0)	(1)	(1)	(1)	(0)	(0)	(0)	(1)	(0)	(1)	(0)	(9)

Failure Mode (DB Version)	Calendar Year													
	1985	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**Σ**
Crack (as of 12-31-1997)	0	2	1	0	0	0	1	1	1	2	0	2	2	12
(as of 12-31-2004)	(0)	(65)	(4)	(1)	(1)	(2)	(3)	(6)	(33)	(10)	(2)	(7)	(5)	(139)
Leak (as of 12-31-1997)	6	7	10	7	3	15	10	9	2	9	5	5	3	91
(as of 12-31-2004)	(4)	(11)	(9)	(9)	(6)	(14)	(23)	(12)	(15)	(12)	(10)	(11)	(20)	(156)
Rupture (as of 12-31-1997)	0	0	3	1	0	2	1	1	1	2	0	0	0	11
(as of 12-31-2004)	(0)	(0)	(1)	(0)	(1)	(2)	(1)	(1)	(1)	(1)	(0)	(0)	(0)	(8)

Table B.2-4. Event Count by Calendar Year (100 < DN ≤250 Piping)

Failure Mode (DB Version)	Calendar Year													
	1972	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**Σ**
Crack (as of 12-31-1997)	0	0	0	1	1	2	2	5	2	0	5	7	7	32
(as of 12-31-2004)	(0)	(0)	(0)	(5)	(1)	(2)	(3)	(5)	(29)	(4)	(26)	(34)	(42)	(151)
Leak (as of 12-31-1997)	1	2	18	21	18	16	16	16	10	6	19	21	6	170
(as of 12-31-2004)	(0)	(0)	(8)	(18)	(18)	(10)	(16)	(14)	(14)	(6)	(19)	(22)	(10)	(155)
Rupture (as of 12-31-1997)	1	1	0	0	1	5	0	0	0	0	3	2	2	15
(as of 12-31-2004)	(1)	(1)	(0)	(0)	(1)	(3)	(0)	(0)	(1)	(0)	(4)	(3)	(1)	(15)

Failure Mode (DB Version)	Calendar Year													
	1985	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**Σ**
Crack (as of 12-31-1997)	1	6	2	0	3	2	3	0	3	1	6	17	7	51
(as of 12-31-2004)	(17)	(9)	(14)	(15)	(9)	(9)	(19)	(42)	(42)	(2)	(13)	(31)	(24)	(246)
Leak (as of 12-31-1997)	7	27	17	7	5	5	5	8	9	9	11	9	4	123
(as of 12-31-2004)	(3)	(26)	(19)	(12)	(9)	(13)	(18)	(10)	(16)	(9)	(20)	(23)	(15)	(178)
Rupture (as of 12-31-1997)	4	4	1	4	1	1	4	0	3	1	2	2	0	27
(as of 12-31-2004)	(4)	(4)	(2)	(3)	(1)	(2)	(4)	(1)	(3)	(1)	(2)	(1)	(0)	(28)

Table B.2-5. Event Count by Calendar Year (> DN250 Piping)

Failure Mode	Calendar Year													
(DB Version)	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	Σ
Crack (as of 12-31-1997)	0	0	0	0	2	1	0	6	6	0	13	43	5	76
(as of 12-31-2004)	(1)	(0)	(0)	(0)	(3)	(1)	(3)	(6)	(7)	(1)	(22)	(195)	(77)	(315)
Leak (as of 12-31-1997)	0	1	4	1	9	3	2	4	1	2	7	11	15	60
(12-31-2004)	(0)	(1)	(4)	(0)	(9)	(4)	(3)	(5)	(1)	(3)	(16)	(7)	(14)	(67)
Rupture (as of 12-31-1997)	2	1	1	0	0	0	0	0	1	2	4	2	3	16
(as of 12-31-2002)	(0)	(1)	(1)	(0)	(0)	(0)	(0)	(0)	(1)	(1)	(3)	(2)	(4)	(13)

Failure Mode	Calendar Year													
(DB Version)	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	Σ
Crack (as of 12-31-1997)	23	0	5	2	0	11	2	9	1	2	3	2	4	64
(as of 12-31-2004)	(67)	(47)	(25)	(12)	(12)	(41)	(28)	(19)	(5)	(5)	(19)	(14)	(67)	(361)
Leak (as of 12-31-1997)	9	8	9	1	7	9	7	8	4	4	2	0	2	70
(as of 12-31-2004)	(13)	(24)	(15)	(11)	(8)	(16)	(16)	(13)	(16)	(8)	(5)	(3)	(17)	(165)
Rupture (as of 12-31-1997)	2	2	2	0	4	1	2	0	1	0	0	1	1	16
(as of 12-31-2004)	(2)	(2)	(3)	(0)	(3)	(1)	(2)	(1)	(1)	(0)	(1)	(3)	(2)	(21)

Table B.3-1. Degradation and Failure Mechanisms in Piping ≤DN25

Degradation & Failure Mechanism	System Group	Failure Mode		
		Crack	Leak	Rupture
Corrosion / Erosion-Corrosion / Erosion-Cavitation	PCS	1 (1)	51 (66)	4 (4)
	Fire Protection	0 (0)	4 (6)	1 (0)
	LOCA Sensitive	0 (2)	21 (20)	0 (3)
	Aux. Cooling Water	0 (0)	48 (63)	0 (0)
Corrosion-Fatigue / Vibration-Fatigue	PCS	1 (14)	64 (116)	19 (26)
	Fire Protection	0 (0)	1 (3)	0 (0)
	LOCA Sensitive	5 (21)	284 (381)	11 (17)
	Aux. Cooling Water	0 (2)	31 (56)	2 (5)
IGSCC / SCC / TGSCC	PCS	0 (0)	3 (0)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	8 (13)	68 (98)	0 (0)
	Aux. Cooling Water	0 (2)	0 (0)	0 (0)
Human Error / Design & Construction Error	PCS	0 (0)	14 (20)	2 (8)
	Fire Protection	0 (0)	0 (2)	0 (1)
	LOCA Sensitive	0 (3)	88 (106)	4 (2)

Degradation & Failure Mechanism	**System Group**	**Failure Mode**		
		Crack	**Leak**	**Rupture**
	Aux. Cooling Water	0 (0)	12 (11)	0 (0)
Thermal Fatigue (Thermal Cycling / Stratification)	PCS	0 (0)	3 (5)	2 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	0 (0)	9 (9)	0 (0)
	Aux. Cooling Water	0 (0)	5 (3)	1 (2)
Other (includes ‘unreported’, overloading, water hammer)	PCS	1 (1)	21 (10)	2 (1)
	Fire Protection	0 (0)	1 (0)	0 (1)
	LOCA Sensitive	1 (2)	43 (13)	7 (6)
	Aux. Cooling Water	0 (0)	6 (4)	0 (1)

Table B.3-2. Degradation and Failure Mechanisms in Piping $25 < DN \leq 50$

Degradation & Failure Mechanisms	**System Group**	**Failure Mode**		
		Crack	**Leak**	**Rupture**
Corrosion / Erosion-Corrosion / Erosion-Cavitation	PCS	1 (2)	32 (45)	6 (5)
	Fire Protection	0 (0)	4 (3)	0 (0)
	LOCA Sensitive	0 (3)	7 (24)	1 (1)
	Aux. Cooling Water	1 (1)	26 (75)	0 (0)
Corrosion-Fatigue / Vibration-Fatigue	PCS	1 (2)	16 (21)	5 (5)
	Fire Protection	0 (0)	1 (1)	0 (0)
	LOCA Sensitive	1 (29)	57 (66)	2 (0)
	Aux. Cooling Water	0 (0)	2 (14)	0 (2)
IGSCC / SCC / TGSCC	PCS	0 (0)	0 (0)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	9 (15)	34 (36)	0 (0)
	Aux. Cooling Water	0 (5)	0 (0)	0 (0)
Human Error / Design & Construction Error	PCS	0 (0)	6 (8)	1 (2)
	Fire Protection	0 (0)	2 (1)	2 (2)
	LOCA Sensitive	0 (6)	16 (24)	1 (1)
	Aux. Cooling Water	0 (0)	2 (3)	0 (0)
Thermal Fatigue	PCS	0 (0)	4 (4)	0 (1)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	6 (4)	6 (8)	1 (0)
	Aux. Cooling Water	0 (0)	0 (3)	0 (2)
Other (includes ‘unreported’, overloading, water hammer)	PCS	0 (0)	5 (2)	2 (3)
	Fire Protection	0 (0)	2 (0)	2 (2)
	LOCA Sensitive	4 (6)	5 (5)	1 (2)
	Aux. Cooling Water	0 (0)	4 (6)	1 (0)

Table B.3-3. Degradation and Failure Mechanisms in Piping 50 < DN ≤ 100.

Degradation & Failure Mechanisms	**System Group**	**Failure Mode**		
		Crack	**Leak**	**Rupture**
Corrosion / Erosion-Corrosion / Erosion-Cavitation	PCS	2 (4)	27 (35)	7 (5)
	Fire Protection	0 (0)	3 (6)	0 (0)
	LOCA Sensitive	2 (12)	6 (5)	1 (1)
	Aux. Cooling Water	1 (4)	45 (81)	0 (0)
Corrosion-Fatigue / Vibration-Fatigue	PCS	1 (2)	6 (13)	1 (1)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	1 (4)	18 (18)	1 (1)
	Aux. Cooling Water	1 (2)	3 (6)	0 (0)
IGSCC / SCC / TGSCC	PCS	0 (0)	0 (0)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	18 (160)	55 (63)	0 (0)
	Aux. Cooling Water	0 (1)	0 (0)	0 (0)
Human Error / Design & Construction Error	PCS	0 (0)	7 (5)	2 (1)
	Fire Protection	0 (0)	0 (2)	2 (1)
	LOCA Sensitive	0 (4)	11 (13)	1 (1)
	Aux. Cooling Water	0 (0)	8 (4)	0 (0)
Thermal Fatigue	PCS	0 (2)	0 (13)	0 (1)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	2 (7)	5 (11)	0 (0)
	Aux. Cooling Water	0 (0)	1 (0)	0 (0)
Other (includes 'unreported', overloading, water hammer)	PCS	1 (2)	16 (10)	5 (5)
	Fire Protection	0 (0)	1 (0)	0 (0)
	LOCA Sensitive	0 (1)	8 (7)	1 (1)
	Aux. Cooling Water	0 (0)	5 (1)	1 (0)

Table B.3-4. Degradation and Failure Mechanisms in Piping 100 < DN ≤ 250

Degradation & Failure Mechanisms	**System Group**	**Failure Mode**		
		Crack	**Leak**	**Rupture**
Corrosion / Erosion-Corrosion / Erosion-Cavitation	PCS	3 (17)	68 (85)	22 (28)
	Fire Protection	0 (2)	0 (19)	1 (1)
	LOCA Sensitive	0 (0)	0 (0)	0 (0)
	Aux. Cooling Water	0 (16)	26 (70)	1 (0)
Corrosion-Fatigue / Vibration-Fatigue	PCS	0 (0)	17 (17)	1 (2)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	1 (2)	22 (18)	1 (0)
	Aux. Cooling Water	0 (1)	1 (0)	0 (0)
IGSCC / SCC / TGSCC	PCS	0 (1)	0 (0)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	60 (302)	74 (69)	0 (0)
	Aux. Cooling Water	0 (10)	0 (11)	0 (0)
Human Error / Design & Construction Error	PCS	0 (0)	6 (7)	1 (1)
	Fire Protection	0 (0)	0 (5)	1 (1)
	LOCA Sensitive	0 (10)	19 (19)	0 (0)
	Aux. Cooling Water	1 (1)	1 (5)	0 (0)
Thermal Fatigue	PCS	5 (8)	0 (0)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	8 (18)	11 (10)	0 (1)
	Aux. Cooling Water	0 (0)	1 (0)	0 (0)
Other (includes 'unreported', overloading, water hammer)	PCS	3 (3)	9 (6)	8 (6)
	Fire Protection	0 (0)	3 (2)	2 (1)
	LOCA Sensitive	1 (1)	13 (4)	1 (2)
	Aux. Cooling Water	0 (0)	4 (2)	3 (1)

Table B.3-5. Degradation and Failure Mechanisms in Piping DN > 250.

Degradation & Failure Mechanisms	Affected Systems	Failure Mode		
	System Group	Crack	Leak	Rupture
Corrosion / Erosion-Corrosion / Erosion-Cavitation	PCS	8 (41)	26 (31)	12 (13)
	Fire Protection	0 (0)	0 (5)	1 (2)
	LOCA Sensitive	0 (22)	0 (1)	0 (0)
	Aux. Cooling Water	0 (15)	20 (80)	0 (0)
Corrosion-Fatigue / Vibration-Fatigue	PCS	0 (1)	5 (6)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (1)
	LOCA Sensitive	1 (2)	3 (8)	0 (0)
	Aux. Cooling Water	0 (0)	0 (1)	0 (0)
IGSCC / SCC / TGSCC	PCS	0 (0)	0 (0)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	35 (535)	38 (61)	0 (0)
	Aux. Cooling Water	0 (0)	0 (0)	0 (0)
Human Error / Design & Construction Error	PCS	2 (3)	6 (6)	4 (4)
	Fire Protection	0 (0)	0 (1)	2 (4)
	LOCA Sensitive	4 (18)	1 (6)	0 (0)
	Aux. Cooling Water	0 (0)	1 (2)	2 (0)
Thermal Fatigue	PCS	16 (7)	8 (4)	0 (0)
	Fire Protection	0 (0)	0 (0)	0 (0)
	LOCA Sensitive	3 (19)	0 (3)	0 (0)
	Aux. Cooling Water	0 (0)	5 (0)	1 (0)
Other (includes ‘unreported’, overloading, water hammer)	PCS	5 (9)	14 (14)	13 (11)
	Fire Protection	0 (0)	0 (0)	2 (2)
	LOCA Sensitive	3 (4)	2 (2)	1 (0)
	Aux. Cooling Water	0 (1)	6 (3)	3 (0)

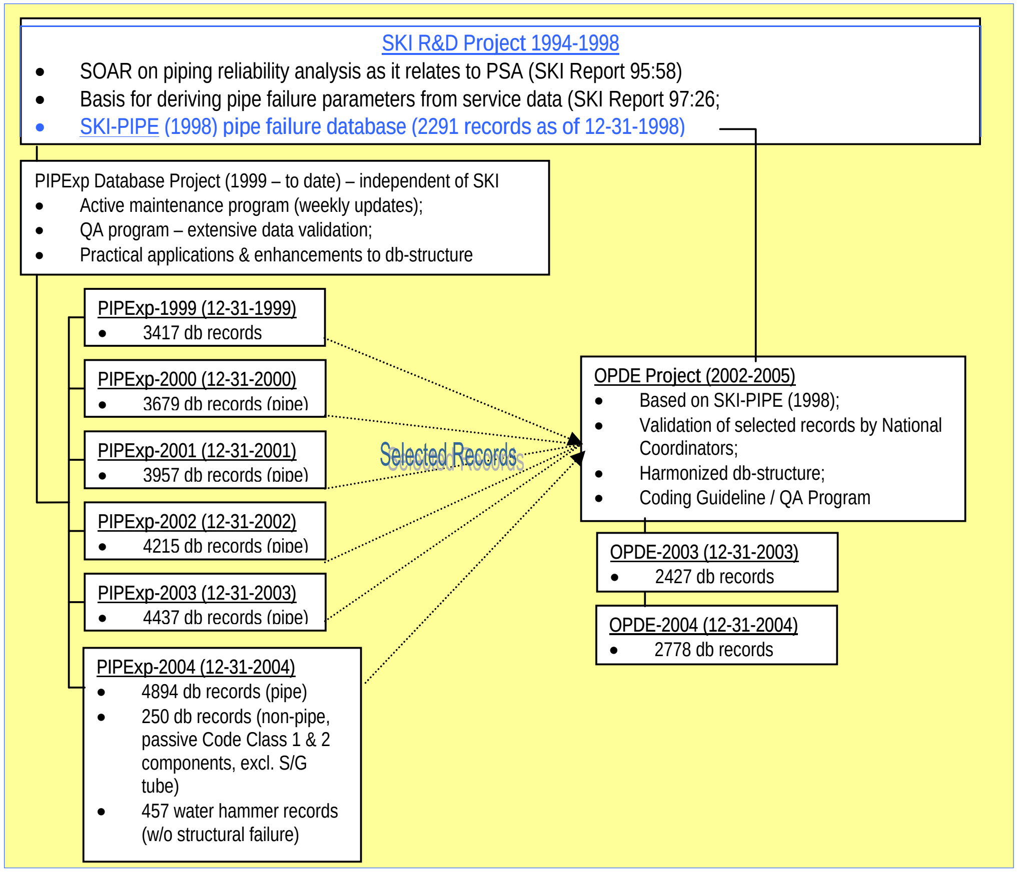

Figure B-1. Evolution of the PIPExp Database

Table B-4. Piping Component Population Data (From NUREG/CR-4407[20]

NPP Type	System	Approximate Length of Piping [m]	Approximate Number of Welds
PWR	RCS	750	970
	HPSI (50 ≤ DN < 150)	320	559
	HPSI (> DN150)	110	(a)
	LPSI (50 ≤ DN < 150)	52	122
	LPSI (> DN150)	510	468
	RHRS (50 ≤ DN < 150)	52	122
	RHRS (> DN150)	510	468
	CVCS (50 ≤ DN < 150)	950	928
	CVCS (> DN150)	30	19
	Main Steam	1800	2177
	AFWS (50 ≤ DN < 150)	160	159
	AFWS (> DN150)	30	48
	MFWS	1770	1900
	Condensate	2160	1500
	CCWS (50 ≤ DN < 150)	260	504
	CCWS (>DN150)	945	1155
	ESWS (50 ≤ DN < 150)	328	1719
	ESWS (> DN150)	1183	710
GE-BWR	RCS (50 ≤ DN < 150)	6	96
	RCS (> DN150)	(a)	173
	HPCI (50 ≤ DN < 150)	120	101
	HPCI (> DN150)	750	401
	RCIC (50 ≤ DN < 150)	85	49
	RCIC (> DN150)	118	160
	Core Spray (50 ≤ DN < 150)	22	51
	Core Spray (> DN150)	178	205
	RHRS (50 ≤ DN < 150)	393	215
	RHRS (> DN150)	411	360
	SLCS	18	39
	Main Steam	420	214
	MFWS (50 ≤ DN < 150)	309	51
	MFWS (> DN150)	226	276
	Condensate (50 ≤ DN < 150)	182	175
	Condensate (> DN150)	307	433
	RBCCWS (50 ≤ DN < 150)	609	608
	RBCCWS (> DN150)	255	515

(a). Where no distinction is made between (50 ≤ DN < 150) and (> DN150) piping, one number represents the average total length of piping or the average total number of welds in a system.

Note: The piping component population differs between plants. For a give type of system the population count could differ by as much as an order of magnitude for.

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[20] Wright, R.E., J.A. Steverson and W.F. Zuroff, 1987. *Pipe Break Frequency Estimation for Nuclear Power Plants*, Appendix B, EGG-2421 (NUREG/CR-4407), EG&G Idaho, Inc., Idaho Falls (ID), pp B-7-11

APPENDIX C

ABBREVIATIONS, ACRONYMS & GLOSSARY

C.1 Abbreviations & Acronyms - Engineering Terms

AUXC	Auxiliary Cooling Water System
BA/CC	Corrosion Cracking in Stagnant Borated Water
BBL	Break-Before Leak
BOP	Balance of Plant
C/F	Corrosion-Fatigue
CRC	Corrosion Resistant Cladding
CVCS	Chemical and Volume Control System
DEGB	Double-Ended Guillotine Break
DN	Nominal Diameter [mm]
E/C	Erosion/Corrosion
EPIX	Equipment Performance and Information Exchange System (database operated by INPO)
ERF	Event Reporting Form (IAEA)
FPS	Fire Protection System
FW	Field weld
FWS	Feedwater System
HAZ	Heat-Affected Zone
HIC	Hydrogen Induced Cracking
HSCC	Hydrogen Stress Corrosion Cracking
HWC	Hydrogen Water Chemistry
IGSCC	Intergranular stress corrosion cracking
IHSI	Induction Heating Stress Improvement
ISI	In-service Inspection
LBB	Leak-Before-Break
LER	Licensee Event Report
LOCA	Loss of Coolant Accident
LWGR	Light Water Cooled and Graphite Moderated Reactor
MR	Median Rank
MSIP	Mechanical Stress Improvement Process
MS/R	Moisture Separator / Reheater
NDE	Non-Destructive Examination
NPS	Nominal Pipe Size [inch]
NSSS	Nuclear Steam Supply System
NWC	Neutral/Normal Water Chemistry
PCS	Power Conversion System
PFM	Probabilistic Fracture Mechanics
PNO	Preliminary Notification of Event or Unusual Occurrence
POS	Plant Operational State
PT	Penetrant Testing
PTS	Pressurized Thermal Shock
RCPB	Reactor Coolant Pressure Boundary
RCS	Reactor Coolant System
RT	Radiographic Test
SCC	Stress Corrosion Cracking
SICC	Strain Rate-Induced Corrosion Cracking

SLAP	SKI's LOCA Affected Piping Database
SN	Schedule Number
SS	Stainless Steel
SSCC	Sulfide Stress Corrosion Cracking
SW	Shop weld
TC	Thermal Cracking
TEM	Thomas Elemental Model
TF/TS	Thermal Fatigue by Thermal Stratification
TGSCC	Transgranular Stress Corrosion Cracking
TWC	Through-Wall Crack
TWD	Through-Wall Defect
UT	Ultrasonic Test
WD	Weld Defect
WH	Water Hammer
WOR	Weld Overlay Repair

C.2 Abbreviations & Acronyms - Organizations

ANSI	American National Standardization Institute
ASME	American Society of Mechanical Engineers
CSNI	Committee on the Safety of Nuclear Installations
EPRI	Electric Power Research Institute
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
IAEA	International Atomic Energy Agency
INES	International Nuclear Event Scale (IAEA)
INPO	Institute of Nuclear Power Operations
KSU	Kärnkraftsäkerhet och Utbildning AB
NEA-IRS	(OECD) Nuclear Energy Agency - Incident Reporting System
OECD	Organization for Economic Cooperation and Development
SKI	Statens Kärnkraftinspektion
U.S.NRC	United States Nuclear Regulatory Commission

C.3 Glossary

Abrasion (or Particle Erosion): Erosion process due to flowing gases or vapors containing solid particles.

Aging: Degradation of a component resulting in the loss of function or reduced performance caused by some time-dependent agent or mechanism. The agent or mechanism can be cyclic (e.g., caused by repeated demand) or continuously acting (e.g., caused by the operational environment). The change in the component failure probability resulting from the degradation will be monotonically increasing with the time of exposure to the agent or mechanism unless the component is refurbished, repaired, or replaced. In reliability statistics, aging is represented by that part of the "bathtub curve" where the failure rate changes from being approximately constant to increasing.

Balance of Plant: The turbine-generator portion of a nuclear power plant with the associated piping and controls.

Break-Before-Leak: Used to describe the ratio of ruptures to total number of events involving ruptures and leaks. Various, experience-based correlations exist for determining this ratio.

Complete Failure: A failure that causes termination of one or more fundamental functions. If the failure is sudden and terminal it is also referred to as 'catastrophic.' The complete failure requires immediate corrective action to return the item to satisfactory condition. The effect of the complete failure on the unit can be a reduction in the feed rate or unit shutdown.

Database Coverage: Percentage of reportable/known failure events that reside in a database.

Degraded Failure: A failure that is gradual or partial. If left unattended (no immediate corrective action) it can lead to a complete failure.

Direct DEGB: Complete pipe break ("double-ended guillotine break", DEGB) induced by fatigue crack growth resulting from the combined effects of thermal, pressure, seismic, and other cyclic loads.

Disruptive Failure: A breaching of the piping by failure of the wall or weld, accompanied by a rapid release of a large volume of the contained pressurized fluid.

Droplet Impingement Erosion (or Liquid Impact Erosion): Erosion process due to flowing vapors and gases containing liquid inclusions.

Erosion-Cavitation (E-C):[21] Occurs downstream of a directional change or in the presence of an eddy. Evidence could be seen by round pits and is often misdiagnosed as FAC (see below). Like erosion, E-C involves fluids accelerating over the surface of a material; however, unlike erosion, the actual fluid is not doing the damage. Rather, cavitation results

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[21] Definition is courtesy of Vogt Power International, Inc. (2004).

from small bubbles in a liquid striking a surface. Such bubbles form when the pressure of a fluid drops below the vapor pressure, the pressure at which a liquid becomes a gas. When these bubbles strike the surface, they collapse, or implode. Although a single bubble imploding does not carry much force, over time, the small damage caused by each bubble accumulates. The repeated impact of these implosions results in the formation of pits. Also, like erosion, the presence of chemical corrosion enhances the damage and rate of material removal. E-C has been observed in PWR decay heat removal and charging systems.

Erosion/Corrosion (E/C): Degradation caused by both mechanical and chemical processes. A form of materials degradation that affects carbon-steel piping systems carrying water (single-phase) or wet steam (two-phase) in both BWRs and PWRs. E/C-damage due to single-phase flow conditions usually manifest as uniform wall thinning similar to that caused by general corrosion. E/C-damage due to two-phase flow is less uniform and often has the appearance of "tiger-striping". Piping systems susceptible to E/C-damage include feedwater, condensate, extraction steam, turbine exhaust, feedwater heater, heater and moisture separator reheater vents and drains. There has been no documented evidence of E/C in dry steam lines (e.g., Code Class 1 BWR main steam lines).

Fabrication: The term applies to the cutting, bending, forming, and welding of individual pipe components to each other and their subsequent heat treatment and nondestructive examination (NDE) to form a unit (piping subassembly) for installation.

Flow Accelerated (or Assisted) Corrosion (FAC). EPRI defines FAC as “a process whereby the normally protective oxide layer on carbon or low-alloy steel dissolves into a stream of flowing water or water-steam mixture.” It can occur in single phase and in two phase regions. According to EPRI, the cause of FAC is a specific set of water chemistry conditions (e.g., pH, level of dissolved oxygen), and absent a mechanical contribution to the dissolution of the normally protective iron oxide (magnetite) layer on the inside pipe wall.

Hazard Analysis: Structured identification of physical conditions (or chemicals) that has the potential for causing damage to people, property, or the environment. Hazard analysis techniques include ‘hazard-and-operability study’ (HAZOP), what-if analysis, failure mode and effects analysis (FMEA), etc.

Hazard Plotting: Data plots used for display and interpretation of data; often used to analyze field and life test data on mechanical equipment (including heavy industrial equipment). The probability and data scales on a hazard paper are exactly the same as those on the corresponding probability paper. The cumulative hazard scale is an aid for plotting the data. The ‘hazard value’ for each failure is calculated from the reverse rank. The cumulative hazard values have no physical meaning and may exceed 100%. For details on the hazard plotting technique, see W. Nelson (1983): *How to Analyze Reliability Data*, Vol. 6, ASQC Quality Press, Milwaukee (WI), ISBN 0-87389-018-3.

High Energy Piping System: Any system, or portion of system, where the maximum operating pressure exceeds 1.9 MPa (275 psig), or the maximum operating temperature exceeds 93 C (200 F), during normal plant operating conditions. Those piping systems that operate above these limits for only a relatively short portion (less than approximately 2 percent) of the period of time to perform their intended functions, may be classified as moderate energy. An example of such a system could be the residual heat removal systems in some plant designs.

[*Reference: ANSI/ANS-58.2-1980*]

Incipient Failure: An imperfection in the state or condition of equipment such that a degraded or complete failure can be expected to result if corrective action is not taken in time.

Indirect DEGB: Complete pipe break (double-ended guillotine break) resulting from seismically-induced failure of NSSS supports.

Induction Heating Stress Improvement: Heat treatment process which is preventing stress corrosion cracking by reducing tensile residual stresses.

Installation: The term refers to the physical placement of piping subassemblies, valves, and other specialty items in their required final location relative to pumps, heat exchangers, turbines, tanks, vessels, and other equipment; assembly thereto by welding or mechanical methods; final NDE; heat treatment; leak testing; and cleaning and flushing of the completed installation.

Intergranular Stress Corrosion Cracking (IGSCC): A condition of brittle cracking along grain boundaries of austenitic stainless steel caused by a combination of high stresses and a corrosive environment. Primarily a problem in BWR environments. IGSCC has also been discovered (mid-1970's) in the PWR environment, especially in piping containing stagnant boric acid solutions.

Leak-Before-Break (LBB): Most nuclear high-energy piping is made of high-toughness material, which is resistant to unstable crack growth. This type of piping would leak a detectable amount well in advance of any crack growth that could result in a sudden catastrophic break.

LBB Screening: LBB methodology is not applied to systems in which excessive or unusual loads or cracking mechanisms can be present because these phenomena adversely affect the piping behavior. The excessive/unusual loads or cracking mechanisms of concern include IGSCC, erosion, creep, brittle fracture and fatigue.

LOCA Sensitive Piping (External LOCA, LSPE): Piping in which a break results in a loss of reactor coolant or steam. For a BWR it mainly consists of the part of the main feedwater system upstream of the outer isolation valves, the part of the main steam system upstream of the MSIVs, the piping of the intermediate component cooling water system, and some other auxiliary supporting systems. For a PWR, see topics described for BWR.

LOCA Sensitive Piping (Internal LOCA, LSPI): Piping in which a break results in a loss of reactor coolant. For a BWR it consists of the RCS, the part of the main feedwater system downstream of the isolation check valves, the part of the main steam system downstream of the MSIVs, the piping of the core cooling system, the piping of the containment spray system, and some other auxiliary supporting systems. For a PWR it consists of the primary coolant system excluding the steam generators.

Noncritical Piping Failure: A local degradation of the pressure boundary that is limited to localized cracking with or without minor leakage. Such a crack would not reach critical size and lead to disruptive piping failure.

Nondisruptive Failure: A condition of crack growth or flaw size that is corrected, and which if it had not been corrected, could have reached a critical size and led to disruptive failure.

Non-LOCA-Sensitive Piping (NLSP): Piping associated with systems that would be used to help mitigate a core damage sequence.

Pipe Rupture: Loss of pressure integrity of a pipe run in the form of a circumferential break, longitudinal break or through-wall crack.

[*Reference: ANSI/ANS-58.2-1980*]

Pipe Section (as defined by WASH-1400): A segment of piping between major discontinuities such as valves, pumps, reducers, etc. WASH-1400 indicated that, on average, a pipe section consists of 12 feet (3.6 m) of piping.

Pipe Section: A segment of piping between welds as indicated on isometric drawings. A pipe section can be either an elbow (e.g., 90° or 180°) or a straight, or a tee.

Pipe Whip: Uncontrolled motion of a ruptured pipe. Rupture of a pressurized piping system gives rise to a thrust as a reaction to the expulsion of the contained fluid. The thrust can generate rapid displacements of the broken pipe, a phenomenon termed ‘pipe whip.’

Piping schedule designation: The schedule number (SN) is defined as: SN = 1000 x P/SE, where P is operating pressure in lb/in^2 and SE is allowable stress range multiplied by joint efficiency in lb/in^2. Two examples are given:

(i) ND-1", Schedule 40 - wall thickness is 0.133 in.
ND-1", Schedule 80 - wall thickness is 0.179 in.
(ii) ND-4", Schedule 40 - wall thickness is 0.237 in.
ND-4", Schedule 80 - wall thickness is 0.337 in.

Some of the failure event reports give details of the Schedule number of affected piping. There have been instances where a pipe segment has failed simply because the initial design specifications were inappropriate by calling for, say, Schedule 40 instead of Schedule 80 piping - an example of design error.

Piping segment: Continuous length of piping with the same degradation mechanism and failure consequence.

[Reference: EPRI TR-106706./\’, June 1996]

Probabilistic Fracture Mechanics: A procedure for determining pipe failure (leak or break) probabilities, especially large-diameter piping in the RCS. The procedure incorporates deterministic (either empirical or analytic) models into a probabilistic "framework" that allows the results of deterministic growth calculations for literally thousands of individual cracks to be consolidated, along with the effects of other factors such as NDE intervals and earthquake occurrence rates, into a single convenient result. The PFM models only apply for anticipated degradation mechanisms; e.g., IGSCC with long time between crack initiation and leak.

Reactor Coolant Pressure Boundary: All pressure containing components of light water reactor nuclear power plants, such as pressure vessels, piping, pumps, and valves that are either:

(1) Part of the reactor coolant system (RCS); or
(2) Connected to the RCS up to and including any or all of the following:
  (a) the outermost primary containment isolation valve in system piping that penetrates the primary containment;
  (b) the second of two valves normally closed during normal reactor operation in system piping that does not penetrate primary containment; or
  (c) the RCS safety and relief valves.

For a direct cycle BWR, the RCS extends to and includes the outermost primary containment isolation valve in the main steam and feedwater piping.

[*Reference: ANSI/ANS-58.14-1993*]

Reliability Attribute: The inherent piping reliability established through application of recognized (e.g., nominated) piping system design principles and engineering standards. Factor(s) that is believed to have a significant impact on pipe reliability; e.g., combination of metallurgy and application, type of pipe section, exposure time, load cycles; *c.f.* 'reliability attribute.' The inherent reliability cannot be changed without making design modifications.

Reliability Influence Factor: The achieved reliability through controlled/manageable environmental impacts (i.e., influences) or NDE, ISI, etc.

Sensitization: Precipitation of carbides during welding. When austenitic stainless steels are heated in the range of about 425 C - 870 C, carbon in excess of about 0.02% will come out of solution and diffuse to the grain boundaries where it will combine with adjacent chromium to form chromium carbide ($Cr_{23}C_6$). These grain boundaries are then preferentially attacked by corrosive media.

Stabilization: To minimize the formation of carbides in austenitic stainless steels, niobium (Nb) or titanium (Ti) is added to the grain boundary area so that Nb- or Ti-carbides are formed. Purpose of stabilization is to minimize the susceptibility to sensitization.

Transgranular Stress Corrosion Cracking (TGSCC): A form of environment-assisted cracking (just as IGSCC); complex interaction of metallurgy, process medium and stresses. The resistance against corrosion that stainless steel has is depending on a passive oxide film that has low electron movement. Chlorides and sulfides travel into the film to create oxide chlorides/sulfides that result in high electron movement. Outside and inside diameter TGSCC have been observed.

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