SKI Report 95:61

Reliability of Piping System Components

Volume 4: The Pipe Failure Event Database

Ralph Nyman
Stig Erixon
Bojan Tomic
Bengt Lydell

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Ralph Nyman [1]
Stig Erixon [1]
Bojan Tomic [2]
Bengt Lydell [3]

[1] Swedish Nuclear Power Inspectorate, Department of Plant
Safety Assessment (SKI/RA), S-106 58 Stockholm, Sweden

[2] ENCONET Consulting GesmbH
Hansi Niese Weg 19
A-1130 Vienna, Austria

[3] RSA Technologies
1736 Promenade Circle
Vista, CA 92083-6172, U.S.A.

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Disclaimer: This report concerns a study conducted for the Swedish Nuclear Power Inspectorate (SKI). The conclusions and viewpoints presented in the report are those of the authors and do not necessarily coincide with those of the SKI.

SUMMARY

1. Background

Passive component failures seldom receive explicit treatment PSA studies. To expand the usefulness of PSA, the Swedish Nuclear Power Inspectorate (SKI) has undertaken a research project to: 1) establish a comprehensive passive component failure database; 2) validated failure rate parameter estimates; and 3) a model framework for integrating passive component failures in existing PSAs. SKI recommends that piping failures be explicitly included in PSA reliability models. Phase 1 of the project (completed in spring of 1995) produced a relational database on worldwide piping system failure events in the nuclear and chemical industries. The subject report includes Phase 2 results.

2. Implementation

Available public and proprietary databases on piping system failures were searched for relevant information; e.g., U.S. LERs, Swedish ROs, NEA and IAEA databases, INPO, MHIDAS, etc. Using a relational database to identify groupings of piping failure modes & failure mechanisms, together with insights from extensive reviews of published PSAs, the project team determined ***why***, ***how*** and ***where*** piping systems fail.

3. Results

Volume 4 of the Phase 2 reports represents a compendium of technical issues important to the analysis of pipe failure events, and statistical estimation of failure rates with their distribution parameters. The technical information presented in Volume 4 provided background information for the Main Report (Volume 1, SKI Report 95:58), and for the Phase 3 of the project. Interim statistical analysis insights are generated for comparison with published information on pipe failure rates. Inadequacies of traditional PSA methodology are addressed, with directions for PSA methodology enhancements. A "data-driven-and-systems-oriented" analysis approach is proposed to enable assignment of unique identities to risk-significant piping system component failures. Overall objective is to ensure piping system failures explicitly appear in cutset lists.

4. Conclusions

Sufficient operating experience does exist to generate quality data on piping failures. Passive component failures should be addressed by today's PSAs to allow for aging analysis and effective, on-line risk management. Insights and results also will be presented at PSAM-III in June 1996 and PSA'96 in October 1996.

SAMMANFATTNING

1. Bakgrund

Dagens PSA studier behandlar fel i passiva komponenter på samma sätt som i den mer än tjugo år gamla WASH-1400. Grundläggande antagande har alltid varit att passiva komponenter är betydligt mindre felbenägna än aktiva komponenter. Därför är explicit och detaljerad analys av sådana fel ej nödvändig. Ett sådant synesätt bidrar dock till en begränsad praktisk använbarhet av PSA studierna. Så belyser exempelvis inte PSA inverkan av åldringsfenomen i rörkomponneter.

Under våren 1994 tog SKI (Enhet för anläggningssäkerhet, RA) initiativ till nytt forskningsprojekt med avsikt att ta fram en databas över inträffade rörskador i världens kärnkraftverk och en analysmetodik som möjliggör en konsistent samsyn på aktiva och passiva komponentfel.

2. Implementering

I projektets Fas 1 (slutförd under april 1995) utvecklades en databas i MS-Access® över fel i rörkomponenter. I föreliggande Fas 2 rapport utnyttjades databasen för att identifiera felmoder och felmekanismer i rör av kolstål och rostfritt stål. Parallellt med databasarbetet granskades ett stort antal PSA studier avseende behandlingen av passiva komponentfel, inlusive LOCA klassifiering och frekvensbestämning. Insikter från dessa båda arbetssteg utgjorde bas för bestämning av rekommenderad PSA-baserad analysförfarande.

3. Resultat

Utgående från ca. 2300 felrapporter ges presentation av drifterfarenheter med rörsystem i världens kärnkraftverk. Likaledes presenteras resultaten från granskning av sextiotalet PSA studier. Preliminär rörfelsstatistik återges tillsammans med en analysstruktur som möjliggör realistisk och detaljerad integrering av rörkomponentfel i existerande PSA modeller (d.v.s. felträd och händelseträd). Tillsammans har Fas 1 + 2 givit en inventering av rörfelsproblematiken från ett PSA-perspektiv och allmänt säkerhetsperspektiv.

4. Slutsatser

Tillräckligt med drifterfarenheter möjliggör meningsfull statistisk bearbetning. Sådan bearbetning skall beakta ***hur*** och ***varför*** rörsystem felar. Denna förståelse möjligör också konsistent behandling av passiva komponentfel i PSA studier. Förutom denna delrapport i fyra volymer kommer projektet at presenteras vid PSAM-III och PSA'96 under 1996.

ACKNOWLEDGEMENTS

The Phase 2 report on "Reliability of Piping System Components" represents a joint effort between SKI and its two contractors, Enconet Consulting and RSA Technologies. Volumes 1 and 4 were written by Mr. Bengt Lydell of RSA Technologies, with assistance of project team members from SKI and Enconet. Volumes 2 and 3 were written by Mr. Bojan Tomic, with assistance of project team members from SKI and RSA.

The project team gratefully acknowledges the encouragement and support from the following individuals and organizations: Mr. Kalle Jänkälä (IVO International Ltd., Finland) for providing pipe failure information from Loviisa Power Plant; Dr. Yovan Lukic (Arizona Public Service, Phoenix, AZ) for providing work order information on leak events at Palo Verde Nuclear Generating Station; Mr. Vic. Chapman (Rolls Royce and Associates Ltd., UK) for providing technical papers on risk-based in-service inspection of piping system components; Mr. Jerry Phillips (TENERA, Idaho Falls, ID) for introducing us to the work by "ASME Research Task Force on Risk-Based Inspection"; our colleagues at the Nuclear Research Institute, Div. of Integrity and Materials (Řež, Czech Republic) for information on their research on leak-before-break concepts; Mr. Mario van der Borst (KCB, the Netherlands) for providing information on plant-specific LOCA frequency estimation in Borssele PSA.

A special thank you is extended to Messrs. Rudolf Häussermann and Henk van Ojik of Kernkraftwerk Leibstadt AG (KKL, Switzerland) for valuable discussions on piping system design, and for sharing KKL's operating experience. We also gratefully acknowledge the insights provided by Messrs. Ralph-Michael Zander and Adelbert Gessler of Kernkraftwerke Gundremmingen Betriebsgesellschaft mbH (KGB, Germany).

NOTICE

This report documents interim data analysis insights from Phase 2 of a project entitled "Reliability of Piping System Components". It represents a joint effort between SKI and its two contractors, Enconet Consulting and RSA Technologies. Volumes 1 (SKI Report 95:58) and 4 (SKI Report 95:61) were written by Mr. Bengt Lydell of RSA Technologies, with assistance of project team members from SKI and Enconet. Volumes 2 (SKI Report 95:59) and 3 (SKI Report 95:60) were written by Mr. Bojan Tomic, with assistance of project team members from SKI and RSA. The Phase 2 reports are intended for PSA practitioners. Data presentations in Volume 4 are based on Version 3.0 (Revision 1) of the relational database (SLAP).

The work was conducted under contracts with the Swedish Nuclear Power Inspectorate, Department of Plant Safety Assessment (SKI/RA), and within the Safety Analysis Program.

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1: INTRODUCTION

1.0 Overview

This report summarizes reliability data considerations important to a consistent PSA treatment of piping system component failures. Since the earliest PSA studies, only modest progress has been made on a structured, plant-specific evaluation of passive component failures. The report develops a basis for advancing the estimation of piping reliability data parameters.

The Swedish Nuclear Power Inspectorate (SKI) in 1994 commissioned a multi-year, four-phase research project on piping system component reliability. That is, determination of reliability of passive components, such as pipe (elbow, straight, tee), tube, joint (weld), flange, valve body, pump casing, from operating experience data using statistical analysis methods compatible with today's probabilistic safety assessment (PSA) methodology. Directed at expanding the capability of PSA practices, the project scope includes development of a comprehensive pipe failure event data base, a structure for data interpretation and failure rate estimation, and an analysis structure to enhance existing PSA models to explicitly address piping system component failures[1-1].

Phase 1 of the research consisted of development a relational, worldwide database on piping failure events. This technical report documents Phase 2 results. *Interim piping failure data analysis insights are presented together with key piping reliability analysis considerations*. Phase 3 will be directed at detailed statistical evaluations of operating experience data, and development of a practical analysis guideline for the integration of passive component failures in PSA. Finally, Phase 4 will include pilot applications.

A fundamental aspect of PSA is access to validated, plant-specific data and models, and analysis insights on which to base safety management decisions. As an example, in 6,300 reactor-years of operating experience[1-2] no large loss-of-coolant accident (LOCA) has been experienced. Interpretation and analysis of the available operating experience indicates the large LOCA frequency to be about $1.0 \cdot 10^{-4}$/year[1-3]. Several probabilistic fracture mechanics studies indicate the large LOCA frequency to be $1.0 \cdot 10^{-8}$/year[1-4].

Decision makers should be able to confidently rely on PSA. The challenge facing PSA practitioners is to ensure that an investment of, say, 20 kECU[1-5] in analysis services accurately supports a 2 MECU investment decision. By definition, PSA uses applicable operating experience and predictive techniques to identify event scenarios challenging the engineered safety barriers. *The usefulness of PSA is a function of how well operating experience (including actual failures and incident precursor information) is acknowledged during model (i.e., event tree and fault tree) development*.

The past twenty years have seen significant advances in PSA data, methodology, and application. *An inherent feature of PSA is systems and plant model development in presence of incomplete data*. The statistical theory of reliability includes methods that account for incompleteness of data. Expert judgment approaches are frequently (and successfully) applied in PSA. Legitimacy of expert judgment methods rests on validation of results by referring to the "best available" operating experience. Despite advances in PSA methodology, it remains a constant challenge to ensure models and results accurately reflect on what is currently known about component and system failures and their effects on plant response.

One technical aspect of PSA that has seen only modest R&D-activity is the integrated treatment of passive component failures. Most PSA projects have relied on data analysis and modeling concepts presented well over twenty years ago in WASH-1400[1-6]. Piping failure rate estimates used by WASH-1400 to determine frequency of loss of coolant accidents (LOCAs) from pipe breaks were based on approximately 150 U.S. reactor-years of operating experience (Figure 1-1) combined with insights from reviews of pipe break experience in U.S. fossil power plants.

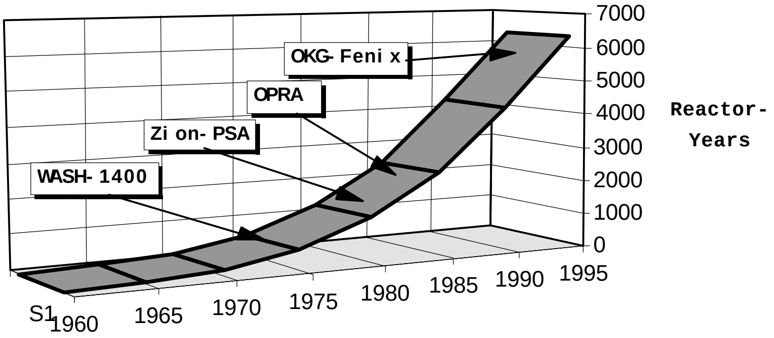


Figure 1-1: *The Worldwide Commercial Nuclear Power Plant Operating Experience According to SKI Data Base Adapted from IAEA-Statistics[1-2,7].*

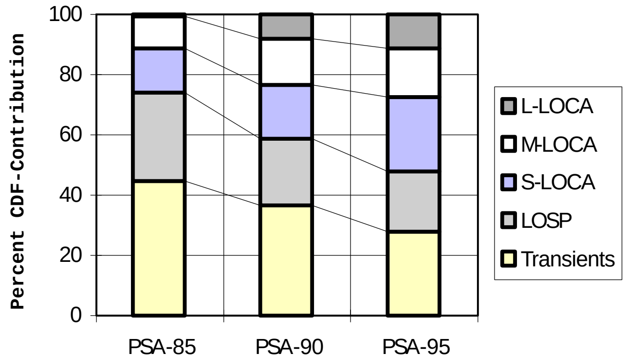
In this context, the SKI-project is directed at enhancing the PSA "tool kit" through a structure for piping failure data interpretation and analysis. Phase 2 results are documented in four volumes:

- Volume 1 (SKI Report 95:58). Reliability of Piping System Components. Piping Reliability - A Resource Document for PSA Applications. This is a summary of piping reliability analysis topics, including PSA perspectives on passive component failures. Some fundamental data analysis considerations are addressed together with preliminary insights from exploring piping failure information contained in a relational data base developed by the project team. A conceptual structure is introduced for deeper analysis of passive component failures and their potential impacts on plant safety.

- Volume 2 (SKI Report 95:59). PSA LOCA Data Base. Review of Methods for LOCA Evaluation since the WASH-1400. The scope of the review included about 60 PSA studies.
- Volume 3 (SKI Report 95:60). Piping Reliability - A Bibliography. The bibliography includes over 800 technical reports, papers, and conference papers.
- Volume 4 (SKI Report 95:61), this report.

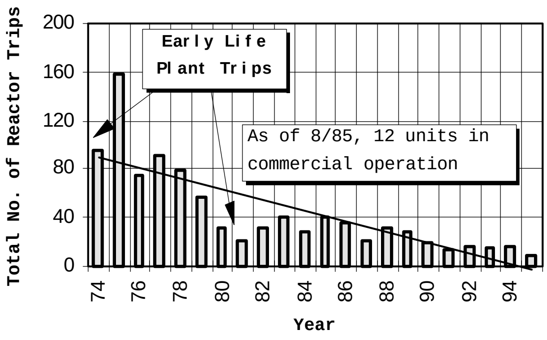
1.1 Need to Address Piping Failures in PSA

Plant risk is highly dynamic. Results from plant-specific PSAs change with advances in data, modeling, operating experience, and changes in system design. The significance of risk contributions from passive component failures tends to become more pronounced by each living PSA program iteration. Shifts in risk topography are caused by strengthened defense-in-depth and decreasing transient initiating event frequencies. As the relative worth of risk contributions from transient initiating events decreases, the relative worth of LOCAs caused by passive component failures increases. The relative contributions from LOCAs and transients identified by early PSA studies (i.e., 1975-1987[1-8]) may no longer be universally applicable.



A Conceptual Living PSA Program

Directed at PSA, this project provides a consolidated perspective on passive component failures. This volume of the Phase 2 reports addresses fundamental data analysis issues, and develops an integrated, structured approach to modeling of passive component failures.



Swedish Reactor Scram History

1.2 Report Outline

The topic of this report is the use of operational data on pipe failure events. Especially how to address trends, data pooling, competing failure modes, distribution types, and component boundaries in the estimation of failure rates for piping system components. Before proceeding with a formal data analysis, the operating experience must be interpreted in a consistent way. For that purpose the prevalent pipe failure modes and mechanisms must be understood.

This report presents an analytical "interface" between the raw data sources and the failure rate estimation process. The interface defines necessary steps to estimate pipe failure rates from operating experience, and considers quality and credibility of reliability data in view of the worldwide operating experience as documented in a relational database on pipe failures. Reliability data estimation should be based on a validated model of failure. Before applying statistical analysis methods the operating experience must be understood and organized/structured so that failure modes, failure mechanisms, and reliability attributes are correctly accounted for. Volume 4 of the Phase 2 reports is the "precursor" to statistical estimation by displaying the database contents, and identifying the significant piping reliability attributes.

Section 2 summarizes data analysis considerations important to the estimation of realistic and valid piping failure data parameters. Because of the scarcity of failure data for piping systems, the pooling of "raw data" from different sources must consider the unique failure modes and mechanisms. Uncritical pooling of data could result in unrealistic failure rates. Section 3 gives a summary of qualitative insights from exploring the over 2,300 failure records in the SLAP database. These insights have direct implications for the statistical analysis process. A structure for a statistical analysis process specifically applied to piping failures is presented in Section 4. Unless stated otherwise, the representations throughout this report reflect global pipe failure information.

There are three appendices to Volume 2. Appendix A includes selected failure record printouts from SLAP data base. Appendix B includes the database format and field definitions. Finally, Appendix C includes abbreviations, acronyms and a glossary.

2: PIPING RELIABILITY DATA ANALYSIS

2.0 Overview

Piping reliability data estimation should acknowledge available operating experience to the broadest extent possible. Since no uniform reporting requirements exist for piping failures the data analysis process has to go beyond the primary failure event reports to identify underlying causes of failure. The effort involved in such data analysis is considerable, ***and*** necessary. The objectives of the SKI-research include: (i) assemble the best available pipe failure event data, and (ii) develop an appropriate statistical analysis procedure that recognizes the unique failure modes, failure mechanisms, and reliability influence factors. Section 2 summarizes data analysis considerations important to estimation of valid pipe failure data parameters. It is an introduction to development of a formal statistical analysis process that meets the needs of PSA.

2.1 PSA-Based Pipe Failure Rate Estimation

Achievement of quality in PSA is obtained through *appropriate* implementation of data processing methodology, logic modeling, and final assembly of results. Poorly selected data sources, inappropriate model selection for data analysis, too many simplifying assumptions, etc., could (and has been shown to) affect PSA results and the usefulness of system and plant models. Quality and credibility of piping reliability data is controlled by[2-1]:

- Raw data, data estimation & application. The reliability data processing methodology should be compatible with intended applications; Figure 2-1:

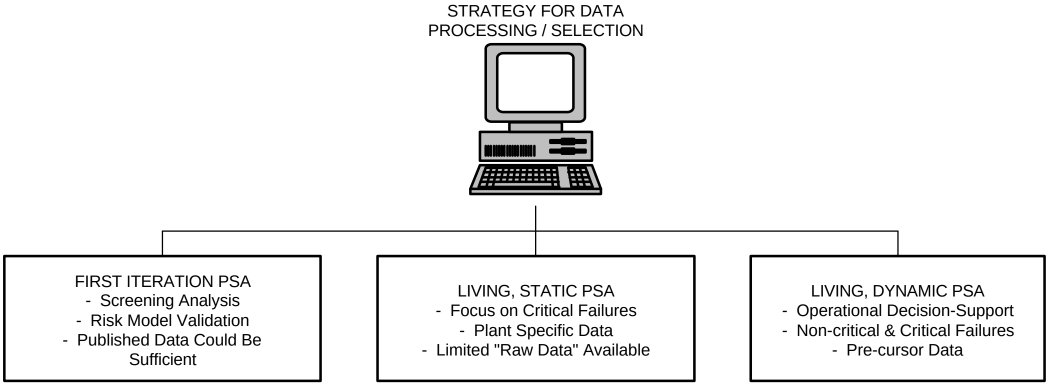


Figure 2-1: *Methodology for Processing of Data a Function of Intended Risk analysis Application.*

  - For the first-time, scoping risk analysis it is usually sufficient to use published data. Too heavy reliance on published data could inflict biases that mask plant-specific vulnerabilities, however. In contrast, highly plant specific data reflecting on preventive maintenance strategies, in-service inspection practice, and operating philosophies are needed for the dynamic (time-dependent) risk model application in support of operational decisions. Also, the data processing methodology should acknowledge unique failure modes and failure mechanisms and their impact on plant safety.

■ Extent by which available data sources have been ***explored*** for applicability to particular problem being investigated. "Do data sets exhibit trends?"; "Do data sets include evidence of maintenance- or testing-induced failures?"; "Do data sets distinguish between homogenous and inhomogeneous failure event populations?"; "Do the data sets allow identification of 'outliers'?" It is conceivable that a failure report gives incomplete information on failure symptoms, and apparent and underlying causes. Therefore, the data analysis process should include provisions (within reason) for additional incident investigation to ensure that correct conclusions are derived from the failure reports. The data analysis process should highlight areas where additional information is needed.

■ Rules for pooling of raw data. Different statistical methods are applied to estimation of failure rates from one sample and for pooling of data from several samples. It is often necessary to pool data from several samples to generate common generic failure rates. Uncritical pooling could cause vastly different failure events to be combined, therefore leading to errors in risk analysis calculations.

■ Basis for mixing generic data, or old with new data. Often generic nuclear industry data are applied to PSA for no other reason than ease-of-access. For some types of equipment, the process medium or operating practice yields unique reliability influences that are not addressed by the generic data. Bayesian statistics is sometimes a cost effective way of updating old data with new operating experience. But it is not a substitute for detailed engineering-based interpretations of operational data. Choice of prior distributions and development of posterior distributions should be based on knowledge of applicable design and operations factors. Tomic and Lederman[2-2] identify the following problems associated with uses of generic data:

  - Component boundary definition. Different definitions could change failure rates substantially. In general, modern data sources have developed detailed component boundary definitions for active components, and as data collections evolve more uniform definitions are used. For piping the appropriate component boundary definition is highly dependent on ultimate application, and also on failure mode definition and failure mechanisms. Welds or piping sections could be used as the structural unit for which failure rates are derived.

  - Failure mode definition. Differences in wording can cause difficulties in applying published data. Also, if a specific PSA-application requires recognition of non-critical and critical failures, several kinds of failure modes may have to be pooled; e.g., leakage and rupture of piping component.

  - Operating mode definition. Many data sources do not state the operating mode; e.g., standby, alternating, running. The operating mode has an effect on reliability since some failure mechanisms are "mode-dependent". For standby components it is required to have information on standby (or test) periods. Some failures occur during standby, while others occur during a demand. Therefore some applications require an hourly failure rate <u>and</u> a demand related failure probability to correctly describe component reliability. For piping system components the definition of operating mode requires knowledge not only of system functions and design intents, but also knowledge of prevalent failure mechanisms. Based on the operational data, some failures have occurred in systems in intermittent use; e.g., during plant startup and shutdowns. Correlations between plant transient history and failures should be considered when assessing pipe reliability; c.f. Aaltonen, Saarinen and Simola[2-3].

  - Operating environment. The operating environment can be poorly described by data sources, or are implicitly stated; e.g., a data source for equipment in nuclear power plant assumes that the analyst is intimately familiar with specific operating environment. The vast majority of data collected stems from maintenance work order systems and reflect on anticipated failures (or failure effects) under normal operating conditions. In risk analysis one is interested in predicting equipment performance in severe (aggressive) incident environments where, as an example, a high-temperature environment occurs as a function of lost room cooling. The data analyst must identify those equipment types that could be affected by abnormal environmental conditions before supplying data to the risk model quantification process. The operating environment is also used to control and enhance reliability; e.g., hydrogen water chemistry is used to minimize the susceptibility to intergranular stress corrosion cracking (IGSCC) in BWR units (c.f. Section 2.3).

- Validation of data by reference to published data source (including event descriptions and failure rate parameters). For reasons of cost-efficiency and project scope, it is appropriate to rely on data already existing in the public domain. Such reliance assumes that the data analyst has sufficient knowledge of the background; i.e., <u>***how***</u> were the failure rates derived?

- Interpretation of failure event descriptions. For piping failures the existing LER- and RO-systems are not detailed enough to determine the underlying cause(s) except by inference from failure location; c.f. Murphy et al[2-4]. As examples, charging lines in PWRs experience vibrations and are susceptible to vibration-fatigue, elbows in steam extraction lines are susceptible to erosion-corrosion. Such data interpretations must be based on detailed knowledge of failure modes, failure mechanisms, and their influence factors.

- Reporting of failure events. Ultimately a quality reliability data set is coupled to how failure events are reported and the coverage of the reporting systems; i.e., are all significant failures reported? For piping failures, the degree of coordination between the licensee reporting system (as specified by the plant Technical Specifications) and the reporting of findings from in-service inspection (ISI) could be an important factor in the data base coverage.

In PSA the typical approach to failure rate estimation is based on "direct estimation" using statistics of historical piping failure event data; Figure 2-2. An advantage of direct estimation methods lies in the compatibility with PSA methodology and modeling approaches. The direct estimation methods also can be validated relatively easily. A disadvantage of direct estimation is statistical uncertainty due to scarce data points. Perhaps more important than this uncertainty is ***not*** knowing how a failure rate was derived through direct estimation. That is, how was the operational data explored, what data pooling strategies were used? As we shall see in Section 3, the pit falls of direct estimation are many. A couple of variations on the direct estimation approach exist:

- Maximum likelihood estimation using pooled data. Based on assumptions about the applicability of actual failures in a variety of piping systems to a specific piping system; e.g., failures in carbon steel piping versus failures in stainless steel piping.

- Derivation of validated prior piping failure distributions that are modified using Bayesian statistics.

- Derivation of generic, industry-wide piping failure distributions that are modified using analysis of variance (ANOVA) techniques.

Scarcity of data points often results in pooling of data to enhance the qualitative and quantitative robustness of estimates. Data pooling must be based on engineering knowledge about failure modes, failure mechanisms, and reliability influence factors. Uncritical pooling could result in statistical biases that ultimately impact PSA results. A concern when addressing piping component reliability is the appropriate failure event population groupings. As an example (and depending on intended application), LOCA-sensitive piping should not be pooled with LOCA-insensitive piping to enhance population numbers, or failures in carbon steel piping should not uncritically be pooled with failures in stainless steel piping. Similarly, in developing generic piping failure rate distributions, the effects of unique and plant specific failure modes and failure mechanisms must be identified by the analyst. *Most piping failures have occurred in carbon steel piping, rather than stainless steel piping.* In deciding on estimation approach, the ultimate use of results should be recognized by the analyst.

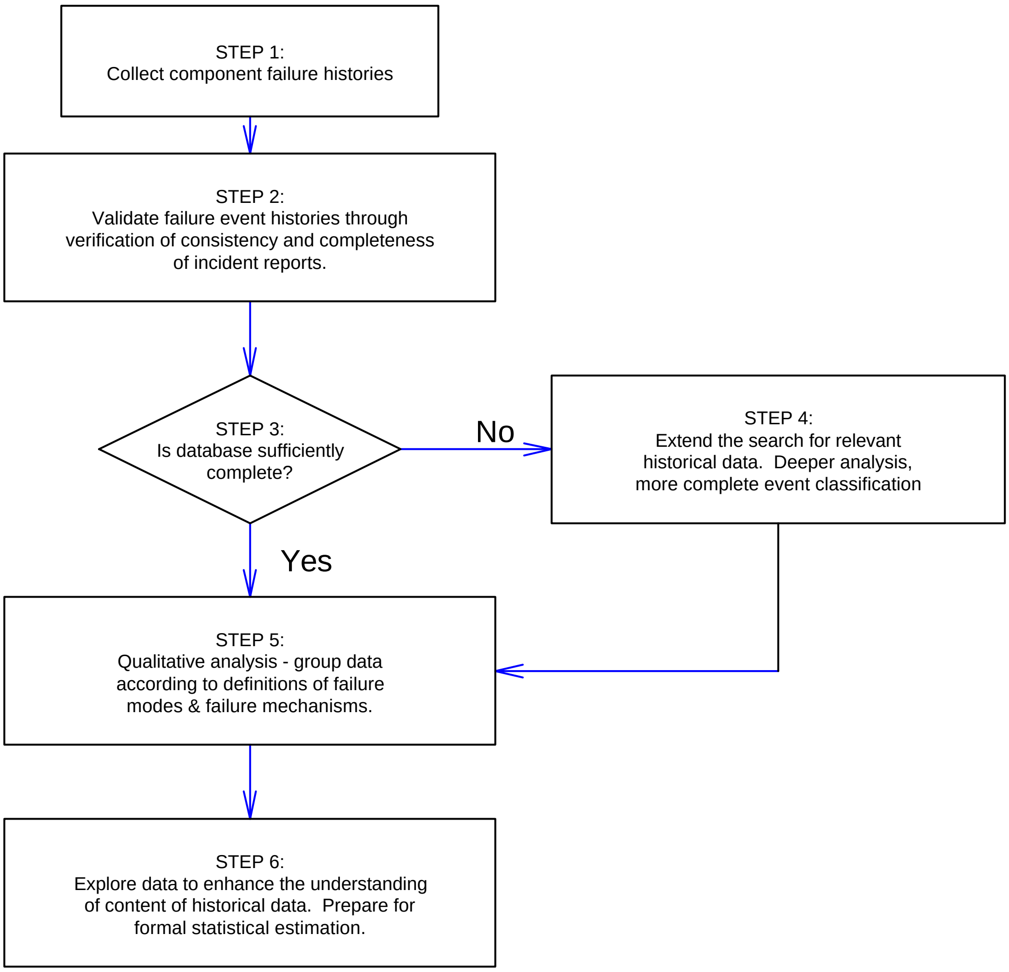


Figure 2-2: *Structure of Direct Estimation Strategy - Preparatory Steps.*

2.2 Pipe Failure Modes

Reviews of operating experience with piping systems highlight a basic problem with published compilations of piping failure rate estimates. A scarcity of (public domain) robust and homogenous failure information for the range of piping classes and applications have led to over-simplifications resulting in statistical biases and uncertainties. Objectives of piping failure event data collection include developing a basis for failure rate estimation compatible with the needs of PSA; i.e., supporting direct estimation techniques. A key question is whether it is feasible to systematically and consistently apply statistical evaluation methods to piping failure event data? The general process of collecting and analyzing piping failure event data is complicated by following factors:

- No uniform failure event recording requirements are available. Existing licensee event reporting (LER) or "reportable occurrence" (RO) reporting systems were developed for safety related, active components as defined by the plant technical specifications. Piping failures are captured by LER-/RO-systems given that the consequence is reactor trip, or degradation of defense-in-depth. Beyond providing information on apparent cause(s) of failure and brief event narratives, these reports often require substantial interpretation or additional incident investigation efforts. The divisions between symptom and cause, or apparent and underlying cause are seldom clearly identified in the LER- or RO-reports.

Most of the piping failure events are captured by other information systems; e.g., NSSS owners groups information bulletins, NEA/IRS, IAEA/ERF, inspection reports and work order systems. Also, instances of significant piping integrity degradations are usually identified during annual refueling/maintenance outages when regulatory reporting requirements are relaxed. It is noted that information submitted for inclusion by NEA/IRS and IAEA/ERF is considered "final", and therefore not subjected to updates or revisions. These two databases do not reflect the detailed information typically available to utilities and regulatory agencies.

- Compared with active component failures, on a system-by-system level, piping failures are rare events. Therefore, PSA analysts are forced to direct considerable time to interpretation of limited amounts of data. The need for data interpretation is compounded by a lack of uniform failure event recording requirements.
- Piping reliability is determined by many different influence factors; Figure 2-3. There are inherent, phenomenological factors, and operational and organizational influence factors. Piping components of like metallurgy, dimensions and application could (and often do) exhibit widely different reliability characteristics in two similar plants because of unique operational philosophies, inspection practices, or safety culture. The "inherent, phenomenological" influence factors relate to metallurgy selections and fabrication methods conducive to certain failure mechanisms. The operational and/or organizational influence factors could lead to piping failures that are independent of basic piping system design features. Latent and active human errors are known to impact piping reliability; Section 2.5.

INFLUENCE	EFFECT	OPERATIONAL MONITORING
... some examples Vibration Mechanical load Thermal load Corrosion Erosion Irradiation Water Chemistry	*... some examples* Cracking / crack propagation Change in mechanical properties Reduced wall thickness	Process instrumentation Vibration instrumentation Fatigue monitoring Water chemistry monitoring Leak monitoring In-service inspections Loose part monitoring Functional tests Maintenance/repair

Figure 2-3: *Piping Reliability Influence Factors and Their Effects; c.f. Seibold, Bartonicek and Kockelmann*[2-5].

- Causes of failures in primary-side piping tend to be fundamentally different from secondary-side piping. Therefore, uncritical pooling of piping failure event populations could lead to misleading statistical insights.

- Causes of failures in large-diameter piping tend to be different from small-diameter piping. When analyzing causes of failures it is important to address the consequences. It is quite feasible that a small leakage in a large-diameter piping has the same consequence as a large leakage in a small-diameter piping. Also, an isolateable piping section normally has less risk criticality than a non-isolateable piping section.

- Piping failure mechanisms are functions of design, fabrication/installation, operating practices (e.g., base-load versus peak-load versus extended power reductions), metallurgy, inspection practices, application (e.g.,primary versus secondary-side). Failure mechanisms are symptoms of underlying (root) causes that reflect, say, unique design or operational factors. While aspects of a failure mechanism are inherent to specific metallurgy, operating conditions, operating mode, etc., the effects are controllable through reliability management actions.

Looking at the operating experience with piping systems (and as documented by the reporting systems) it becomes obvious that a lack of data homogeneity makes it challenging for PSA analysts to make direct failure rate estimation. Data homogeneity refers to data collection conditions under sets of uniform reporting guidelines, failure classification systems, and completeness in reporting. Piping failure event data collections tend to be biased by such factors as regulatory attention to specific failure mechanisms. That is, as a new failure mechanism is discovered it tends to be appropriately recognized by the event reporting systems. This recognition then shifts to new failure mechanisms as they are discovered. The degree of database coverage of piping failures varies over time.

Without formal reporting requirements, consistent, systematic event reporting is never guaranteed, however. There is an urgent need for reporting schemes, tied to plant technical specifications, for documenting piping system degradations and failures. By necessity, such a reporting scheme needs to be comprehensive, and reflect the multiple-cause incident anatomy[2-6,7]. Piping failure rates derived from operating experience should relate to internal and external operating environments, metallurgy, failure modes (how piping fails), and failure mechanisms (why piping fails). It is practical to distinguish between *incipient*, *degraded*, and *complete* piping failure (see below) and between *critical* and *non-critical* piping failure (Figure 2-4) :

- Incipient piping failure
  - Wall thinning; e.g., insufficient corrosion allowance to allow prolonged operation.
  - Embrittlement from neutron irradiation.
  - Embrittlement from thermal aging.
  - Crack indication; e.g., a typical incipient failure would be cracking due to IGSCC in BWR piping detected by UT.

- Degraded piping failure.
  - Restricted flow.
  - Visible leak from through-wall crack. Leak area < 10% of flow area could be used to characterize the failure, or through-wall cracking < 270-degree circumferential crack.

- Complete piping failure.
  - Visible leak from through-wall crack. Leak area > 10% of flow area is often used to characterize the failure. Leak rate exceeds about 3 kg/s.
  - Rupture/break. The traditional, complete piping failure addressed by PSAs is the "double-ended guillotine break" (DEGB). Also includes gross "fish-mouth" failures resulting in leak rates of tens of kg/s. Rupture/break events could occur without advance warning.
  - Severance or separation due to external impact.

Much of the available (unreported and reported) piping operating experience represents incipient and degraded failures. Questions arise regarding extrapolation of such information to represent complete piping failures. In addition, *some incipient or degraded failures detected during major maintenance and refueling outages may not be reported*. Before making quantitative assessments of reliability it is important to determine all the significant causes of failure. The available knowledge about likely failure modes and mechanisms should be part of PSA. A combination of operational and organizational influences contribute to the occurrence of each failure phenomena.

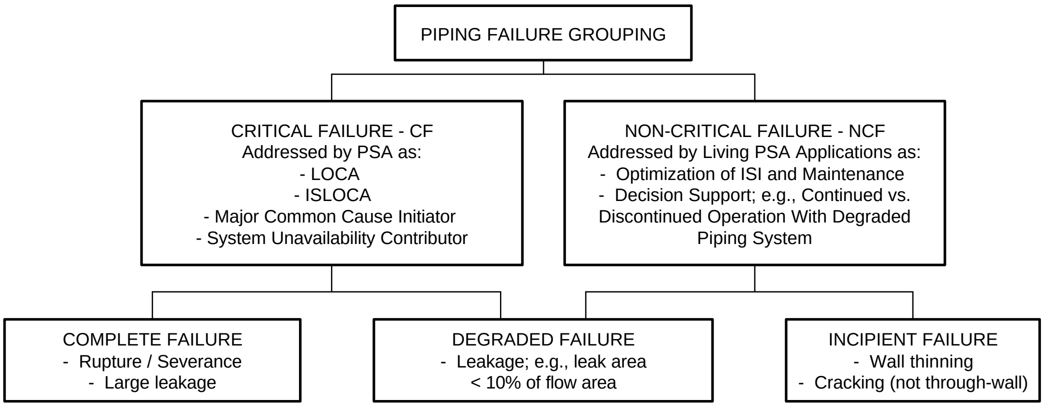


Figure 2-4: *Example of Piping System Component Failure Grouping.*

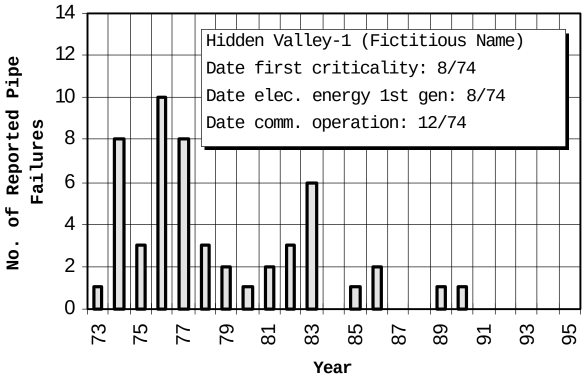
2.3 Failure Mechanisms and Failure Influence Factors

Reviews of operating experience with piping systems highlight a basic problem with published compilations of piping failure rate estimates. Lack of formal, uniform reporting requirements has meant that insufficient background information has been available for data interpretation. Equally important, a substantial amount of repeat failures have occurred (as documented in the SKI database) due to insufficient feedback of operating experience to plant personnel. Objectives of piping failure event data collection include developing a good "interface" between the normal event reporting schemes (e.g., licensee event reports) and the PSA requirements, ***and*** basis for failure rate estimation compatible with the needs of PSA (i.e., supporting direct estimation techniques). A key question is whether it is feasible to systematically and consistently apply the standard statistical evaluation methods to piping failure event data? The general process of collecting and analyzing piping failure event data is complicated by the following factors:

- Much of the operating experience represents incipient and degraded piping failures. Questions arise regarding extrapolation of such information to be representative of complete piping failures. As an example, during the recent (1992-95) Oskarshamn-1 extended maintenance outage a drop-leakage was found in a non-isolateable RHR pipe section. What would be a reasonable PSA-type interpretation of this discovery? In view of acceptable operational "risk increase", what is the reasonable PSA-type interpretation of this discovery; i.e. for how long can continued operation be allowed? Should PSA only be concerned with observed, critical failures (e.g., large leakages and ruptures) in unisolateable piping systems? To what extent should piping failures in BOP-piping be included in the statistical analysis process?

- Before making quantitative assessments of reliability it is important to determine all the significant causes of failure. The available knowledge about likely failure modes and mechanisms should always be part of PSA. A combination of operational and organizational influences contribute to each failure phenomena. Often this combination consists of a complex interplay of different influences; i.e., the multiple-cause incident model applies to the analysis of piping failures.

Pipe failure mechanisms are symptoms of underlying influence factors such as process conditions (temperature, pressure, flow, steam quality, water chemistry), operational, and organizational factors. This means that piping reliability is controllable. Reliability growth is achieved by modifying known influence factors. Before commencing with estimation of piping failure rates, the applicability of failure event data should be established. As an example, older operating experience (say pre-1985) involving certain failure mechanisms may no longer be applicable because of subsequent improvements in design, operations or ISI-strategies. An example would be the cracking caused by thermal fatigue in the junction of AFW and RHR piping



Example Pipe Failure Trend (from SLAP)

in some BWR plants during 1979/80. Subsequent modifications of piping design and operating procedures seem to have been effective in preventing new failures at the affected plants. At more recent dates, there have been similar thermal fatigue failures at newer plants, however. This points to the question about effective feed-back of operating experience and how it effects data interpretation.

Equally important, the data analysis must establish whether a pipe failure rate is increasing or decreasing (i.e., showing a trend). In pooling failure data it is important to apply consistent data selection criteria that include consideration of underlying reliability influences and potential failure rate trends. Older data sets should not be dismissed based on *unvalidated* assumptions about their current relevance.

Evaluation of trends in pipe failure data is complex. While statistical trend analysis - using current data analysis methodology and tools - is straightforward, it is also recognized that results and insights are only as good as the source information. When failure data are extracted from a reporting system with known low coverage of pipe failures, the resulting trends would reflect more on the data base coverage than on the actual pipe failure behavior. A question therefore arises whether the trends generated from the preliminary analysis of SKI's data base (as presented in Section 3) also reflect "true" reliability trends.

Many pipe failures represent repeat failures. That is, failures of a certain type (same failure mode and failure mechanism) have recurred in a system of a particular plant type. Also, a repeat failure is a kind of dependency caused by design and/or operational factors. Often, repeat failures reflect insufficient feedback of operating experience within (or between) organizations, systematic errors in ISI, etc. Much of the operating experience has generic implications. Failure mechanisms and failure modes occurring at one plant could be applicable to an entire plant design generation. Repeat failures in planning of maintenance, testing or inspection activities could, in extreme cases, imply that a piping integrity deterioration remains undetected for several years.

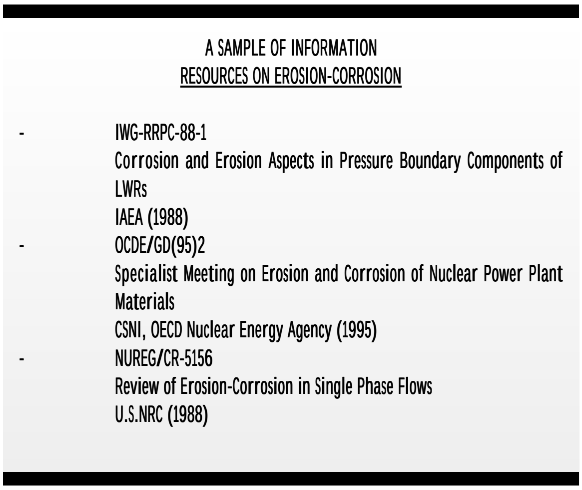
Similar to repeat failures, construction errors reflect on organizational factors. Ineffective QA/QC-function during construction and commissioning could result in non-detection of significant piping system design and/or installation errors. Such errors could usually be revealed early in plant life; e.g., pre-startup testing. Construction errors also could involve complex combinations of failure influences and failure mechanisms first revealed after years of operations. Shop fabricated piping sometimes exhibits vastly different reliability characteristics from field fabricated piping because of the different environmental conditions during fabrication.

The quality of failure rate estimates is intimately coupled with access to "good" failure event data and interpretations and groupings that reflect on the current state-of-knowledge about piping failures; the *why's* and *how's*. Data quality has little to do with statistical confidence levels, however. *It is a function of how well the estimates reflect the state-of-knowledge and the coverage of piping failures by licensee reporting systems.*

Some failure mechanisms develop over a relatively short period of time (e.g., within 10 to 10^4 hours), while others represent long-term degradation effects (or, possibly, aging phenomena). Problem is, there is no sharp division between short- and long-term failure mechanisms. Time as such could in fact be a poor reliability indicator. *Number of cyclic transients in some instances could be a better indicator*. Closely related to the topic of short- versus long-term degradation is the (almost "mythical") topic of ***component aging***. According to some investigators (c.f. Sanzo et al[2-8]) aging-risk analysis requires inclusion of principal degradation mechanisms such as fatigue, SCC, embrittlement, and erosion corrosion (which is an idea supported by the companion report; c.f. SKI Report 95:58, Sections 6 and 7). That is, the types of degradation mechanisms we see in piping components must be included in the "aging-risk analysis". The aging concept implies presence of increasing trends in failure rates. This concept of increasing trend is not well supported by the results from the preliminary data analysis presented in Section 3, although some recognized aging mechanisms are included among the data sets. Should it be so that for piping we see a mixture of increasing. decreasing and constant failure trends (as is implied by Section 3), this seems to support the notion that data from LER- and RO-systems (i.e., incomplete data sources) do not support requirements for deeper investigation of failure mechanisms and their underlying causes. In fact, a prime reason for developing SKI's data base on pipe failures was to develop an appropriate "interface" between the "raw data sources" and a statistical analysis framework.

Often, the short-term failure mechanisms result in self-revealing piping failures. The long-term degradation effects mostly are revealed through extensive metallurgical surveys in connection with prolonged maintenance outages coupled with major primary system decontamination work. This latter observation impacts our ability to directly estimate piping failure rates using operating experience data; i.e., the extent of piping damage could be revealed after decades of full-power operation, or towards end-of-life of a power plant. There is no strong division between short- and long-term degradations. What is seen as short-term at one plant may appear as long-term degradation at another plant despite the similarities in symptoms. Safety culture does play an important role in piping reliability. Predominant types of failure mechanisms are discussed in further detail below.

Examples of short-term failure mechanisms include (but are not limited to): (i) erosion-corrosion, (ii) cavitation-erosion, and (iii) vibratory fatigue. Since these failures mostly cause self-revealing piping damage, subsequent incident investigations have yielded valuable information on cause-consequence relationships and influence factors.



A SAMPLE OF INFORMATION
RESOURCES ON EROSION-CORROSION

- IWG-RRPC-88-1
  Corrosion and Erosion Aspects in Pressure Boundary Components of LWRs
  IAEA (1988)
- OCDE/GD(95)2
  Specialist Meeting on Erosion and Corrosion of Nuclear Power Plant Materials
  CSNI, OECD Nuclear Energy Agency (1995)
- NUREG/CR-5156
  Review of Erosion-Corrosion in Single Phase Flows
  U.S.NRC (1988)

<u>Erosion-corrosion</u> (or flow-assisted corrosion) phenomena have been subjected to extensive investigations (see side-bar), including development of PC-based computer codes for predicting erosion-corrosion effects in single-phase-

and two-phase-flow carbon steel piping systems. These codes help define the depth and extent of wall thinning that can be safely left in service. Based on operating experience, piping failures tend to be *concentrated near elbows* (in the case of steam, or two-phase erosion), and *in mini-flow lines downstream of flow control valves and in elbows* (in the case of single-phase erosion-corrosion). Failures have occurred by "fish-mouthing" resulting in large openings, or by complete separation of piping sections. Detection is mostly synonymous with failure and leakage.

Erosion-corrosion failures are functions of balance-of-plant (BOP) piping system design (e.g., geometry, number of tees and elbows, accessibility for ISI or NDE), operational influences, and ISI-practices. It is a problem common to all NPPs, and the extent of the problem is a function of steam quality, water chemistry, piping design and layout, material selection, etc., as discussed by Cragnolino, Czajkowski and Shack[2-9]. Except for catastrophic or major failures, erosion-corrosion damaged areas are normally repaired by weld overlays. Erosion-corrosion damage is not generally a plant safety concern, but often a significant economical concern because of the resulting forced plant outages for pipe repair or replacement. Safety concerns would arise where a leakage or rupture can cause internal flooding or plant transients from loss of support systems that result from steam release or water jets on electrical cabinets or motors. The effects of erosion-corrosion damage could also be a significant occupational hazard.

Austenitic and ferritic stainless steels are virtually immune to erosion-corrosion damage. A permanent solution to erosion-corrosion susceptibility has been to replace elbows in carbon steel by elbows in ferritic stainless steel. Several catastrophic failures of carbon steel piping systems during the eighties resulted in significant industry programs to better understand the erosion-corrosion phenomena, and to develop reliability improvement programs. In the U.S., the December 1986 catastrophic failure of a pipe in a main feedwater suction pipe at Surry-2 (see Appendix A) triggered industry actions to address the generic problem of erosion-corrosion damage. Similar experiences in other countries led to parallel or complementary investigation efforts enhancing the combined body of knowledge.

According to Morel and Reynes[2-10], cavitation-erosion incidents have occurred downstream of control valves in RHRS and CCWS of French standardized 900 MWe PWRs. According to Thoraval[2-11], during the 1985 refueling outage at Bugey-5, a leakage was detected in the residual heat removal system. It was located in a weld between a flange downstream from a butterfly valve and the conical transition of the pipe; *similar* events were also reported at Fessenheim-1 and Cruas-1. As cavitation develops, it entails harmful effects such as noise, vibration, and erosion of solid surfaces near the cavitation source. Based on the French operating experience, susceptible piping system locations include elbows located less than 5D downstream of a single orifice, and gradual piping enlargements located less than 5D from cavitation source.

Vibratory fatigue phenomena have been surveyed by Weidenhamer[2-12] and Bush[2-13], among others. Most pipe vibratory fatigue problems have occurred in small-diameter piping (DN < 100). Some failures have occurred in large-diameter (DN > 350) feedwater system piping in PWRs. The failures tend to initiate at the fillets in socket and support attachment welds due to the high stress concentration at the juncture of the weld and base metal. Once initiated, fatigue cracks propagate circumferentially and radially from outside to inside, often leading to a total severance with very little advance warning. Crack surfaces are quite smooth and progress transgranularly. Detection is usually synonymous with failure and leakage.

Examples of long-term failure mechanisms, developing over a relatively long period of time (e.g., 10^4 to 10^5 hours), include: (i) thermal fatigue, and (ii) stress corrosion cracking. The former mechanism has led to self-revealing piping damage, while the latter typically has manifested itself as latent piping damage. Both categories include numerous subcategories that are unique to specific NSSS or system designs.

According to Bush[2-13], the first reported instances of thermal-fatigue were related to hot standby operations in PWRs. During hot standby, the feedwater pumps are off and hot water in the S/G's flow into the feedwater lines, replacing and floating above the remaining cold water. On S/G level drop the feedwater pumps are reactivated to maintain appropriate levels. Hot water mixes with cold water causing abrupt cooling of the hot portion of the pipe, and abrupt heating of the cold section. The cyclic temperatures in the mixing zone could cause low-cycle fatigue. Should a condition of thermal stratification remain rather than mixing, high-cycle fatigue could lead to cracking.

Thermal fatigue is also a problem in BWRs in mixing tees. About fifteen years ago cracks were discovered in ABB-BWR units where three different coolant streams at three different temperatures were mixed intermittently; main feedwater, auxiliary feedwater, and water from reactor water cleanup system. A first instance of such thermal fatigue cracking, causing a pipe rupture, occurred at TVO-I in Finland during commissioning of that unit in 1979[2-14]. During the 1980 refueling outage at Barsebäck-2, cracking of feedwater system piping was detected; c.f. Burkhart[2-15]. As explained by Nordgren[2-16], mixing tee problems have occurred after 20,000 to 40,000 hours of operation. At TVO-I the problem occurred after a very short time of operation, and this particular failure was attributed to latent and active human errors (in combination with thermal fatigue).

Another form of thermal fatigue has resulted from cold water leaking through closed check or globe valves in ECCS lines of RCS hot and cold legs. Thermal stratification occurred with temperature fluctuation periods of 2 to 20 minutes. Such events have been reported at Bugey-3, Tihange-1 and Farley-2[2-10,13]; see Appendix A for details.

Stress corrosion cracking (SCC, a form of environmental cracking) problems were first identified in the early sixties in the U.S. SCC is a phenomenon in which time-dependent cracking occurs in a metal product when certain metallurgical, mechanical and environmental conditions exist simultaneously; c.f. Sprowls[2-17]. Failure of austenitic stainless steel recirculating piping occurred at Vallecitos BWR in 1962. Pipe cracking in a commercial power plant was first observed in 1965 in Dresden-1[2-18]. A primary cause of failure in BWR piping made of unstabilized austenitic stainless steel has been intergranular stress corrosion cracking (IGSCC). IGSCC is a condition of brittle cracking along grain boundaries of metals caused by a combination of high stresses (especially in piping of 75 ≤ DN ≤ 280) and a corrosive environment. IGSCC is not a unique BWR problem. Instances of stress corrosion cracks have occurred in austenitic stainless steel piping in PWRs containing relatively stagnant boric acid solutions; e.g., containment spray and RHRS lines.

A SAMPLE OF INFORMATION
RESOURCES ON PIPE CRACKING

- NUREG-0531
  Investigation and Evaluation of Stress-Corrosion Cracking in Piping of Light Water Reactor Plants
  U.S.NRC (1979)
- NUREG-0679
  Pipe Cracking Experience in Light-Water Reactors
  U.S.NRC (1980)
- NUREG-0691
  Investigation and Evaluation of Cracking Incidents in Piping in PWRs
  U.S.NRC (1980)
- 14. MPA-Seminar
  Stress Corrosion and Thermal Fatigue. Experience and Countermeasures in Austenitic Stainless Steel Piping of Finnish BWR-Plants
  Staatliche Materialprüfungsanstalt (MPA), Stuttgart (Germany), 1988

In most cases the IGSCC indications have been revealed through UT surveys and subsequent metallurgical analyses. Instances of through-wall cracks are known where detection has been possible by leak detection. There are three conditions that must be satisfied to get IGSCC. ***First***, the material must have sensitized microstructure; i.e., precipitation of carbides during welding and due to growth of the carbides during the plant operation. ***Second***, a general opinion has been that the operating environment must be sufficiently oxidizing. There is some evidence that IGSCC also occurs in oxygen free environment, however. ***Third***, there must be relatively high tensile stresses in the material. Consequently, the methods for elimination or reduction of IGSCC in stainless steel pipes fall in three categories:

(1) Selection of corrosion resistant material; e.g., stabilized austenitic stainless steels, or unstabilized austenitic stainless steels having low carbon contents. An eighties opinion was that stabilized austenitic steels are virtually immune to IGSCC. Recent experience indicates that these steels are susceptible to IGSCC too, however[2-19].

(2) Improvement of water chemistry; e.g., hydrogen injection into feedwater. Swedish experience indicates hydrogen water chemistry (HWC) as highly effective in combating IGSCC[2-20].

(3) Modification of stresses. Methods for stress distribution include a) induction heat stress improvement (IHSI); b) mechanical stress improvement process (MSIP); and c) welding overlay repair (WOR). The IHSI and MSIP are commonly used where cracking has not yet occurred or where the crack depth is still shallow in the through-wall direction. When IGSCC is too deep, the crack tip will be situated within the tensile stress zone. In such case IHSI or MSIP would greatly enhance the crack growth and would therefore be unsuitable. For piping components with such deep cracks in the through-wall direction, the application of WOR is required.

Content of chlorides in reactor water cause transgranular stress corrosion cracking (TGSCC) in austenitic stainless steels. The resistance against corrosion that stainless steel has is depending on a passive oxide film that has low electron movement. Chlorides travels into the film to create oxide chlorides that result in high electron movement. Impurities such as copper in the steel have a suppressing effect, whereas inclusions of manganese sulphide with phosphorous and boron enhance the TGSCC susceptibility.

2.4 Human Factors & Human Reliability Considerations

So far we have addressed the failure modes and failure mechanisms of piping; i.e., the emphasis has been on ***how*** piping fails. A generic insight from industrial incident investigations points to the importance of human error contributions. Official incident statistics show that between 20% and 90% of all incidents are indirectly or directly caused by human error. The situation is no different for piping failures. A preliminary evaluation of our database (with 2,611 failure reports in Version 3.0) indicates that ***at least*** 20% of the failures include obvious elements of human factors deficiencies and related human performance problems.

Human errors are either ***latent*** or ***active***; c.f. Reason[2-21] and Embrey et al[2-22] . Effects of a latent error may lie dormant within a system for a long time, only becoming evident after a period of time when the condition caused by the error combines with other errors or particular operating conditions. An example of latent error affecting piping reliability is the design or construction error first revealed, say, several years after commercial operation began. A root cause of such an error could be lack of design knowledge; c.f. Kletz[2-23]. Another example of latent human error affecting piping reliability is the maintenance and ISI-strategy that does not acknowledge existing, generic operating experience with a particular type of piping system. Yet another example would be if a pipe manufacturer has gone out of business, and notice of defective welds made by that company might not have been properly disseminated properly to all potentially affected plants. By contrast, effects of an active human error are felt almost immediately. Examples would be water hammer due to improper post-maintenance restoration of a piping system, or inadvertent overpressurization due to failure to follow procedure.

To date, the most comprehensive assessment of human error contributions to piping failures was commissioned by the UK Health and Safety Executive (HSE) about six years ago; Hurst et al[2-24]. This assessment concentrated on piping failures in the chemical process industry. About 500 piping failure events where analyzed by first developing two event classification schemes: (i) a three-dimensional scheme consisting of layers of immediate failure causes (e.g., operating errors), and (ii) each immediate cause was overlaid with a two-way matrix of underlying cause of failure (e.g., poor design) and preventive mechanism (e.g., task checking not carried out). Hence, each event was classified in three ways; e.g., corrosion as the immediate cause due to design error (the underlying cause), and not recovered by routine inspection (the preventive mechanism).

The British study shows that "operating error" was the largest immediate contributor to piping failure (30.9% of all known causes). Overpressure (20.5%) and corrosion (15.6%) were the next largest categories of known immediate causes. The other major areas of human contribution to immediate causes were human initiated impact (5.6%) and incorrect installation of equipment (4.5%). The total human contribution to immediate causes was therefore about 41%. For the underlying causes of piping failure, maintenance (38.7%) and design (26.7%) were the largest contributors. The largest potential preventive mechanisms were human factors review (29.5%), hazard study (25.4%) and checking and testing of completed tasks (24.4%). A key conclusion of the study was that based on the data analysis, about 90% of all failure events would be potentially within the control of management to prevent.

In NPPs an important direct cause of piping failure has been water hammers; c.f. Uffer et al[2-25]. Underlying cause of several water hammer events has been (active) human errors in operations or maintenance; e.g., operating procedures have not been followed when starting up a system subjected to maintenance, or systems have not been properly drained in connection with maintenance outages. Water hammer events often are avoidable through enhanced operator training, operating procedures with explicit guidance on water hammer vulnerabilities, and system designs with venting/drain provisions, etc.

CAUSES OF PIPING FAILURES

Level:		Examples:
Direct Causes	Corrosion	
		Erosion
		External Loading/Impact
		Overpressure
		Vibration
		Wrong In-line Equipment or Location
		Operator Error
		Defective Pipe or Equipment
Underlying Causes	Design	
		Fabrication or Assembly
		Construction or Installation
		Operations During Normal Activities
		Inspection (e.g., High Radiation Preventing Inspection)
		Regulatory Constraints
		Maintenance Activities
Recovery	Appropriate Hazard Study of Design or As-built Facility	
		Human Factors Review
		Task-driven Recovery Activities (e.g., Checking, Testing)
		Routine Recovery Activities
		Non-Recoverable

Adapted from: Geyer et al[2-26]

Since piping failures are preventable through reliability improvements, attempts to estimate pipe failure rates must recognize the different causes of failure. Because of ongoing piping reliability improvements, some of the information contained by historical data is no longer applicable. Therefore, the data estimation process must be selective. Recognition of the human factors and human reliability perspectives on piping failures is one key step towards selective data estimation.

An important human factors and human reliability consideration is detectability of a piping failure. A large portion of piping failures are detected by plant personnel performing shiftly walk-throughs and system walkdowns to verify equipment status. Timely operator response to a piping failure depends on when and how detection is made, and the nature of the failure (e.g., rupture, leakage, dynamic effects that fail vital support systems - incl. instrumentation - and location). Even relatively benign piping failures could result in significant plant transients should failure detection fail or be delayed. Detectability of piping failures is a function of location in the plant, accessibility, reliability and applicability of leak detection systems, or reliability of non-destructive testing methods[2-27].

The further away from RCS, the more likely is prompt detection. Licensed operators are sensitized to RCS leak detection, however. The pipe failure event database contains ample evidence of the effectiveness of simulator training and good symptom-based abnormal and emergency operating procedures in identifying leaks inside containment.

2.5 Data Exploration

Behind the general category of "piping failure" lies a spectrum of failure modes, and failure mechanisms with their underlying causes. Each failure has unique effects on vital safety function operability and plant response. Piping failure data estimation using operating experience is difficult. All piping failures are not *like* events. This means that certain failure modes and failure mechanisms are unlikely to affect primary system piping. Further, while a leakage in a certain piping system could be benign, a similarly sized leakage in another piping system could be a serious event. Therefore, a *classical statistical analysis approach using pooled data and maximum likelihood estimators could result in misleading insights*. Before estimating failure data parameters, the failure event data must be understood. The thesis that *operational experience is of limited value unless it is interpreted through validated models* is particularly relevant for piping reliability. Validation is accomplished through data interpretation that includes: a) trend analysis; b) structured pooling of data; c) investigation of competing failure modes/mechanisms; and d) identification of an appropriate distribution to describe the data.

The SLAP data base includes a large volume of information on piping failure events. Different plant designs, piping designs, failure mode & mechanisms, metallurgy, operations & inspections philosophies are represented. Before commencing statistical analysis it is vital to understand the implications of these failure event data. As an example, it would be incorrect to pool, say, *all* piping rupture events to generate LOCA frequencies. Carbon steel piping in steam systems exhibit reliability characteristics that differ from stainless steel piping in the RCS, etc. Data exploration begins by searching for *relevant* information, and interpreting and reducing the data against a model of failure:

- As a first step a set of data queries should be developed to sort the event database and to perform preliminary validation of individual event descriptions. New information is added to data records as needed.

- As an example, a first query in SLAP data base (using the MS-Access® functions) considered [Plant-Type]-[Age-of-Component- Socket]-[Event Type]. This query enabled a first check for consistency in failure event type classifications. Database enhancements were made by researching additional information regarding failure modes, failure mechanisms, and consequences of failure.
- As a second example, a query was performed on [Plant-Type]-[Age]-[Event-Type]-

[Cause]-[System-Affected].

- Data exploration should consider failure trends; e.g., increasing or decreasing failure rates. It is feasible that certain combinations of failure modes and failure mechanisms are no longer relevant because of reliability improvement efforts.

- Grouping of failure modes and failure mechanisms. Failure mechanisms could be separated according to piping material; carbon steel versus stainless steel to distinguish RCS- from BOP-piping systems. The piping failure mechanisms are not inherent characteristics of carbon steel and stainless steel, respectively. The mechanisms are ***prevalent*** in respective piping material class because of influence factors typical of the applications for which carbon steel and stainless steel are used, however.

- Piping failure mechanisms are controllable. Each piping system possesses intrinsic failure mechanisms. That is, a certain degree of degradation of the piping material integrity is expected over the lifetime of a system. Deviations from this "base-line" degradation occur because of changes in water chemistry, steam quality, or other plant operating conditions. Deviations can also occur because of differences between the as-designed piping system and the as-installed piping system. Changes in influence factors could have dramatic impact on failure susceptibilities. Over the years extensive piping reliability improvement programs have been implemented, and new ISI-techniques and strategies more effectively address incipient failures. Therefore, some of the older failure data sets may no longer be applicable.

- Majority of piping failure event records in SLAP were extracted from event reporting systems like the U.S. LER-system and Swedish RO-system. Such systems were never intended to directly support PSA applications. Considerable interpretations are sometimes needed to determine cause-and-effect. Relationships such as those described above assist in interpreting piping failure event records. The "relationships" represent a framework for piping failure *pattern recognition*. Given information on failure mechanisms and influence factors (e.g., operating environment), it is possible to draw conclusions about piping material and piping systems involved in a failure event.

- ***Data quality*** is determined by relevance of data interpretations and groupings. As examples; Should steam and water piping be grouped together or treated separately? Should single-phase and two-phase erosion-corrosion failures be treated separately?

- In view of the research on erosion-corrosion mechanisms during the eighties, should failure events that occurred during the seventies (or earlier) be considered by the statistical analysis? Insights from metallurgical analyses have been used to propose reliability improvement programs and some of the historical data may no longer be applicable.

- In the absence of a good piping reliability model there could be an incompatibility problem between PSA requirements and pipe failure rates derived using simple maximum likelihood estimates and uncritical pooling of failure event records. The failure rate of piping is influenced by many factors and generic failure rate distributions must address failure modes, mechanisms, and application.

- Plant-to-plant piping failure rate variability could be considerable (more than an order of magnitude) because of design, operations and aging factors.

- Piping systems are subjected to reliability improvement activities. Selection of piping material of different metallurgy than the original is known to alleviate failure susceptibility or, possibly, eliminate certain failure mechanisms.

2.6 Summary

Failure rate estimation is more than calculating maximum likelihood estimates (i.e., number of failures over total exposure time, or other key reliability attribute). Statistical estimation is the culmination of a reliability engineering effort, and ***after*** relevant operating experience has been interpreted and organized according to failure modes and failure mechanisms with their influences. In deriving generic and plant-specific pipe failure rates, the emphasis should be on the quality of information and assumptions input to the statistical estimation process. *Consistent, integrated interpretations are obtained through multi-disciplinary data review processes where PSA analysts and structural engineers cooperate.*

3: OPERATING EXPERIENCE WITH PIPING SYSTEMS

3.0 Overview

Central to the research on piping reliability is the relational database on pipe failure events as documented in Appendices A and B. The available operating experience will be used to generate pipe reliability data parameters for use in PSA. In preparation for statistical estimation of reliability parameters, the data base content was screened and grouped according to failure modes and mechanisms. Different data pooling strategies were also explored, and a limited trend analysis of the data was performed. Section 3 summarizes the data base content intended for estimation of pipe failure data parameters. The data presentation consists of three parts: (i) the database content, (ii) global pipe failure trends, and (iii) pooled pipe failure event data.

3.1 The Database Content

In constructing the pipe failure event database, mainly four information resources were utilized: 1) the U.S. Licensee Event Report data base for information on piping failures in U.S. NPPs; 2) SKI's Reportable Occurrence data base (STAGBAS) for information on piping failures in Swedish NPPs; 3) the Nuclear Energy Agency's "Incident Reporting System" (IRS); and 4) proprietary incident investigation reports on pipe failures made available to the project by utilities.

These primary data sources were supplemented by data extracted from a large number of topical reports on operating experience with piping systems. To facilitate a preliminary comparison between the nuclear and chemical industries, piping failure event data were extracted from the UK Major Hazard Incident Analysis System (MHIDAS) and selected proprietary information databases on pipe failures in the oil refinery industry[3-1].

All failure events recorded in SKI's database have, as a minimum, resulted in repair or replacement of a piping system component. An overview of SKI's database content is given by Tables 3-1 and 3-2, and Figures 3-1 through 3-4. The pipe failure modes considered included "crack/indication", "pinhole leakage", "leakage", "rupture", and "severance". Only a selection of significant events involving detection of pipe cracking were included in the database. The fault locations were either in the base metal, heat affected zone (HAZ) or weld metal. Cracks/indications are detected through special inspections during maintenance/refueling outages. Leakages are caused by through-wall cracks or openings resulting in measurable loss of process medium (e.g., reactor water, steam). Most leak events are self-revealing and found by leak detection systems, or by maintenance personnel performing periodic system walkdowns. The effects of leakage on plant operation depend on location and piping system.

Plant Type	No. of Records on Crack / Indication	No. of Records on P/H-Leakage + Leakage + Rupture
BWR	73	659
PWR	52	1353
LWGR	1	56
PHWR	8	83

Note: P/H-Leakage = Pinhole leakage

Table 3-1: *Overview of Database Content on Pipe Failures in Commercial Nuclear Power Plants - SLAP Version 3.0 (Rev. 1).*

Mode of Operation When Failure Occurred	No. of Records on Crack / Indication	No. of Records on P/H-Leakage + Leakage + Rupture
Commissioning	4	176
Cold Shutdown	91	113
Hot Shutdown	1	13
Startup	-	20
Power Operation	37	1830

Table 3-2: *Overview of Database Content in SLAP Version 3.0 (Rev. 1): Nuclear Power Plant Mode of Operation When Pipe Failure Occurred.*

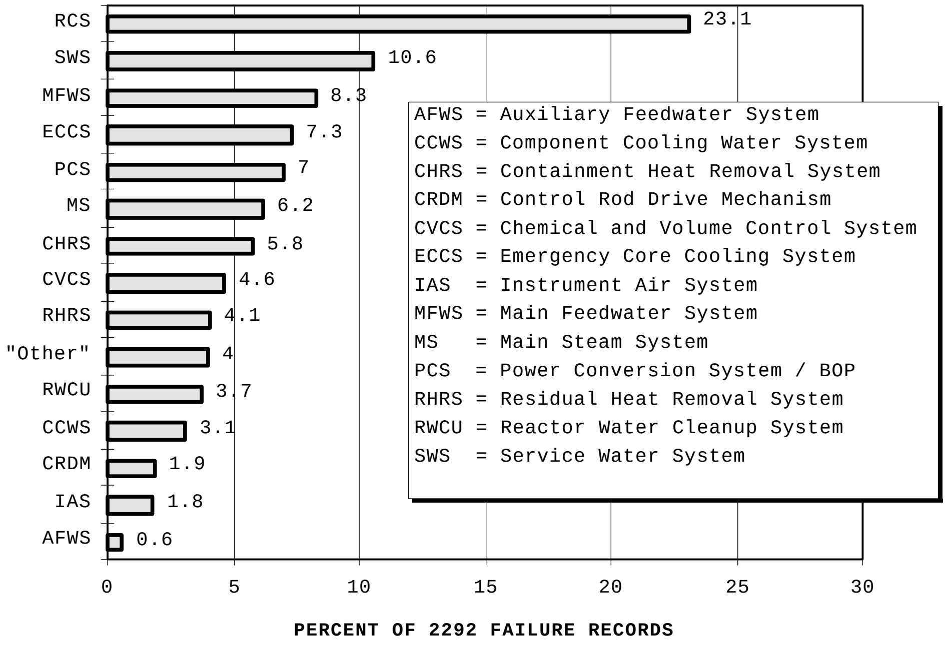


Figure 3-1: *Pipe Failure Events in Nuclear Power Plants Categorized by System - SLAP Version 3.0 (Rev. 1).*

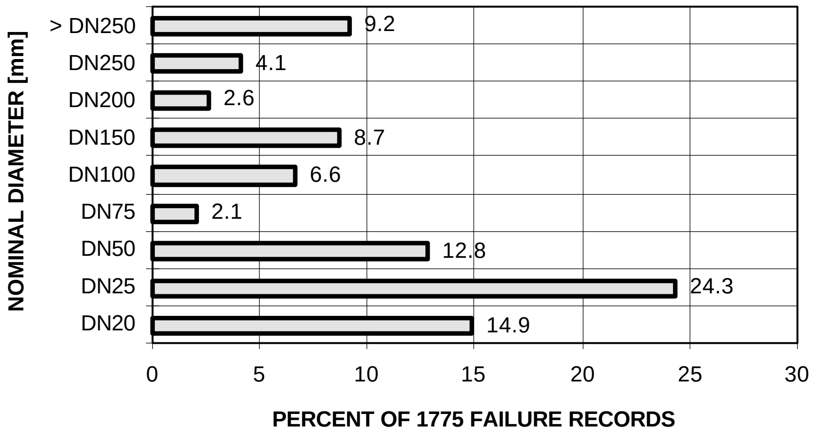


Figure 3-2: *Pipe Failures Categorized by Pipe Diameter - SLAP Version 3.0 (Rev. 1).*

Majority of failures in "RCS" and safety systems connected to RCS have occurred in piping < DN100, and majority of failures in PCS have occurred in piping > DN200. Examples of apparent causes (or symptoms) of piping failures are summarized in Figures 3-3 and 3-4, and Figures 3-8 through 3-11. The "No Cause/Other" in Figure 3-3 represents failure events records without information on apparent and underlying root causes. The proportion of "human errors" in SLAP is considerable. This failure cause category includes active and latent human errors.

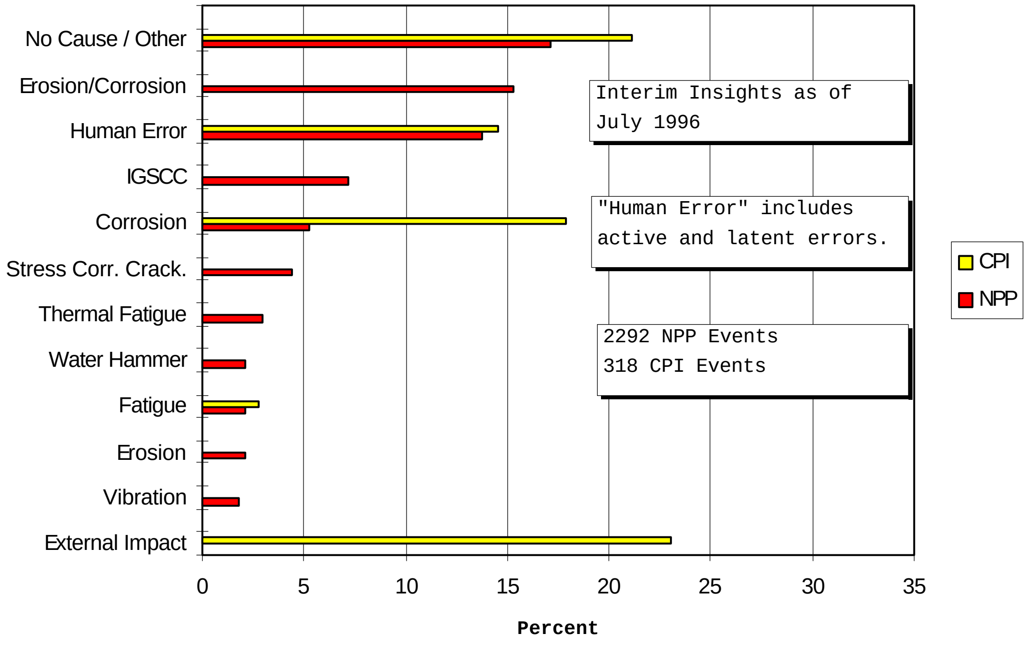


Figure 3-3: *Pipe Failure by Apparent Cause (Nuclear vs. Chemical Industry Data).*

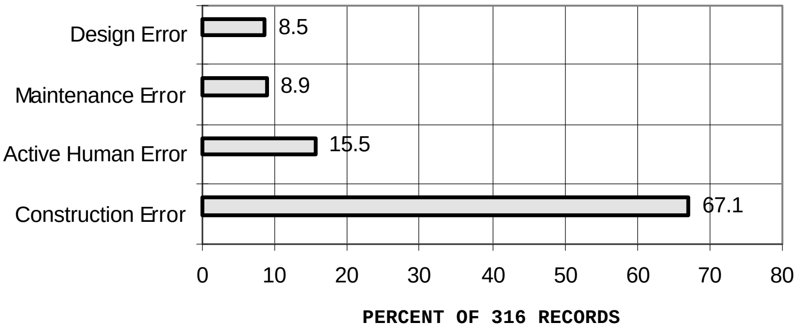


Figure 3-4: *Underlying Causes of Piping Failures (Nuclear Industry Data) - SLAP Version 3.0 (Rev. 1). Active Versus Latent Human Errors.*

Data interpretations of the "human error" information is complex. Active human errors rarely cause piping failures on their own. They typically constitute "trigger events" that in combination with one or more failure/degradation mechanisms (e.g., corrosion, erosion-corrosion) and a unique mode of plant operation result in pipe leakage, severance or rupture. Further, active human errors could be symptoms of underlying latent human errors such as design or construction errors, and organizational errors. Construction and design errors are normally revealed during plant commissioning. In some instances they could be revealed after several years of operation[3-2], and only after full-system decontamination. These errors therefore add complexity to data interpretation as well as pooling of data (i.e., which data sets should be included/excluded from a sample?).

3.2 Global Pipe Failure Trends

Data exploration involves identification of trends in reliability data. The trends might represent a long term decline in times between failure (TBF) or presence of reliability growth in the TBFs. Simple graphing can shed light on the possible presence and nature of trend in TBFs. As an example, plotting the cumulative number of failures against the accumulated operating time, the plot should be approximately ***linear*** if no trend is present, but ***concave*** (***convex***) corresponding to an increasing (decreasing) trend.

The database content reflects on the quality of the reporting systems from which the information on piping failures have been extracted. The ***coverage*** by these reporting systems of failure events involving piping systems is relatively low; e.g., considerably less than 100% of actual failures in BOP systems get reported. Biases in the data due to the level of data base coverage could influence the validity of trends. The next suite of plots (Figures 3-5 through 3-13) display some global pipe failure data trend insights.

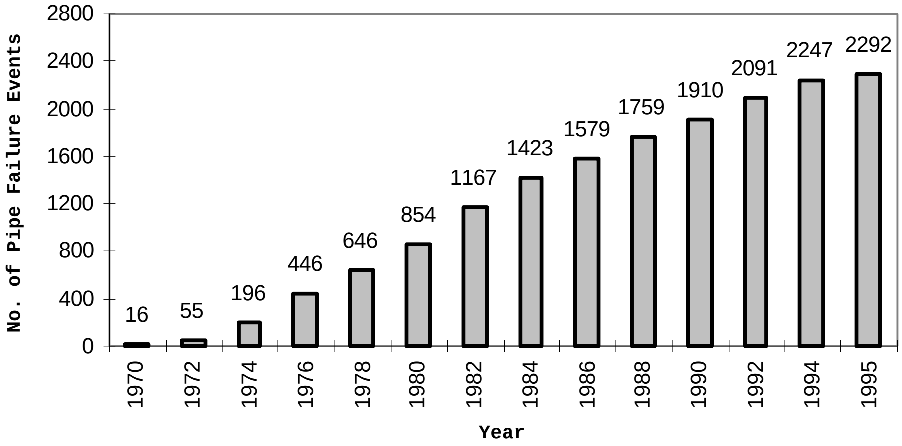


Figure 3-5: *Cumulative Number of Pipe Failures in NPPs (Critical and Non-Critical Failures - SLAP Version 3.0 (Rev. 1).*

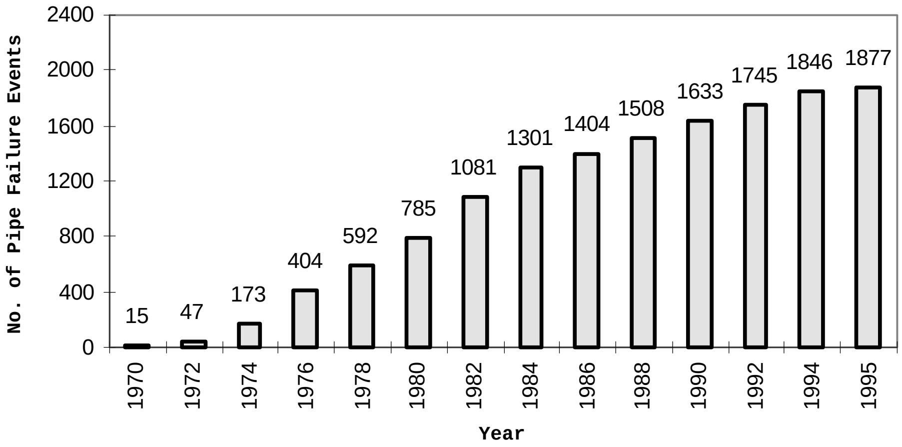


Figure 3-6: *Cumulative Number of Pipe Failures (Critical and Non-Critical) in Swedish and U.S. NPPs - SLAP Version 3.0 (Rev. 1).*

The histogram in Figure 3-5 reflects on the data base content ***and*** respective reporting system's ***coverage*** of piping failures. The same presentation format is used in Figure 3-6, but limited to the Swedish and U.S. operating experience. As expected, Figures 3-5 and 3-6 exhibit nearly identical trends. A comparison of number of reported failure events per reactor-year for Swedish and U.S. BWRs is given by Figure 3-7. The data presentation in Figure 3-7 possibly highlights differences piping reliability as well as regulatory attention to piping failures and the reporting requirements. The trends in Figures 3-5 through 3-7 reflect:

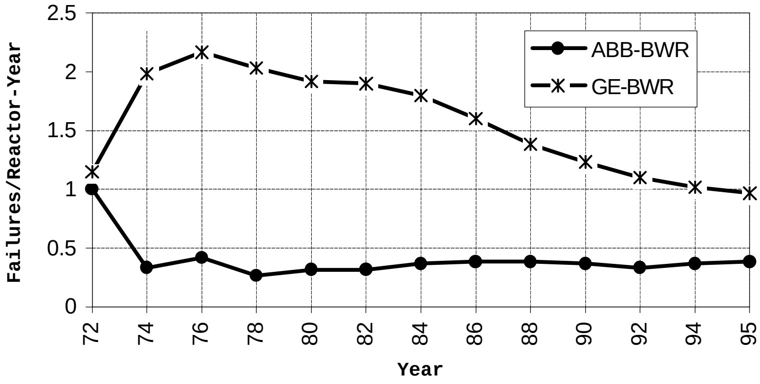


Figure 3-7: *Global Pipe Failure Trends - Comparison of Pipe Failure Events in Swedish and U.S. BWR Plants.*

- The event reporting criteria (i). Non-uniform reporting of piping failures means that it is difficult to assess database coverage. As an example, piping failures that do not result in automatic or manual reactor trip are subject to discretionary reporting.

- The event reporting criteria (ii). No uniform, all-encompassing reporting requirements exist for piping system components. Changes in the number of reported failures from year-to-year are functions of the attention to particular problems by industry and regulators. IGSCC problems during the mid-seventies and erosion-corrosion problems during the mid-eighties resulted in improved reporting.

- Corrective actions. Programs have been implemented to address erosion-corrosion damage, IGSCC, thermal fatigue and vibration-fatigue. These programs have improved short-term pipe reliability. The global trends do not address aging contributions. Deeper analysis of failure data is needed for evaluation of the aging phenomena.

- Database coverage. Failures in carbon steel piping (outside containment) are usually more easily repaired than stainless steel piping (inside containment). Failures occurring in, say, BOP-piping are often repaired without impacting the availability of reactor system and safety systems. While such failures are included by work order systems, they are not necessarily included by LER- and RO-systems. For the Swedish plants no reports on erosion-corrosion were found in the RO-system, yet several failures have occurred over the years; c.f. Hedström[3-3]. In a search of the Swedish reliability data system (TUD) a total of 800 reports on weld repairs were found, and about 400 of these are believed to have been made on IGSCC-sensitive piping which is a factor of ten more reports than found in the RO-system.

The experience with erosion-corrosion, vibration-fatigue, stress corrosion cracking and thermal fatigue, respectively, is summarized in Figures 3-8 through 3-11. Erosion-corrosion (Figure 3-8) is a phenomena seen in carbon steels and low-alloy steels found in BOP-systems. Following the major erosion-corrosion incidents at Trojan and Surry-2 in 1985 and 1986, respectively, most utilities have instituted monitoring programs to predict pipe failures and take corrective action.

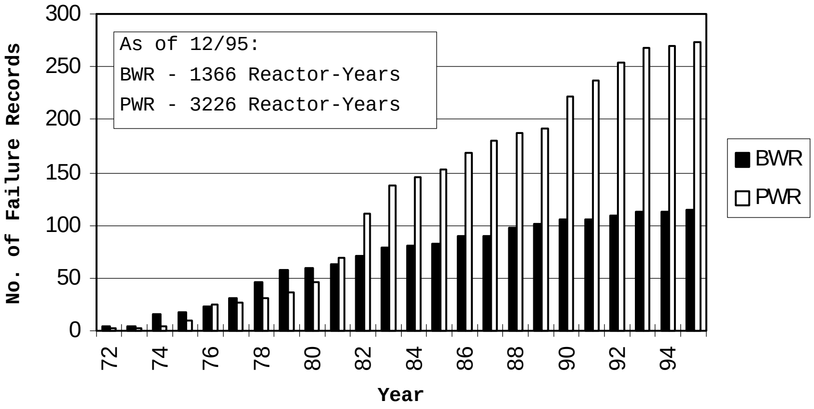


Figure 3-8: *Erosion-Corrosion Damage in LWRs - SLAP Version 3.0 (Rev. 1).*

Mechanical (vibration-induced) fatigue is mainly a problem in small-diameter piping (≤ DN25). It is reported as the failure mechanism for 425 events (in BWRs and PWRs) examined in this study; Figure 3-9, page 30.

In Finnish and Swedish BWRs, thermal fatigue damage has occurred in "mixing tees" where feedwater (at 20 - 180°C) is mixed with water returning from the reactor coolant clean-up system (at 270°C). Pipe failures due to thermal fatigue have occurred in feedwater lines in PWRs during hot standby and during startup and shutdown when the feedwater heaters are not being used. Thermal fatigue is reported as the failure mechanism for 69 events (in BWRs and PWRs) examined in this study; Figure 3-10, page 30.

Stress corrosion cracking, SCC (including IGSCC and TGSCC), has been reported for most, if not all, operating reactors. IGSCC is mainly a BWR problem manifested as cracking in the heat-affected zone (HAZ) adjacent to girth welds that join austenitic steel piping. It is associated with the synergistic interaction between stress in the material, the oxygenated coolant, and a sensitized weld HAZ. In PWRs SCC-damage has been found in containment spray and safety injection systems containing stagnant borated water. In BWRs IGSCC-damage has been found in recirculation lines, core spray lines, reactor water clean-up lines, and control rod drive return lines. No severe failures (e.g., severances or ruptures) have been reported, however. Stress corrosion cracking resulting in leakage is reported as the failure mechanism for 258 events (in BWRs and PWRs) examined in this study; Figure 3-11, page 30.

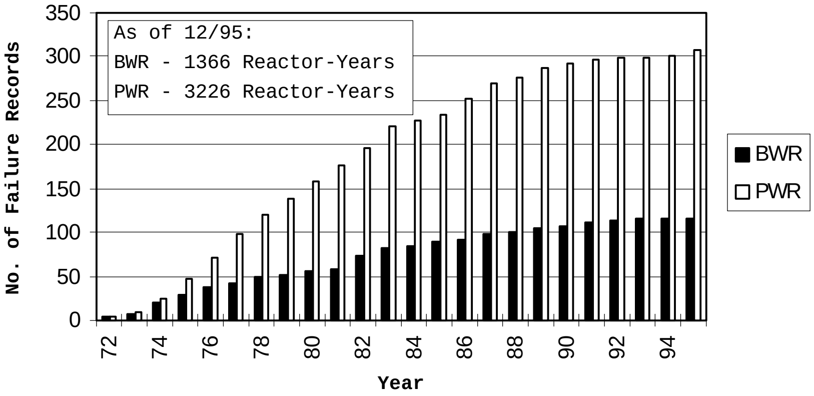


Figure 3-9: *Vibration-Fatigue Damage in LWRs - SLAP Version 3.0 (Rev. 1).*

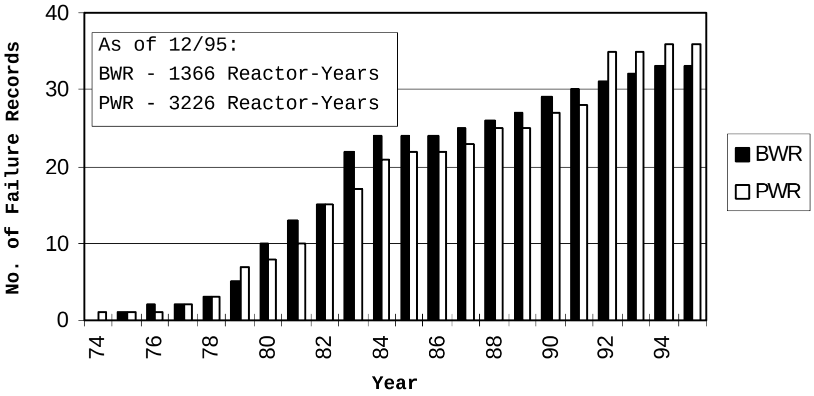


Figure 3-10: *Thermal Fatigue Damage in LWRs - SLAP Version 3.0 (Rev. 1).*

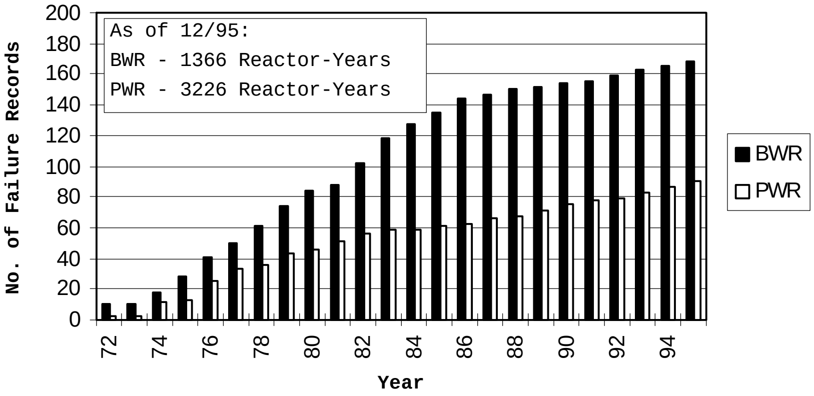


Figure 3-11: *Stress Corrosion Cracking Experience in LWRs - SLAP Version 3.0 (Rev. 1).*

Some results from statistical trend analysis are given by Figures 3-12 and 3-13. In Figure 3-12, time to pipe rupture due to erosion-corrosion is represented by a convex model. Water hammer events that have caused pipe failures are shown in Figure 3-13.

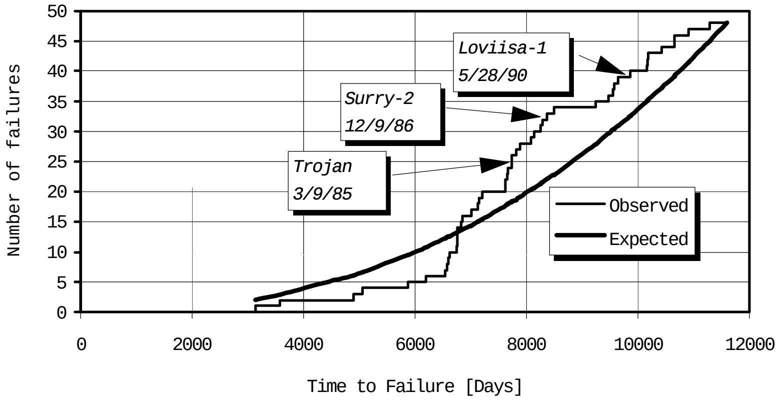


Figure 3-12: *Cumulative Number of Pipe Ruptures Due to Erosion-Corrosion*[3-4].

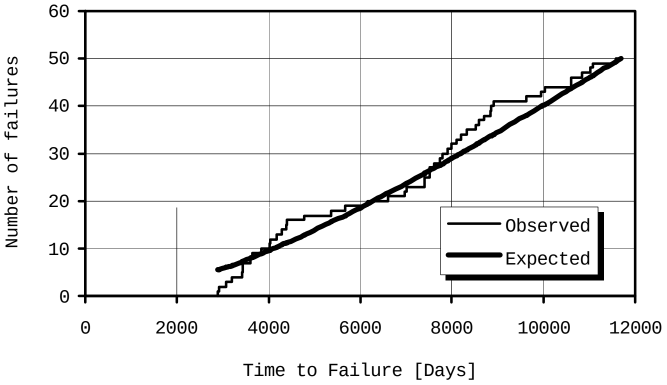


Figure 3-13: *Cumulative Number of Pipe Failures Due to Water Hammer*[3-4].

3.3 Pooled Pipe Failure Event Data

Event records residing in SKI's pipe failure event data base come from several different sources; mostly from regulatory reporting systems. In preparing for (deep) statistical estimation these records are pooled according to the following reliability attributes:

- Apparent failure cause and failure mode. It is recognized that by only addressing the "apparent failure cause" vital information about failure mechanisms and influence factors can be lost. This is a problem being addressed in Phase 3 of this project.

- Pipe diameter (e.g., small-, intermediate- and large-diameter piping) and metallurgy (e.g., carbon steel and stainless steel). In this summary the following classification is used:

  - Small-diameter piping; DN ≤ 150
  - Intermediate-diameter piping; 150 < DN ≤ 350
  - Large-diameter piping; DN > 350

- Apparent failure cause, failure mode and affected system.

An exposé of results from pooling of event records are summarized in a suite of cumulative distribution plots (hazard plots); Figures 3-14 through 3-19. These plots are ***visual aids*** for continued data reduction and analysis. They were developed using the MS-Excel® software as a first step in organizing the data for formal statistical analysis. Each plots generates a set of questions to be used in the deeper analysis of failure mechanisms and their impact on piping reliability. The hazard plots assist in identifying data clusters that could reflect "dependencies" caused by design commonalities or inherent reliability characteristics. The plots can be seen as tools for pooling failure data. Each of the plots identifies outliers. In some cases, such outliers (i.e., early-life failures) could be the result of over-stressed piping systems caused by design or installation errors. In summary, the hazard plots as used here are visual aids for continued data reduction and analysis:

- Figure 3-14: Rupture events in LWRs caused by erosion-corrosion damage. The events are divided into failures in small-, intermediate and large-diameter piping. Of ruptures in large-diameter piping, only one occurred among the BWRs. The scatter plot for small- and intermediate-diameter piping consists of several distinct subsets; i.e., the plot represents mixed distributions.

- Figure 3-15: Leak and rupture events in small-diameter piping (DN ≤ 25) due to damage from vibration-fatigue. Early-life failures (failures within the first year of commercial operation) are not included in the plot.

- Figure 3-16: Through-wall cracks/leaks in stainless steel piping in BWRs caused by IGSCC.

- Figure 3-17: Through-wall cracks/leaks in stainless steel piping in PWRs caused by stress corrosion cracking (SCC). Stagnant borated water in ECCS piping has been a contributing factor behind several of the events (about 30%).

- Figure 3-18: Leaks in LWR piping due to thermal fatigue. Thermal fatigue is a failure contributor ***and*** also a symptom of underlying problems in system operation practices.

- Figure 3-19: Leaks and ruptures in LWR piping due to water hammer. The pipe failure event data base includes pipe ruptures caused by the combined effects of water hammer ***and*** a pipe failure mechanism like erosion-corrosion.

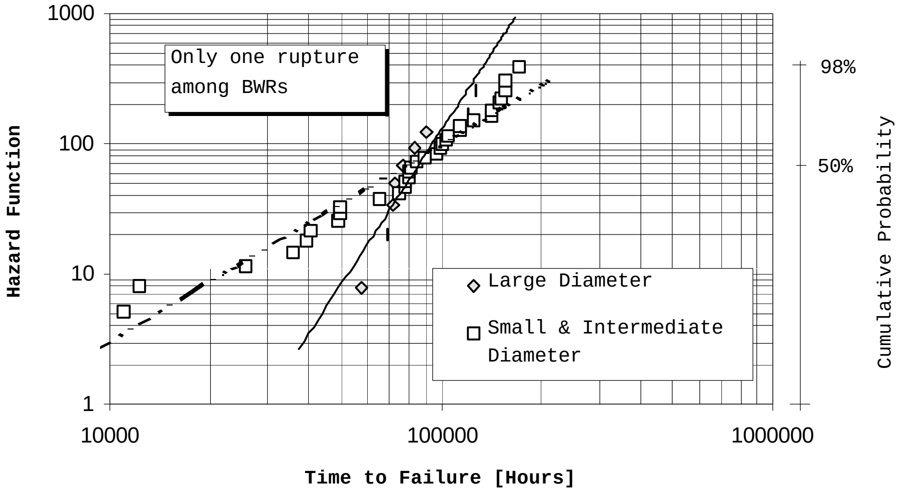


Figure 3-14: *Pipe Rupture in LWRs Due to Erosion-Corrosion - Carbon Steel Piping.*

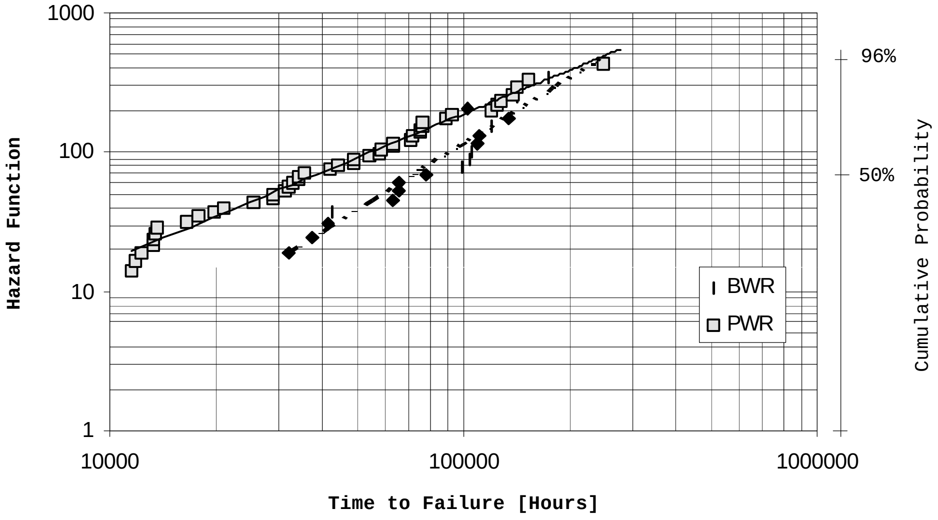


Figure 3-15: *Pipe Leaks & Rupture in RCS Piping (DN ≤ 25) Due to Vibration-Fatigue.*

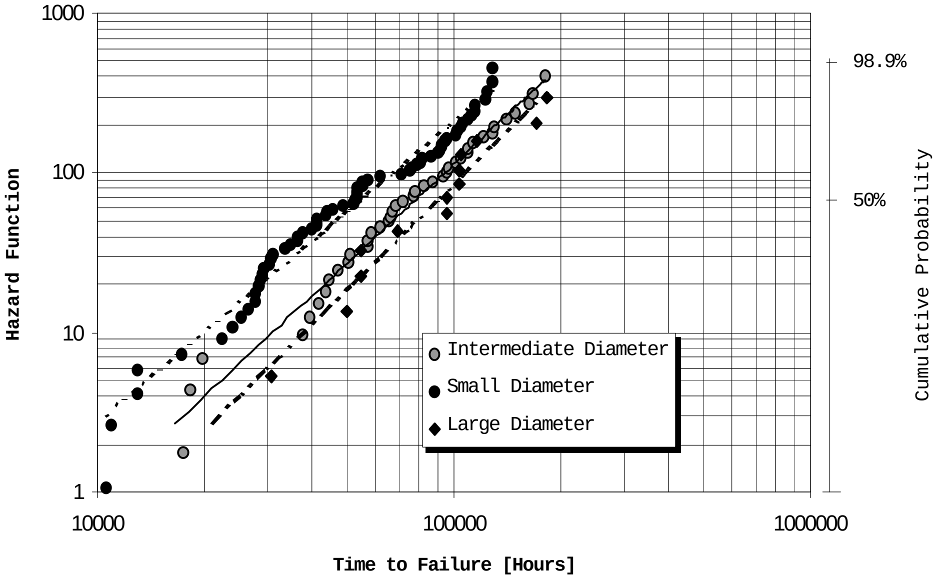


Figure 3-16: *Pipe Leaks in BWR Piping Due to IGSCC - Stainless Steel Piping.*

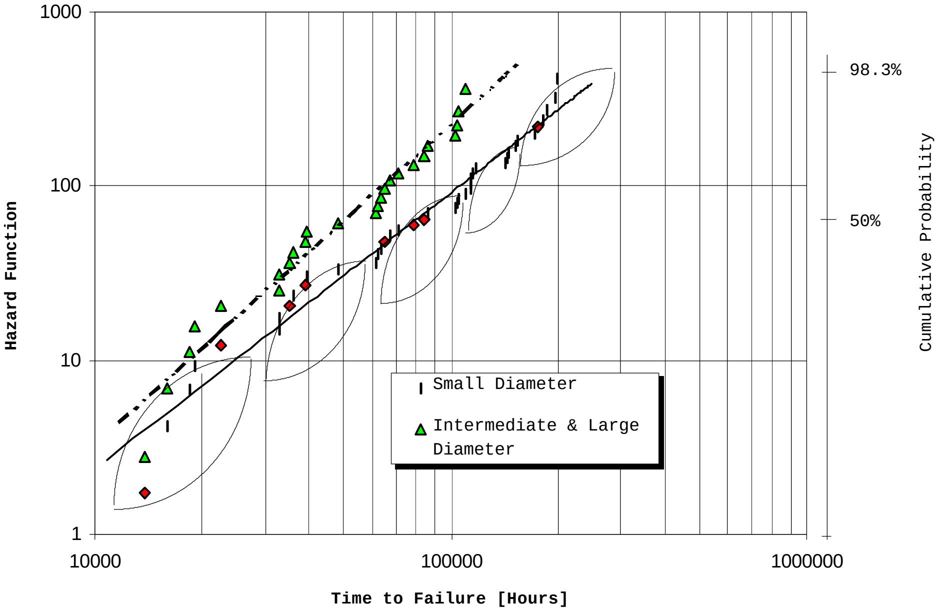


Figure 3-17: *Pipe Leaks in PWR Piping Due to SCC - Stainless Steel Piping.*

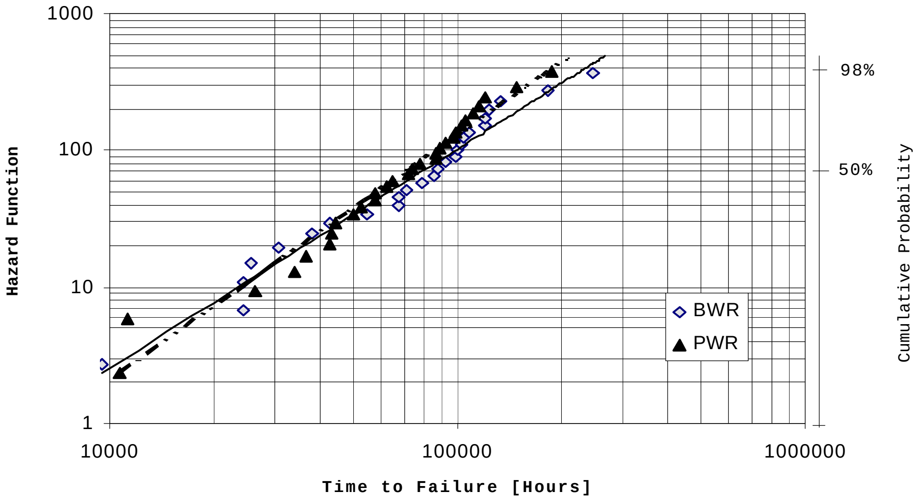


Figure 3-18: *Pipe Leaks and Ruptures in LWR Piping Due to Thermal Fatigue.*

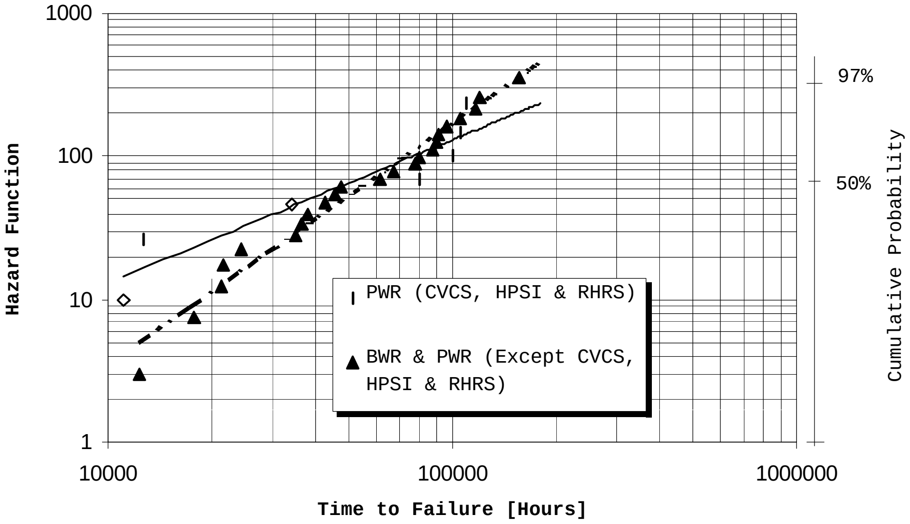


Figure 3-19: *Pipe Leaks and Ruptures in LWR Piping Due to Water Hammer.*

Questions To Be Addressed in Phase 3 of Project:

- Most of the erosion-corrosion failures in large diameter piping have occurred in steam extraction lines. What are the correlations between fault location, ISI procedure and failure frequency?

- For small and intermediate diameter piping there have been several erosion-corrosion failures of steam lines for turbine-driven pumps in safety injection systems. It is assumed that most of these failures have occurred during periodic testing. To what extent do the testing protocols address the pressure boundary integrity of these piping systems?

- The current version of SKI's data base show a preponderance of erosion-corrosion induced ruptures in PWRs. What are the key pipe failure correlations of BWR versus PWR piping?

- For BWR piping, the plot in Figure 3-15 (vibration-fatigue damage) shows three data clusters. How do these clusters relate to the specific plant systems and vibration sources.

- Many vibration-fatigue failures in PWR piping have occurred within the first two or three years of commercial operation. How many of these failures have developed in the Chemical and Volume Control System (make-up system)? Is there a correlation between pipe failures in make-up systems with centrifugal or reciprocating pumps?

- What corrective actions have been taken at PWR plants to combat vibration-fatigue in make-up systems?

- What are the sources of vibration, and what are the contributing factors behind pipe failures (e.g., insufficient pipe support)?

- The plot on IGSCC events (Figure 3-16) includes instances of significant damage (i.e., through-wall cracking) to BWR-piping. IGSCC has been studied for over twenty years and several environmental (e.g., water chemistry) and metallurgical (e.g., carbon content) have been identified as contributors to IGSCC failures. What are the correlations between the remedial programs (e.g., improved water chemistry) to combat IGSCC and pipe failure?

- Correlation between welding methods and IGSCC (e.g., gas tungsten arc welding versus shielded metal arc welding)?

- Short term versus long term IGSCC induced pipe damage. According to SKI's data base, IGSCC damage has developed after a relatively short time of operation (e.g., less than 20,000 hours of commercial operation). Under what conditions did through-wall cracks develop? Are the same conditions applicable today?

- IGSCC in large diameter piping. Most of the failures documented in SKI's data base represent small and intermediate diameter piping. Under what conditions did these failure events develop? What are the lessons learned from full-system decontamination and metallurgical surveys (such as those performed on Oskarshamn-1)?

- Time dependencies. Are there reasons to expect increased or decreased IGSCC frequencies as plants get older? Any yet unrecognized failure influence factors?

- There are four principal failure mechanisms contributing to SCC (Figure 3-17) in PWR piping systems: (i) thermal fatigue due to stratification of hot and cold water in feedwater systems, (ii) fatigue induced cracking of small-diameter piping, (iii) SCC of thin-walled piping containing boric acid, and (iv) water hammer or water slugging. What is the extent of overlaps in SKI's data base on SCC events and events classified as, say, thermal fatigue or water hammer?

- Apparent and underlying causes of SCC induced pipe failure. To what extent do data exploration insights change by acknowledging apparent ***and*** underlying failure causes?

- Design differences. There are numerous design and operational differences between the different NSSS vendors (e.g., ABB-Combustion, Babcock & Wilcox and Westinghouse). What would the effects be on data exploration insights by grouping/binning the event data by system, NSSS vendor and piping system designer/manufacturer?

- Boric acid induced corrosion and cracking is a well known problem in CVCS and ECCS. Utilities have taken steps to alleviate the problem by controlling internal and external contamination of piping and by avoiding stagnant boric acid. To what extent can the data exploration distinguish between events before-and-after implementation of such reliability improvement programs.

- Symptoms and root causes of thermal-fatigue damage. Should the continued data analysis differentiate between the underlying causes of failure?

- Several pipe failures have been caused by the combined effects of water hammer events and failure mechanism such as erosion-corrosion and equipment failure (e.g., spurious valve closure) or human error (e.g., air pockets left in piping system due to improper re-commissioning). The continued treatment of water hammer events is a function of PSA modelling needs; i.e., to what extent should water hammer susceptibilities be explicitly addressed by PSA?

- Should the continued data exploration identify the key contributing factors of water hammer events?

3.4 Summary

Failure rate estimation is more than calculating maximum likelihood estimates (i.e., number of failures over total exposure time, or other key reliability attribute). Statistical estimation is the culmination of a reliability engineering effort, and after the relevant operating experience has been interpreted and organized according to failure modes and failure mechanisms with their influences. *Consistent, integrated interpretations are obtained through multi-disciplinary data review processes where PSA analysts and structural engineers cooperate.* The exposé of piping failures is a first step in addressing piping failures and their influences. More detailed data and statistical analysis to obtain mechanism- and metallurgy-specific failure rates will be addressed in future work. This work will also consider the topic of aging (including the research by Vesely[3-5] and others) and how it relates to piping reliability data estimation.

4: CONCLUSIONS & RECOMMENDATIONS

4.0 Overview

Directed at expanding the capability of probabilistic safety assessment (PSA) practices, SKI in 1994 initiated a multi-year, multi-phase research project on piping system component reliability. An important element of the project has been the development of a worldwide piping failure event data base (Phase 1). This report documents Phase 2 results with emphasis on piping reliability estimation from operating experience as included in the data base.

4.1 Conclusions

The SKI database includes about 2,600 piping failure event records (including about 300 piping failures in chemical process industry, CPI), with emphasis on Nordic and U.S. commercial nuclear power plant data. The scope of the Phase 2 of the project is given by Figure 4-1. In evaluating the data base content the following conclusions have been reached:

- Pipe failure rate estimation is sensitive to data interpretations. By exploring the data base it is seen that there is considerable plant-to-plant and system-to-system variability in failure occurrence. The reliability influence factors are many, and location dependency of piping failures is strong. Most failures occur at or near piping system discontinuities such as elbows, tees, welds, control valves. Influences from geometric shape factors (diameter, wall thickness) and metallurgy (e.g., carbon steel versus stainless steel) also are considerable.

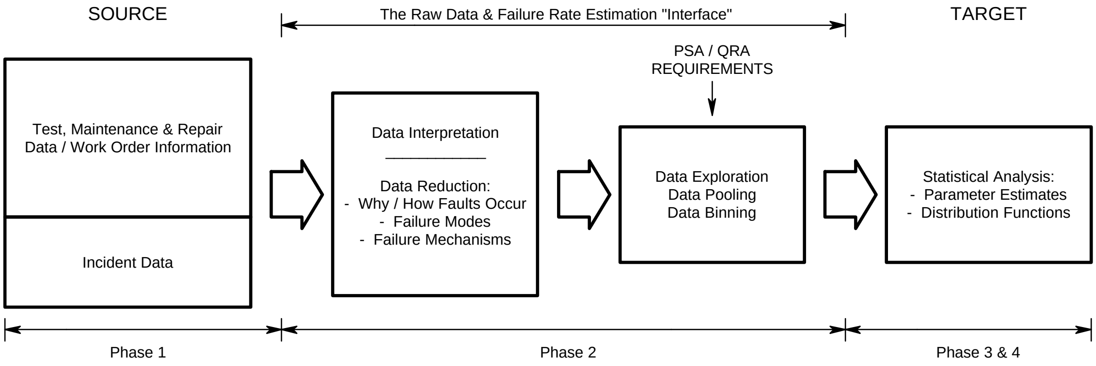


Figure 4-1: *The Reliability Data Analysis Process (Adapted from Lydell[4-1]).*

- About 20% of all piping failure events have human factors deficiencies as underlying cause; e.g., design errors, fabrication/construction errors, deficient operating procedures. These events often reflect directly on organizational factors and safety culture. Hence, a substantial reliability improvement is feasible by addressing these factors in plant safety. Latent human errors are typically revealed during commissioning of systems, active human errors occur throughout the plant life cycle.

- Piping systems are subjected to reliability improvements. Lessons learned from, say, experience with erosion-corrosion damage in steam, wet steam or water piping have been applied to revised ISI-strategies, pipe section replacement policies. Because of learning effects, older failure event data may no longer be applicable.

- Statistical analysis of piping failure event data must be based on thorough understanding of *why*, *how*, *where* piping fails. Event data should be categorized according to failure mode, failure mechanism, and predominant influence factor(s).

- To account for aging of passive equipment, statistical analysis should consider critical and non-critical failures, as well as complete, degraded and incipient failures. Earlier investigations have indicated an approximately linear trend in the aging contribution as the plant age increases. Additional data analysis is required to determine whether the probability of piping failure can be systematically increasing with plant age due to aging mechanisms.

- Analysis of piping failure data requires engineering evaluations to determine the impact of operating conditions, metallurgy, and ISI on piping reliability.

- Effective management of plant safety relies on the use of operating experience; c.f. INSAG-5[4-2]. The preliminary insights about piping reliability reported here reflect existing failure reporting routines. Without a rigorous, systematic evaluation of the operating experience with piping system components, the future plant modernization projects could encounter problems associated with finding optimum design solutions that address specific failure modes and failure mechanisms. The feedback of operational data involving piping system failures must be improved.

- The failure mechanisms addressed in this report are not intrinsic properties of the respective piping systems. Instead, the pipe failure mechanisms are characteristics of carbon steel and stainless steel piping, respectively, and their operating environments. Each failure mechanism is a symptom of underlying influence factors ranging from piping system design, via water chemistry, to plant operating conditions (e.g., number of transients).

4.2 Recommendations

Phases 3 and 4 of the ongoing research will focus on data base validation, statistical analysis of failure data, and pilot applications. Further developments should be directed towards:

- Formalizing the statistical analysis structure and develop a data presentation format that can be accommodated and recommended by future editions of the IE-Book and T-Book.

- Deeper data analysis and statistical analysis of mechanism- and metallurgy -specific failure rates. Analysis of influence of ISI on piping reliability.

- Meaning of incipient failures and precursor events. An effort should be directed to how to acknowledge piping defects in extrapolations of failure data. The incident investigation guidelines should include provisions for probabilistic event analysis that account for passive component failures. Therefore, the Phase 3 and 4 results should be translated into a practical guidance for assessing the safety significance of piping failures.

5: REFERENCES & NOTES

Section 1:

[1-1]. PSA studies have included limited, explicit treatment of passive component reliability using analysis techniques compatible with PSA methodology. In PSA Level 1 (internal events) this treatment typically consists of initiating event frequency estimation using published data (e.g., WASH-1400), and in the case of ISLOCA the assessments have largely focused on valve rupture probability estimation. Many PSA project scope definitions have excluded explicit treatment of piping system components from system analysis tasks.

In PSA Level 1 (external events), seismic evaluations address equipment fragilities. Fragility evaluations involves estimating the seismic input parameter value at which a given component, structural element or an equipment item fails. Estimation of this value (called the ground motion capacity) is accomplished using information on plant design bases, response calculated at the design analysis stage, and as-built dimensions and material properties. Flooding evaluations have sometimes focused on pipe or valve ruptures potentially causing flooding of vital plant areas. PSA Level 2 (containment analysis) includes identification of containment failure modes. A containment event tree is developed for each sequence of interest. If the containment is predicted to fail, the analysis predicts the time at which it will fail, where it will fail, and the energy associated with a release. Failure mode definition is based on reviews of existing structural analysis developed at the design case, and sometimes supplemented with confirmatory structural analyses. Assessments of RPV failure probability are normally included in PSA Level 2.

[1-2]. The combined, worldwide operating experience with commercial nuclear power plants at the end of 1995, based on: International Atomic Energy Agency, 1994. *Nuclear Power Reactors in the World*, Vienna (Austria), ISBN: 92-0-101794-2.

[1-3]. There have been no large LOCA in 6,300 reactor-years of operating experience. In the absence of data on large LOCAs, an upper limit on the frequency may be calculated using the Chi-Square distribution with two degrees of freedom. This would yield approximately 1.0E-4/year.

[1-4]. Woo, H.H. et al, 1984. Probability of Pipe Failure in the Reactor Coolant Loops of Westinghouse PWR Plant. Volume 1: Summary Report, UCID-19988 (NUREG/CR-3660), Lawrence Livermore National Laboratory, Livermore (CA).

[1-5]. ECU = European Currency Unit is the official unit of account of the European Union (EU) institutions, including the European monetary system. It is a composite unit reflecting the values of the currencies of most EU member states. The rate of exchange is approximately: 1 ECU = 1.3 USD.

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OPRA = Oconee PRA, a tutorial PSA co-sponsored by the Nuclear Safety Analysis Center and Duke Power Company. OPRA was completed in June 1984, and published as NSAC-60 by the Electric Power Research Institute. "OPRA" is not to be confused with "OPSA" (Oyster Creek Probabilistic Safety Analysis completed in draft form in 1979).

In support of plant modifications, including extensive primary system piping replacements, OKG AB initiated the Fenix project in 1992. Fenix included the update of Oskarshamn-1 PSA with emphasis on LOCA assessments.

[1-8]. In this report we make distinction between "early" and "contemporary" PSAs. Studies completed prior to 1988 are categorized as "early." The current PC-based codes for PSA became widely available during 1988-1990, and these allowed for today's highly integrated (and detailed) plant and system models.

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Section 3:

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[3-2]. Environmentally induced trans-granular stress corrosion cracking (TGSCC) has been known to occur in stainless steel piping exposed humidity and/or saline air when stored onsite prior to installation. Through-wall cracking of small-diameter piping in the hydraulic scram system in Barsebäck-1 in November 1981 was attributred to TGSCC in piping that had been stored in the turbine building during plant construction. Subsequent investigations noted that the piping had been exposed to saline air during installation work in 1974.

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APPENDIX A: SELECTED PIPE FAILURE EVENTS

A.0 Data Selection Criteria

SKI's "Worldwide Pipe Failure Event Data Base" contains over 2,300 event reports. Appendix A presents selected, representative event reports from the data base that address typical failure mechanisms, and failure modes and effects. The following criteria were applied to the selection of reports:

- Failure mechanisms. Section 3 of this report addresses erosion-corrosion, vibration-fatigue, stress corrosion cracking, thermal fatigue, and water hammer. For each of these, representative event reports (Table A-1 and pages 50 through 73) were selected to demonstrate the type of information available to the data analyst.

FAILURE MECHANISM	SLAP EVENT ID - DATE	PLANT TYPE	COMMENT
Erosion-corrosion	480 - 3/16/85	PWR	
	498 - 12/31/90	PWR	
	545 - 3/9/85	PWR	Triggered by water-hammer.
	595 - 12/9/86	PWR	
	2276 - 3/1/93	PWR	
Vibration-fatigue	476 - 9/15/85	BWR	Acoustically induced.
	606 - 9/23/77	PWR	
	605 - 7/5/84	PWR	
	946 - 9/7/73	PWR	
	1498 - 10/5/80	PWR	
Stress corrosion cracking	337 - 2/24/93	BWR	
	437 - 3/23/82	BWR	
	519 - 12/28/82	PWR	
	623 - 1/27/75	BWR	
	1132 - 1/3/77	PWR	Stagnant boric acid solution.
Thermal fatigue	365 - 7/17/91	BWR	
	375 - 8/1/80	BWR	
	466 - 5/20/79	PWR	
	616 - 12/9/87	PWR	
Water hammer	484 - 11/13/73	PWR	
	491 - 1/25/83	PWR	Thermal fatigue contributor.
	492 - 8/6/84	PWR	
	505 - 12/11/71	BWR	
	977 - 6/9/72	BWR	Led to internal flooding.

Table A-1: *Selected Pipe Failure Events Presented in Appendix A - Public Domain Reports.*

- Public domain information. Only reports based on information from U.S. Licensee Event Reports or Swedish Reportable Occurrence reports are included in this Appendix.

- Failure mode and effect. Reports addressing a cross-section of failure modes (leaks and ruptures) and effects (plant trip and/or CCI-, LOCA-precursor).

- Plant identity. The selected failure event reports represent a cross section of Swedish and U.S. light-water reactor (LWR) plants. Plant identities and NSSS vendor information are included in the SLAP database.

APPENDIX B: DATA BASE FIELD DEFINITIONS

B.0 SKI's Worldwide Pipe Failure Event Data Base

The pipe failure event data base is an MS-Access® (Version 2.0) data base. The data base consists of a table of piping failure event information and a set of queries that summarize the data. Each failure event record consists of forty-three (43) fields as defined below:

B.1 Data Base Fields

Event Identification (EID): The event ID is a counter automatically assigned each new data entry. It is a unique ID that cannot be changed.

Personal Entry Code (PEC): To facilitate QA/QC, the person making an entry provides user ID. Hardcopies of the references from which failure information is extracted are stamped with the assigned PEC and kept on file.

Availability: Distinction is made between public and proprietary information. U.S. licensee event reports (LERs) and Swedish reportable occurrence reports (ROs) by definition are public domain reports and denoted by "FREE" in the data base. All other information is proprietary to the Swedish Nuclear Power Inspectorate, and denoted by "REST" (= restricted) in the data base.

Rating: Subjective rating (1 through 6) of the quality of the source information; e.g., a rating of "1" indicates access to detailed event description including results from incident investigations and metallurgical analyses, and a rating of "6" indicates incomplete information to be enhanced by additional facts regarding failure event influences and root causes. Records with rating > 1 are subject to changes and updates through retrieval of additional information.

> 1 - No additional information from incident investigation anticipated. Case history is closed.
> 2 - The event report form is considered complete, Generic implications still under evaluation, or final incident investigation report not yet available, however. Reports on "crack indications" must include information on the extent of damage (e.g., %-through-wall cracking, crack orientation/length) and exact method of detection.
> 3 - Detailed narrative available and apparent cause of failure and root cause(s) are known. Information not yet available on exact fault location and/or metallurgy. Full text, final LER/RO available on file.
> 4 - Event information originally rated as "6" has been validated against at least one additional information source.

5 - Brief narrative available and affected system and fault location have been positively identified.
6 - Beyond the event heading, details on remaining event information still pending.

Incident Date: This is the date when the piping failure occurred. The date of the source document is entered if no event date.

Type: Only the reactor type is given (e.g., BWR, PWR). The emphasis is on LWRs, but PHWRs and LWGRs are also covered. Should the scope of the database be expanded to address availability engineering considerations, the plant type information will be expanded to include NSSS vendor, architect-engineer, piping manufacturer.

Name: This is the name of the facility at which the piping failure occurred. For U.S. NPPs, this is the name as given by NUREG-0020 (Licensed Operating Reactors, U.S. Nuclear Regulatory Commission). Note, no plant names are revealed in Appendix A of SKI Report 95:61.

Country: This is the country code as defined by the United Nations; a three-letter code.

Started: Date of commercial operation per IAEA statistics. For U.S. NPPs it is the date of commercial operation as defined by NUREG-0020. This information is used to compute the age of the component socket; see below. It is one of the inputs to the piping reliability data base processing methodology. A component socket is a functional position in a system occupied by one piping component during one service sojourn.

In certain instances, and depending on the type and time of piping failure, the date of construction permit, initial criticality or grid connection is more appropriate since events (e.g., transients) during functional testing/commissioning of systems can have effect on the ultimate piping reliability. In some instances the time between date of initial criticality and date of commercial operation has been very long; e.g., years. For field fabricated piping the "date-of-construction-permit" could be a valid indicator, especially for field fabricated piping systems.

Environmentally induced transgranular stress corrosion cracking (TGSCC) has been known to occur in stainless steel piping exposed to humidity and/or saline air while stored onsite prior to installation. Through-wall cracking of small-diameter piping in the scram system at Barsebäck-1 in November 1981 was attributed to TGSCC in piping that had been stored in the turbine building during plant construction. Subsequent investigations noted that the piping had been exposed to saline air during installation work in 1974.

Status: Plant operating mode at the time of the piping failure; e.g., power operation, hot standby, hot shutdown, cold shutdown, refueling.

Reference(s): Citation(s) for the failure event source information; e.g., LER, RO, technical report. The project file includes paper copies of all source information.

Event Type: Based on the source information, and combined with engineering judgment as needed, each event is categorized as:

- Indication
- Crack; through-wall crack that, at most, resulted in weepage.
- P/H-leakage (where P/H = pinhole)
- Leakage
- Severance (through external impact)
- Rupture

In many cases the source information does not contain detailed information on the event type. It is not uncommon that a piping failure is classified as "leakage" to downplay the significance. In Version 3.0 (Rev. 1) the following tentative rule has been adopted:

> *Significant leak from > 270-degree circumferential, through-wall crack is classified as "rupture".*

Category: This field addresses the severity of the piping failure and its impact on plant operations. The following key words are used:

- System disabled - system function is disabled by piping failure (e.g., RHR suction piping)
- CCI precursor - the piping failure has the potential to disable a complete system function and cause a reactor trip.
- CCI - the piping failure constitutes a common cause initiator by disabling another function, or all trains of a safety function and results in a plant trip.
- IFLOOD - the piping failure causes local, internal flooding of, say, a condensate pump room.
- IFLOOD-CCI precursor - an internal flooding event that, under a different set of circumstances, could cause a CCI.
- IFLOOD-CCI - an internal flood event that resulted in a CCI.
- LOCA precursor - RCS leakage resulting in manual reactor shutdown, or an indication/crack discovered during cold shutdown that, if it were to propagate to a through-wall crack during power operation, could require a reactor shutdown.
- LOCA - RCS leakage resulting in automatic reactor trip, safety system actuation, and transition from normal or abnormal operating procedures to an emergency operating procedure.
- CSD-LOCA - RCS leakage during cold shutdown conditions requiring manual initiation of reactor coolant water makeup system.
- CSD-LOCA precursor - RCS leakage during CSD conditions but without need for near-term manual actuation of makeup system.
- SGTL - steam generator tube leak resulting in manual plant shutdown.
- SGTR - steam generator tube rupture resulting in automatic reactor trip and safety system actuation.

Impact on Safety System: This box is checked whenever a piping failure results in automatic safety system actuation.

Impact on Plant: This box is checked whenever a piping failure results in automatic reactor trip.

Repair Time (TTR): The time to repair a piping system component is a function of the event severity and fault location. Primary sources of repair time data are: 1) work orders (the preferred source); 2) NUREG-0020 for U.S. Licensed Operating Reactors; and 3) IAEA's Operating Experience With Nuclear Power Stations in Member States. It is recognized that the given TTR often reflects total out-of-service (OOS) time when a plant remained in a maintenance outage for reasons other than piping repairs; e.g., because of a piping failure the plant was placed in an early major maintenance or refueling outage.

Event Description: Brief narrative of the piping failure with emphasis on facts needed to understand the cause(s) and effect(s) of a failure; e.g., plant status immediately before the failure, sequence of events, impact on operation, consequences. As a minimum, the following information should be provided:

- Method o detection (by whom - SRO, RO, AO, etc. - by which method - leak detection system, leak rate calculation, system walkdown, etc.).
- System(s) affected (leak source and system affected by leak).
- Plant shutdown (automatic or manual turbine trip/reactor trip - for plants with dual turbine-generator sets plant operation could continue at reduced rating while repairs are effected).
- Extent of damage.
- Description of where in plant the failure occurred.

Indications, cracks and through-wall cracking detected during cold shutdown (scheduled maintenance or refueling outages): The narrative should address how the defect was detected; e.g., ultrasonic testing (UT), liquid/dye penetrant testing, x-ray. Cases where an ISI technique has failed to detect an indication/crack must be addressed. How effective have weld overlay repairs been? Induction heat stress improvement (IHSI) is often used on welds to enhance their reliability. The database includes several reports where weepage or pinhole leakage has resulted from IHSI. Where UT has failed to detect an indication, the IHSI tends to expand and accelerate cracking so that the crack tip penetrates the pipe wall.

It is recommended that the extent of repairs and/or piping replacements are addressed in the "Comments" fields; see below.

Quantity Released: The total amount of medium lost during the event, measured in kg.

Duration of Release: Observed of the event, from occurrence to termination. Unit is user defined; e.g., hours, minutes, seconds.

Leak Rate: Observed leak rate measured in kg/s.

Fault Location: Ideally, the exact location per isometric drawings should be given (i.e., drawing coordinates are given). In most cases the isometrics are not available, and, as a minimum, the general geometry/process flow direction should be stated; e.g., "straight section of piping immediately downstream FCV-123", or "reducer base metal, close to the HAZ". In some cases this database field will refer to a graphical description (e.g., line drawing) on the form sheet.

Affected System: This is the location of the source of the leakage.

Other System(s): Secondary effects of a piping failure caused by pipe whip, outstreaming water or steam, loss of component cooling, etc. The database currently (Version 3.0, Rev. 1) contains several (42) events involving failure of instrument air piping that have caused inadvertent valve closures and consequential plant transients. The data field "Category" (see above) reflects presence of secondary effect(s).

Isolateable: This box is checked if the affected piping system is isolateable through remote or local operation of isolation valve(s), or if the outflow of process medium is terminated through the implementation of an abnormal/emergency operating procedure directed at pressure equalization. As an example, SGTL/SGTR is an isolateable event.

Method of Detection: A positive identification of a failed piping system component often involves several steps. As an example, a process alarm or indication in the main control room (PACR) prompts the operators to the existence of a RCS leak inside the containment. After power reduction and containment entry, an auxiliary operator (AO) performs a system walkdown to identify the leak location. Once the leak location has been positively identified, further investigations normally are required to identify the *exact* fault location (e.g., by removing pipe insulation). Below is a list of interim key words that address how a pipe failure was detected and located:

Pipe Failure Occurs During Power/Shutdown Operations

- ISI = Inservice inspection; covers a range of specific methods/ techniques such as corrosion rate sampling, vibration monitoring, etc.
- PACR = Process alarm/indication in the main control room
- PAL = Local process alarm/indication
- ST = Surveillance testing
- TM = Test and maintenance
- TV = Video camera inside containment
- WT = Walk-through / system walkdown

Incipient Pipe Failure Detected During Cold Shutdown

- ECT = Eddy current testing (of steam generator tubes)
- IHSI = Induction heat stress improvement
- NDE = Non-destructive evaluation; this is the default if the source information is incomplete.
- PT = Penetrant testing
- UT = Ultrasonic testing
- VT = Visual testing
- X-ray = Metallurgical survey using X-ray.

Whenever multiple methods are used for leak detection and identification of the exact location of the failed component, the data entry should consist of a string of the applicable techniques; e.g., PACR+TV+WT, or PT+VT.

Defect Size: The geometry and size of defect; e.g., length/depth/width in mm.

Component Type: This is a reliability attribute which identifies where a piping failure occurred. Distinction is made between base metal, heat affected zone (HAZ), and weld. Stress corrosion cracking failures tend to occur in weld metal. Erosion/corrosion damage normally occurs in the base metal. The following interim key words are used:

- Pipe; the default in case of incomplete source information on event.
- Pipe-S; base metal of straight section.
- Pipe-S/W; base metal of straight, near a weld.
- Pipe-S/HAZ; heat affected zone near a weld in a straight section.
- Elbow; base metal of an elbow section.
- Elbow-W; base metal of elbow section, near a weld.
- Elbow-HAZ; heat affected zone near a weld in an elbow.
- Bend; base metal of a cold-bent section of piping.
- Reducer
- Reducer-W
- Reducer-HAZ
- Expander
- Expander-W
- Expander-HAZ
- Bellows
- S/G-tube
- Weld
- Tee
- Flange
- Compression fitting

- Screw fitting
- Valve body
- Pump case

Age: A reliability attribute. The age, in hours, of the piping component socket in hours counted from the date of commercial operation. This means that design or construction errors during the commissioning of a plant are not addressed by the database unless stated otherwise in the comment field (see below). Major primary piping replacements have been made since the early eighties (e.g., Pilgrim in 1983, Cooper in 1984/85), and, therefore, adjustments to the calculated age are as warranted.

Diameter: Diameter (in mm) of piping component.

Wall Thickness: Wall thickness (in mm) of piping component.

Material: A reliability attribute. Distinction is made between carbon steels, austenitic or ferritic stainless steels. Ideally, the metallurgy (e.g., carbon content of stainless steels) is given by using ASTM, ASME or ANSI, unstabilized vs. stabilized austenitic stainless steel, or similar designation. For now, details about metallurgy, where available, should be included in the "Comment" field. Below is a partial list of some typical primary piping materials:

Type (SIS/ASTM)	%C max	%Cr	%Ni	%Mo	Others
SS 2333 / 304	0.05	17.0 - 19.0	8.0 - 11.0	-	
SS 2352 / 304L	0.030	17.0 - 19.0	9.0 - 12.0	-	
SS 2343 / 316	0.05	16.5 - 18.5	10.5 - 14.0	2.5 - 3.0	
SS 2353 / 316L	0.030	16.5 - 18.5	11.5 - 14.5	2.5 - 3.0	
SS2353 / 316NG	0.020	16.5 - 18.5	11.5 - 14.5	2.5 - 3.0	N = 0.06 - 0.10

Medium: A reliability attribute. Description of process medium in the failed piping system; e.g., steam, wet steam, reactor water, demineralized water, borated make-up water, nitrogen, instrument air. Information on water treatment strategies (if any) are included in the "Environment" field (see below). The following interim key words are used:

- RC water
- Demineralized water
- Borated water
- River/sea water
- Steam
- Wet steam
- Instrument air
- Lube oil
- EHC oil

Temperature: Temperature of process medium in degrees Celsius.

Pressure: Pressure (in MPa) of process medium.

Environment: This field identifies the unique operating environment with emphasis on water chemistry. As an example, for BWRs with IGSCC susceptible piping, the strategy for hydrogen injection into feedwater should be stated. Any notes on when hydrogen water chemistry (HWC) was implemented should be included in the "Comment" field". Note, HWC has been known to cause plant transients from turbine trips due to sensitive chemistry detectors. Such transients could cause cracking, or accelerate existing crack tip propagation.

Fabrication: Method of fabrication; e.g., cast or machined, seamlessly drawn or welded. Differentiation between shop- and field-fabricated piping.

Repeat: This field is used to identify repeat failures at the same unit or among plants of the same type or design generation. The field is used to highlight generic failure trends.

Graphical Description: Graphical descriptions (e.g., simplified P&IDs) are provided for selective (e.g., unique and important) piping failures. This data field uses OLE objects; i.e., the field supports object linking and embedding.

Apparent Cause: This field describes the cause of the piping failure; i.e., ***predominant*** failure mechanism. An "apparent cause" is always a symptom of underlying causes. Most LERs/ROs address the apparent cause, whereas the detailed incident investigations go beyond the apparent cause and search for the multiple causes. The following failure mechanisms are represented in the data base:

- Boric acid assisted corrosion cracking (BACC)
- Cavitation-erosion (CE)
- Construction/fabrication error (CFE)
- Corrosion (COR)
- Corrosion-fatigue (CF)
- Design error (DE)
- Erosion (ERO)
- Erosion-corrosion (E/C)
- External impact (EXI)
- Fatigue-corrosion (FC)
- Human error (HE)
- Intergranular stress corrosion cracking (IGSCC)
- Primary water SCC in steam generator tubes (PWSCC)
- Stress corrosion cracking (SCC)
- Thermal fatigue (TF)

- Transgranular stress corrosion cracking (TGSCC)
- Vibration fatigue (VF)
- Water hammer (WH)

The distinction is made between PWSCC and SCC to ensure correct piping failure data populations; i.e., to avoid mixing S/G tube failures with process system piping failures.

RC1: Root cause number 1. An underlying cause of the piping failure.

RC2: Root cause number 2. In the analysis of piping failures, the principle of multiple-cause-systems-oriented failure theory applies when analyzing the cause-and-effect. This means that a primary failure mechanism like IGSCC or erosion/corrosion is a symptom of underlying influences and causes.

Root Cause(s): A memo field intended for free-format discussion on findings from incident investigation, metallurgical surveys, etc. The information in this field should integrate (RC1+RC2 = Apparent Cause). Future versions of the database may be expanded to include "RC3" and "RC4".

Comment(s): Additional, relevant information regarding inspection history, transient history, repair/replacement philosophy, results from metallurgical surveys and incident investigation.

APPENDIX C: ABBREVIATIONS & ACRONYMS + GLOSSARY

Abbreviations & Acronyms - Engineering Terms

AFWS	Auxiliary Feedwater System
ANOVA	Analysis of Variance
BBL	Break-Before Leak
BOP	Balance of Plant
BW/CR	Cracking in Stagnant Borated Water
CCF	Common Cause Failure
CCI	Common Cause Initiator
CCWS	Component Cooling Water System
C/F	Corrosion-Fatigue
CHRS	Containment Heat Removal System
CPI	Chemical Process Industry (in the context of this project taken to include chemical, petrochemical, refining and offshore gas & oil production).
CRDM	Control Rod Drive Mechanism
CSD	Cold Shutdown (plant in RHR mode of operation)
CSS	Containment Spray System
CVCS	Chemical and Volume Control System
DEGB	Double-Ended Guillotine Break
DEPB	Double-Ended Pipe Break
DL	Direct LOCA
DN	Nominal Diameter (in mm)
E/C	Erosion/Corrosion
ECCS	Emergency Core Cooling System
ERF	Event Reporting Form (IAEA)
ESFAS	Engineered Safety Features Actuation System
FACTS	Failure and Accidents Technical Information System operated by TNO in the Netherlands).
FSD	Full-system Decontamination
FW	Field weld
HAZ	Heat-Affected Zone
HIC	Hydrogen Induced Cracking
HPCS	High Pressure Core Spray
HPIS	High Pressure Injection System
HSCC	Hydrogen Stress Corrosion Cracking
HWC	Hydrogen Water Chemistry
IAS	Instrument Air System
IC	Inspection Class
ID	Inside Diameter
IGSCC	Intergranular stress corrosion cracking
IHSI	Induction Heating Stress Improvement
IL	Indirect LOCA

INES	International Nuclear Event Scale (IAEA)
ISI	In-service Inspection
LBB	Leak-Before-Break
LER	Licensee Event Report
LOCA	Loss of Coolant Accident
LPIS	Low Pressure Injection System
LSP	LOCA Sensitive Piping
LWGR	Light Water Cooled and Graphite Moderated Reactor
MCC	Motor Control Center
MHIDAS	Major Hazard Incident Analysis System
MFWS	Main Feedwater System
MLE	Maximum Likelihood Estimate
MOV	Motor Operated Valve
MR	Median Rank
MS	Main Steam
MSIP	Mechanical Stress Improvement Process
MSIV	Main Steam Isolation Valve
MS/R	Moisture Separator / Reheater
NDE	Non-Destructive Examination
NDT	Non-Destructive Testing (also used for Nil Ductility Transition Temperature)
NLSP	Non-LOCA Sensitive Piping
NPE	Nuclear Power Experience (by the Stoller Corporation)
NPP	Nuclear Power Plant
NPRDS	Nuclear Plant Reliability Data System
NSSS	Nuclear Steam Supply System
NWC	Neutral Water Chemistry
OC	Operating Characteristic
PCS	Power Conversion System
PFM	Probabilistic Fracture Mechanics
PISC	Plate Inspection Steering Committee
PRAISE	Probabilistic Reliability Analysis Including Seismic Events
PSA	Probabilistic Safety Assessment
PSI	Pre-service Inspection
PT	Penetrant Testing
PTS	Pressurized Thermal Shock
QA	Quality Assurance
QC	Quality Control
RBS	Reactor Building Spray
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
RO	Reportable Occurrence (SKI's licensee reporting system)
RPV	Reactor Pressure Vessel
RSS	Reactor Safety Study
RT	Radiographic Test
RWCUS	Reactor Water Cleanup System
SCC	Stress Corrosion Cracking

SFD	Safety Function Disabled
SG	Steam Generator
SGTL	Steam Generator Tube Leak
SGTR	Steam Generator Tube Rupture
SICC	Stress-Induced Corrosion Cracking
SLAP	SKI's LOCA Affected Piping Database
SN	Schedule Number
SSCC	Sulfide Stress Corrosion Cracking
SW	Shop weld
SWS	Service Water System
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

Abbreviations & Acronyms - Organizations

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
HSE	UK Health and Safety Executive
IAEA	International Atomic Energy Agency
INES	International Nuclear Event Scale (IAEA)
INPO	Institute of Nuclear Power Operations
INSAG	International Nuclear Safety Advisory Group
KSU	Kärnkraftsäkerhet och Utbildning AB
MPA	Staatl. Materialprüfungsanstalt (MPA), Universität Stuttgart
NEA-IRS	(OECD) Nuclear Energy Agency - Incident Reporting System
NKS	Nordic Nuclear Safety Research
OECD	Organization for Economic Cooperation and Development
PNL	(Battelle) Pacific Northwest Laboratories
SKI	Statens Kärnkraftinspektion
TÜV	Technischen Überwachungs-Vereine
U.S.NRC	United States Nuclear Regulatory Commission

Glossary

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

Active human error: An active human error is an intended or unintended action that has an immediate negative consequence for the system. PSAs explicitly address active errors in system fault trees and event trees.

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.

Analysis of Variance (ANOVA): Statistical analysis technique developed by R.A. Fisher. Practical technique in reliability data analysis for determining the statistical significance of various influence factors in multivariable situations. Computer software packages are available for ANOVA.

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 leakages. 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.

Confidence: If the failure probability for a population of T piping years with F failures is F(T), an estimate for the failure probability is often stated in terms of ν, the population failure rate. Confidence bounds on ν can be obtained using chi-square charts.

Data Base Coverage: Percentage of reportable/known failure events that reside in a data base.

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/Corrosion (E/C): 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.

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.

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 Function: Also known as the "instantaneous failure rate". It is the limit of the failure rate as the interval of time approaches zero ($\Delta \to 0$).

High Energy Piping: Typically defined as piping systems operating at 1.9 MPa (275 psig) or greater, and temperatures equal to or greater than 93 C (200 F).

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 the BWR environment. IGSCC has also been discovered (mid-1970's) in the PWR environment, especially in piping containing stagnant boric acid solutions; plant operators are aware of the problem and have taken steps to avoid stagnant boric acid solutions.

Latent human error: An erroneous action or decision for which the consequences only become apparent after a period of time when other conditions or events combine with the original error to produce a negative consequence for the system.

Leak-Before-Break (LBB): Most nuclear high-energy piping is made of high-toughness material, which 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 piping failure.

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

Piping failure attribute: 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.

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.

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°), a straight or a tee.

Piping Component: The passive components in a piping run whose failure result in leakage or rupture. Includes pipe section, valves, flanges, fittings (elbow, tee, cross, reducer).

Pooled Data: Two or more sets of data collected under different conditions or from different populations that are combined.

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. It is important to note that this is not a PSA-approach utilizing event tree and fault tree analysis. The results of a probabilistic fracture mechanics evaluation have been used as input to PSA; e.g., German Risk Study, Phase B.

Round Robin: In the context of piping reliability and inspection, the purpose of round robin is to define reliability and effectiveness of inservice inspection procedures. Cracked pipe samples are manufactured, and then sent to expert teams who under simulated field conditions determine crack size and location. Test results are then analyzed, and correlated with the destructive assay. Next, results are reported along with recommendations.