SKI Report 95:58

Reliability of Piping System Components

Volume 1: Piping Reliability - A Resource Document for PSA Applications

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SUMMARY

1. Background

Reflecting on older analysis practices, passive component failures seldom receive explicit treatment in PSA. To expand the usefulness of PSA and to raise the realism in plant and system models, the Swedish Nuclear Power Inspectorate (SKI) has undertaken a multi-year research project to establish a comprehensive passive component failure database, validated failure rate parameter estimates, and 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 approximately 2,300 failure events allowed for data explorations in Phase 2 to develop a sound basis for PSA-treatment of piping system failures.

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*** and ***how*** piping systems fail.

3. Results

This Phase 2 report gives a graphical presentation of piping system operating experience, and compares key failure mechanisms in commercial nuclear power plants and chemical process industry. 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 Greece in June 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 Fas 2 (föreliggande 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 möjligör 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 i Grekland i juni 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 workorder 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.

External peer review comments and suggestions were provided by Mr. Alan Chockie (Chockie Group International, Seattle, WA), Dr. Ching Guey (Florida Power & Light, Juno Beach, FL), Mr. Kalle Jänkälä (IVO International Ltd., Finland), Dr. Yovan Lukic (Arizona Public Service, Phoenix, AZ), and Dr. Parviz Moieni (Scientech Inc., San Diego, CA).

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.

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 Research in Piping System Component Reliability

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 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*.

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[1-4] 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[1-5]. Several probabilistic fracture mechanics studies indicate the large LOCA frequency to be $1.0 \cdot 10^{-8}$/year[1-6].

TREATMENT OF PIPING COMPONENT FAILURES IN PSA - TYPICAL APPROACH

- **Loss of coolant accidents (LOCAs); e.g., double-ended pipe breaks in RCS (large LOCA), RCS pipe breaks up to DN50 (small LOCA). Implicit assessment via initiating event frequency.**
- **Interfacing systems LOCA (ISLOCA or V-sequence); e.g., failure of MOVs and/or check valves, and rupture of low-pressure piping outside containment. Explicit analysis of piping component failure probabilities, see PLG-0432[1-2] and EGG-2608[1-3].**
- **Main steam line break (MSLB). Transient that begins with a steam line rupture. Rupture locations inside and outside considered. Initiating event frequency typically calculated from WASH-1400 data.**
- **System analysis. Those instances where a piping rupture constitutes a single failure of ECCS identified and quantified using WASH-1400 data.**
- **Steam generator tube rupture (SGTR); e.g., single or multiple tube rupture. Initiating event frequency estimated from available operating experience.**
- **Reactor vessel integrity; either as initiating event or induced by pressurized thermal shock (PTS). Implicit assessment using published failure probabilities.**

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[1-7] 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[1-8]. 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.

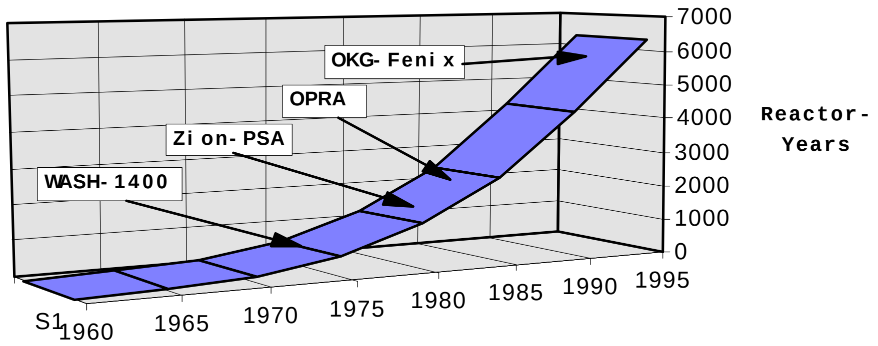


Figure 1-1: *The Worldwide Commercial Nuclear Power Plant Operating Experience According to SKI Data Base Adapted from IAEA-Statistics[1-4,9]*.

In this context, the SKI-project is directed at enhancing the PSA "tool kit" through a structure for piping failure data interpretation and analysis. The following issues are addressed:

- Sections 4, 5 & 6 (the report structure is shown in Figure 1-2). The pipe failure rates used by WASH-1400 were based on about 150 reactor-years of commercial nuclear power plant operating experience combined with selected fossil power plant operating experience. In view of today's (end of 1995) approximately 6,300 reactor-years of experience, are failure rates and LOCA frequencies developed in WASH-1400 still valid?

- Sections 4 & 6. Since publication of WASH-1400, many attempts have been made to derive piping system component failure rates. The statistical uncertainties remain considerable, however. What are the constituent elements of a modern, systematic reporting system for piping failures? What are the key piping reliability influence factors / reliability indicators to be tracked by such a system? In light of PSA modeling requirements, how should the operating experience be interpreted?

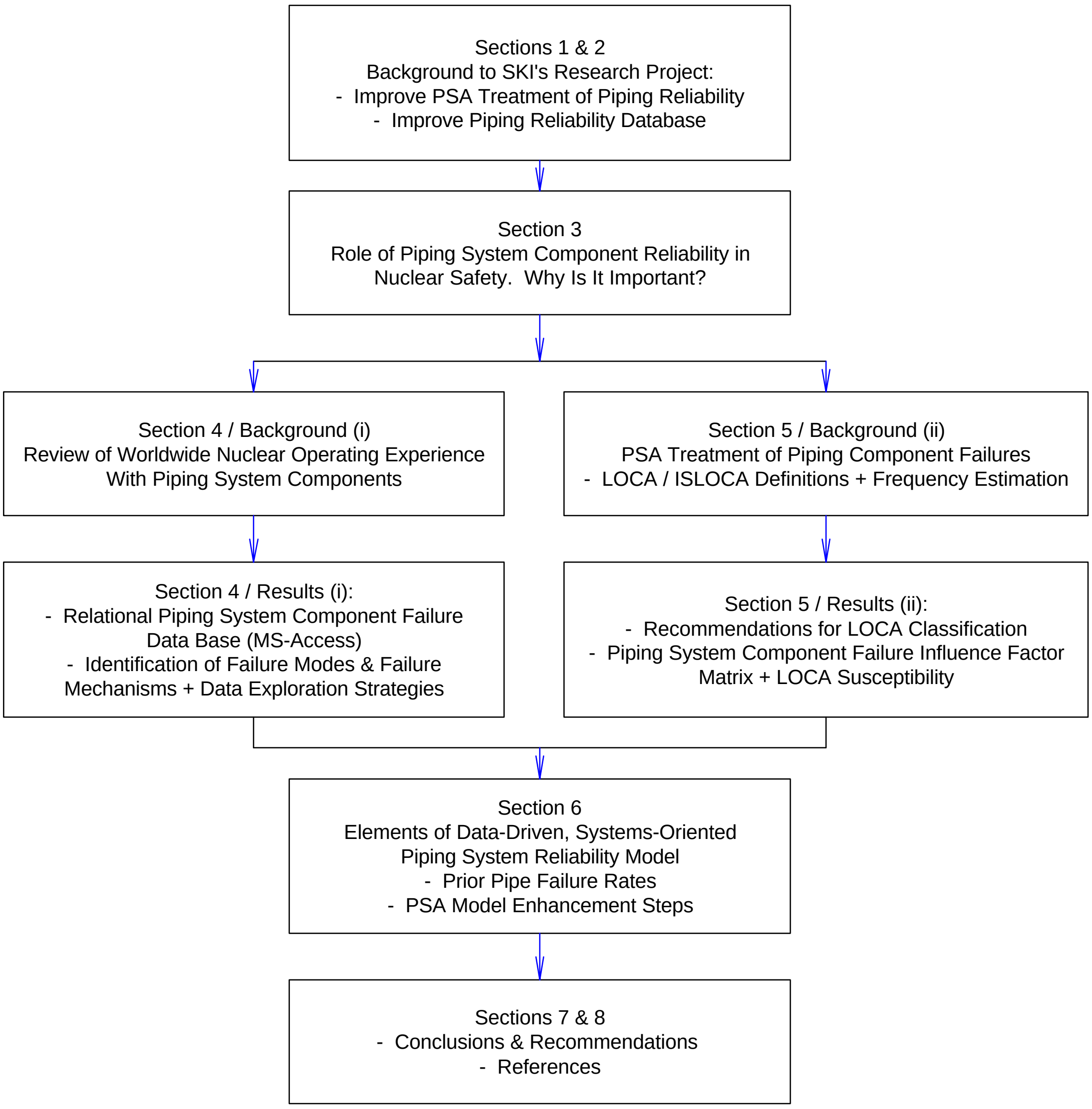


Figure 1-2: *Report Outline (SKI Technical Report 95:58).*

- Section 5. Since WASH-1400 was published, several LOCA and LOCA precursor events have occurred. Does this experience warrant revised LOCA classes and LOCA frequencies?

- Section 6. Implicit versus explicit modeling of piping failures. Past PSA studies mostly have limited the piping failure analysis to implicit modeling by referencing failure rates published in WASH-1400, and cursory (or bounding-type) identification of failure locations. What are the benefits of explicit, data-driven and systems-oriented modeling of piping component failures?

- Section 6. PSA studies focus on active component failures and plant responses to initiating events. To what extent would the discriminating power of PSA be enhanced by expanding the explicit treatment of passive component failures? What would be the effect on dynamic PSA approaches of expanded treatment of passive component failures?

- Sections 5 & 6. WASH-1400 developed a practice for loss of coolant accident (LOCA) definition and analysis that has been almost universally adopted by PSA projects. Is this analysis practice still valid?

An important engineering insight from WASH-1400 was that dominant incident sequences were initiated by small LOCAs, transients, and systems interactions, and not by large LOCAs whose study had been the centerpiece of reactor safety analysis and licensing during the sixties and early seventies. Another insight was that unavailability of engineered safety systems was found to be relatively high (e.g., in the range 10^{-4} to 10^{-1} per demand), and dominated by human error and test/maintenance outages, often in a common cause failure mode.

While significant progress has been made in technical areas such as dependent failure analysis, human reliability analysis and PSA model integration, only modest R&D resources have been directed at the integrated treatment of passive component failures. Many PSA projects continue to rely on data and modeling concepts presented over twenty years ago.

Plant risk is highly dynamic. Results of 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[1-10]) may no longer be universally applicable.

Directed at PSA practitioners, this project provides a consolidated perspective on passive component failures. The project addresses fundamental data analysis issues, and develops an integrated, structured approach to modeling of passive component failures.

1.1 History and Status of Project

Initial project planning took place during February - August 1994, and background and objectives were documented in SKI/RA-019/94[1-11]. During the fall of 1994, SKI established contact with Mr. Bojan Tomic (ENCONET Consulting GesmbH) to access piping failure information for Eastern European nuclear power plants (i.e., RBMK and WWER).

Phase 1 of the project was initiated during October 1994, and the data base design was finalized during April, 1995. By November 1995 a first screening analysis of the database content had been completed. Detailed statistical analysis is scheduled for completion by early summer 1996, followed by a series of pilot applications. A project time-line is shown in Figure 1-3. The project team structure is shown in Figure 1-4.

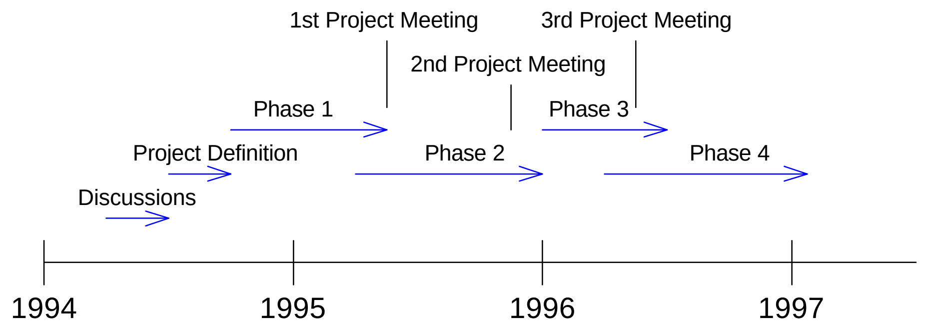


Figure 1-3: *"Reliability of Piping System Component" - The Project Timeline.*

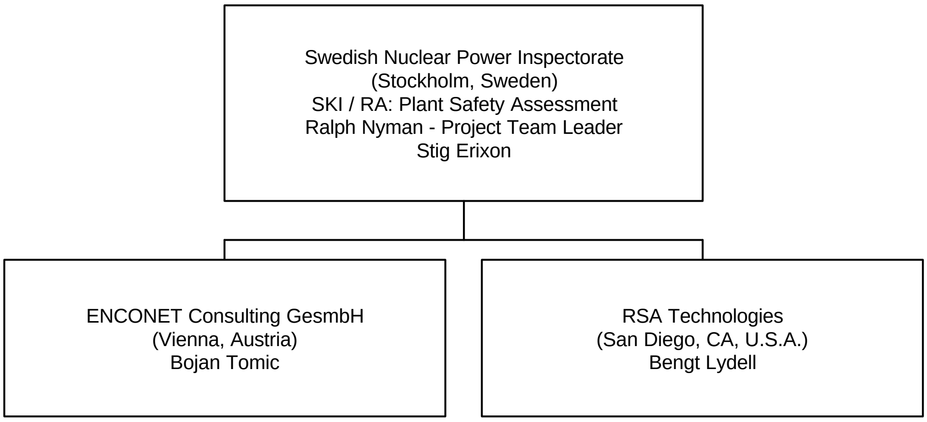


Figure 1-4: *"Reliability of Piping System Components" - The Project Team.*

1.2 Piping Reliability in PSA Context - The Legacy of WASH-1400

PSA projects around the world continue to rely on piping reliability information developed in WASH-1400 well over twenty years ago. WASH-1400 was a first, major pilot study demonstrating the integrated application of PSA methodology. Motivations behind WASH-1400 were many, ranging from political to technological considerations[1-12.13.14,15]. In the sixties and early seventies the study of large loss-of-coolant-accidents (LOCAs) from pipe breaks (e.g., cold leg pipe rupture in PWR, external recirculation loop rupture in BWR) or reactor vessel rupture was the centerpiece of deterministic safety analysis and reactor licensing.

WASH-1400 was an attempt to address the risk-significance of LOCA events using the then available nuclear and non-nuclear operating experience with piping systems. It is important to recognize that data development and PSA model development in WASH-1400 reflected on analysis practices and analysis tools (including computer codes) that were available at the time. By definition, PSA requires the use of historical and/or predictive techniques to arrive at a spectrum of plant damage states versus consequences, taking into account uncertainties. Therefore, validity of PSA is a function of how well analysts address available historical data; e.g., *are the piping reliability considerations developed in WASH-1400 valid today?*

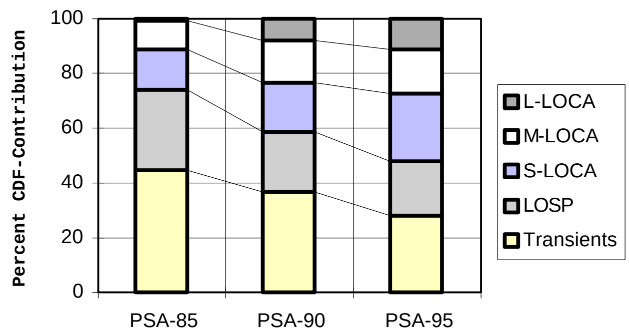
The research by SKI was initiated in part to provide today's PSA analysts with an integrated perspective on piping reliability by acknowledging historical developments and current operating experience. The work represents a re-evaluation of analysis concepts and failure data in WASH-1400.

2: RESEARCH IN PIPING RELIABILITY - MOTIVATIONS & OBJECTIVES

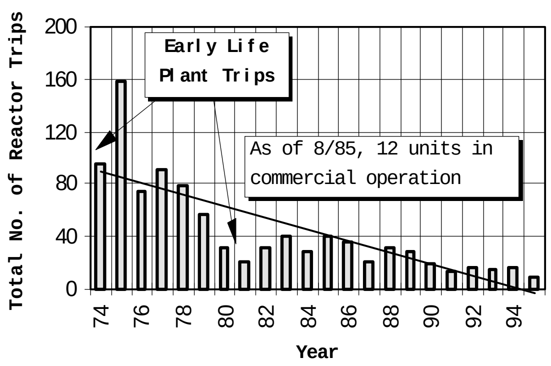
2.0 Overview

Applied risk and reliability analysis is an integral aspect of modern plant safety management and regulation. Based on developments that go back to the sixties, extensive equipment reliability databases, computerized analysis tools, analysis guidelines for system analysis, including human factors and human reliability considerations, are now available to PSA practitioners. A technical area still in its infancy is the incorporation of passive components (e.g., piping, joints (welds), flanges, tubing, fittings) in PSA and system reliability models.

Since the earliest, large-scale pilot studies like WASH-1400[2-1], AIPA[2-2], and the German Risk Study (Phase A)[2-3], modest progress with systems-oriented passive component reliability guidelines has been noted. With plant-specific shifts in risk topographies the importance of including structural reliability in PSA is recognized. Transient-induced incident scenarios tend to be less important now than, say, ten or more years ago due plant design modifications and reduced transient frequencies. Needs have been identified for development of data bases and modeling techniques that allow existing PSAs to be enhanced by plant-specific passive component reliability considerations. This report documents insights from Phase 2 of a multi-year R&D-project sponsored by the Swedish Nuclear Power Inspectorate (SKI) to enhance the current state-of-practice in addressing piping system component reliability by PSA. ***Intended audience is PSA practitioners***.



A Conceptual Living PSA Program



Swedish Reactor Scram History

2.1 Problem Statement

PSA is applied universally, if not uniformly, as a technique for prudent plant safety management and improvements of operations. Modern PSA is technically controlled by three factors:

- Availability of recognized sources of equipment reliability data that directly reflect on the accumulated, worldwide operating experience with nuclear power plant (NPP) systems and equipment.

- Recognized modeling approaches provided via engineering guidelines, analysis frameworks and standards.

- PSA quality considerations through completeness (by acknowledging applicable operating experience), compliance with guidelines and state-of-theory, and usefulness. PSAs should address reasonable sets of incident scenarios, and applicable operating experience should be interpreted via validated models.

PRESSURE VESSEL & PIPING RELIABILITY
SOME HISTORICAL EVENTS (i)

1971: **In-service inspection rules issued in the USA; Section IX of ASME Boiler and Pressure Vessel Code.**

1974: **Advisory Committee on Reactor Safeguards (ACRS) issued report (WASH-1285) on the "Integrity of Reactor Vessels for Light Water Power Reactors."**

1975: **NEA Committee on the Safety of Nuclear Installations (CSNI) formed "Task Force on Problems of Rare Events in the Reliability Analysis of Nuclear Power Plants." One group of experts focused on reliability of mechanical components and structures.**

1975: **American Physical Society released its report on Light Water Reactor Safety. It elaborated on the "leak-before-break" controversy, and piping reliability.**

1976: **UK Atomic Energy Authority issued the "Marshall Commission's" report on "An Assessment of the Integrity of PWR Pressure Vessels."**

1980: **U.S. Nuclear Regulatory Commission issued requirements for DEGB analyses (ANSI/ANS-58.2-1980. NPPs should be designed to ensure safe shutdown in the event of a double-ended guillotine break (DEGB) in high-energy piping.**

1984: **In the U.S., leak-before-break (LBB) technology considered a proven and accepted alternative to the DEGB postulation for PWR primary loops and ASME Class 1 and 2 lines inside and outside containment.**

PSA studies focus on plant-specific reliability estimates of active equipment (e.g., pumps, control valves, switches), dependent failures, and on human factors and human reliability issues, and their risk impacts. A limitation of current PSA studies is the explicit modeling of passive equipment such as piping, vessels, valve bodies, pump casings, exchangers, and flanges. This limitation is especially significant since a leak or a rupture of passive equipment could result in significant (e.g., energetic) hazardous material source terms, and challenging plant transients. Also, it is significant because with aging plants and requirements for plant life extension, the structural integrity of pressure boundary components must be assessed. In view of the worldwide industrial operating experience, the passive equipment can (and often does) represent significant "trigger events" of severe incident scenarios. In the past, the way around the limitation has been to base the quantitative assessments on expert judgment, sometimes poorly validated. The difficulties to properly address the reliability of passive equipment stem from:

PIPING FAILURES & PSA TREATMENT

TYPE	ANALYTICAL TREATMENT
Crack Indication	Difficult to detect; always a question of safety significance. Low likelihood of serious incident. Seldom addressed by PSA, however.
Through-wall crack	Includes leakage events. Normally easy to detect by plant instrumentation and walk-throughs. Could be precursor to serious event. Common-cause initiating event potential. Sometimes explicitly addressed by PSA.
Rupture / break	High detection probability. Addressed by the traditional LOCA initiating event considerations. Implicit treatment of piping failures.

- Low-frequency failures; the passive equipment is typically of high reliability, subjected to extensive QA/QC-programs during the design, installation and operation. In other words, the body of operating experience could be small, and possibly inscrutable. In relative terms, piping failures are rarely experienced.

- In-service inspection (ISI) and testing of passive equipment could be difficult. There are uncertainties in the identification of degradations, and in making clear distinctions between incipient failures and degradations. According to controlled experiments (e.g., PISC[2-4]), the probability of not detecting a crack could be high.

- Practical constraints on ISI and testing. The testing or inspection cannot always be done under realistic operating conditions.

- Uncertainties in interpretation of inspection and test data.

- No widely recognized modelling framework exist for passive equipment. The technical approaches range from the application of limited operating experience combined with expert judgment[2-5], the "Thomas elemental approach"[2-6], integral statistical estimation[2-7], to probabilistic fracture mechanics (PFM)[2-8,9].

- Application of PFM to derivation of pipe break probabilities has sometimes yielded values considerably lower than what the actual operating experience has indicated.

With few exceptions, PSA studies continue to rely on pipe failure data from the 1974

Reactor Safety Study (WASH-1400) or the German Risk Study (Phase B)[2-10]. Often the data from WASH-1400 are interpreted as the lower bounds for pipe breaks. Researchers have worked on various aspects of piping reliability over the past two decades and progress has been made[2-11,12,13,14]. No current, consolidated, public domain data source on the worldwide experience with piping systems yet exists. More importantly, only limited attention has been directed to the modeling of piping components for inclusion in the PSA studies. Therefore, the full risk management potential of PSAs has not yet been fulfilled.

OPERATING EXPERIENCE & PSA TREATMENT

- **AEOD (1985). Probability of ISLOCA approximately $2x10^{-4}$ to $2x10^{-6}$ using available operating experience, versus approximately $1x10^{-7}$ according to WASH-1400 and IREP Studies[1-15].**

- **IAEA-J4-606.4 (1994)[1-16]. Presentation by Stetkar & van Otterloo: IPE study excluded consideration of passive component failures. When study team was challenged to address impact of a failure of a manual isolation valve in a common suction line for HPIS, LPIS and CSS, it was found that passive failure of the valve contributed to final IPE results.**

- **WASH-1400 (1975); based LOCA frequency estimates on about 150 reactor-years of operating experience + selected fossil power plant experience with piping. Today (end of 1995) over 6,300 reactor-years of NPP experience exists, yet most PSAs utilize the data in WASH-1400.**

SKI's R&D project *Reliability of Piping System Components* was initiated to construct a worldwide experience data resource and a modeling structure compatible with today's PSA requirements. As such the project scope includes advancing the state-of-art in PSA. While the technical focus is PSA-oriented, practical plant maintenance considerations are addressed as well.

2.2 Project Interfaces

During the past twenty years SKI has actively sponsored research supporting the Nordic programs for PSA. Emphasis has been on quality PSA through comprehensive, validated analysis tools and databases. The research has provided PSA practitioners with a range of analysis resources (computer codes, databases, etc.). Recent results of this research include the following products:

- SKI Report 89:3. Pipe Break Probabilities Due to IGSCC in Swedish BWRs.

- Reliability Data Book for Components in Nordic Nuclear Power Plants, TUD 94-11 (4th Edition), 1994.

- SKI Report 91:6. Common Cause Failure Analysis of High Redundancy Systems. Safety/Relief Valve Data Analysis and Reference BWR Application, December 1992.

- SKI Report 94:12. Initiating Event Data Book. Initiating Events in Nordic Nuclear Power Plants, 2nd Edition.

- International cooperation on plant aging effects. SKI is a member of the Principal Working Group (PWG) 1 of the Committee for Safety of Nuclear Installations (CSNI). Summary of work in September 1995 report: *Evidence of Aging Effects on Certain Safety-Related Components. A Generic Study Performed by Principal Working Group 1 of the CSNI.*

- International cooperation: International Common Cause Failure Data Exchange (ICDE). Initiated by SKI-personnel, this project is directed at a consolidated perspective on CCF data.

- Ongoing activities within the Nordic Safety Research Program (NKS/RAK-1). Task 2 is directed at pipe breaks as initiating events and includes surveys of operating experience, development of model for determining pipe break probabilities.

- Ongoing project: Development of External Event Data Base for Swedish PSA applications.

- Ongoing SKI-project entitled "Nuclear Reactor Piping Reliability Analysis." Directed at determining the influence of in-service inspection (ISI) in reducing the frequency of piping failures.

The new research project on "Reliability of Piping System Components" will provide input and recommendations to future updates of the "Reliability Data Book" (TUD 94-11) and "Initiating Event Data Book" (Technical Report 94:12). The project is also aimed at generating an integrated, PSA-perspective on passive component reliability.

2.3 Project Scope

A primary objective of the new research project on piping reliability was development of a comprehensive, relational database on piping failures in commercial nuclear power plants. The scope included the worldwide operating experience. Selected non-nuclear operating experience was included to enhance the library of cause-consequence relationships applicable to carbon steel piping. The project should include a reliability data estimation format and a piping reliability analysis format acknowledging such factors as:

- Pipe size (e.g., small diameter versus large diameter piping). Pipe geometry as given by isometric drawings, environmental load factors (e.g., pressure, temperature, flow rate, vibrations, process medium), operational load factors (e.g., cyclic transients, low power versus full power operation), and metallurgy (e.g., stainless steel versus carbon steel piping). Number of welds, flanges elbows, tees, and straight-sections. Number of safety system and instrument line tie-ins.

- Predominant reliability influence factors, failure mechanisms, and failure modes. Detectability of leakage from piping systems. Impact of ISI on piping reliability.

A detailed analysis of the failure information, coupled with reviews of the PSA practices, was anticipated to result in a new pipe break classification scheme. The project should address dynamic effects of pipe whips, and consequences on connecting lines, availability of support systems, and common-cause effects of piping failures (i.e., piping failure as common-cause initiating event). Finally, the development work should include a sample application of the information data base addressing LOCA frequency estimation.

> **PRESSURE VESSEL & PIPING RELIABILITY**
> **<u>SOME HISTORICAL EVENTS (ii)</u>**
>
> **1980:** **Feedwater pipe cracking in Swedish ABB-BWR plants. During the 1980 refueling outage at Barsebäck-2 cracks were detected in mixing tees.**
>
> **1981:** **Generic problem with Westinghouse Model D3 steam generators first discovered in Ringhals-3. After about one year of operation, indications of tube wear in the pre-heater section were noted. The new fretting phenomena signaled the beginning of a troublesome period for many plants with steam generators by Westinghouse.**
>
> **1992:** **Oskarshamn-1 entered a 3 year outage for extensive primary system repairs; the FENIX project. First large-scale demonstration of the viability of full-system decontamination (FSD).**

Failure modes of piping can be described as either (trivial to serious) crack indication, leak from through-wall crack, leak-before-break, or rupture. For NPPs distinction also is made between pipe breaks above and below core; failure location is important. A review of the available operating experience indicates that leaks or ruptures are more prevalent in tee-sections and elbows, than in straights. Further, based on operating experience, carbon steel piping failures tend to be more failure prone than stainless steel piping (i.e., RCS piping components).

Failure rate of piping depends on a range of design, process, and operating conditions. Uncritical extrapolation of operating experience from one information source to a specific application could result in significant over- or under-estimation of the "true" piping reliability. It is important to recognize the cause-consequence relationships of piping failures, and to establish reasonable correlations between failure susceptibility and environmental factors.

The current research is performed in four phases. Ultimate objective is to prepare an updated basis for generation of plant-specific piping leak and rupture failure rates for input to the Swedish "IE-Book" (Initiating Event Data for Nordic Nuclear Power Plants). Also, recommendations will be developed for LOCA classification and frequency estimation. The four work phases are defined as follows:

<u>Phase 1: Piping Failure "Raw Data" File & Data Reduction.</u> This phase was largely completed during the second and third quarters of 1995. All relevant sources of piping failures were surveyed and summarized. The nuclear and selected non-nuclear (chemical, petrochemical, and oil refinery) operating experience was assembled to address failure

symptoms and root causes, and to prepare reasonable cause-consequence relationships.

The "raw data" file was designed using MS-Access® as a relational data base with each data record consisting of 40 data fields. A summary of the database content is given in Figure 2-1. A data base description appears in Volume 4 of this report (SKI Technical Report 95:61), with extensive graphical presentation of the data base content.

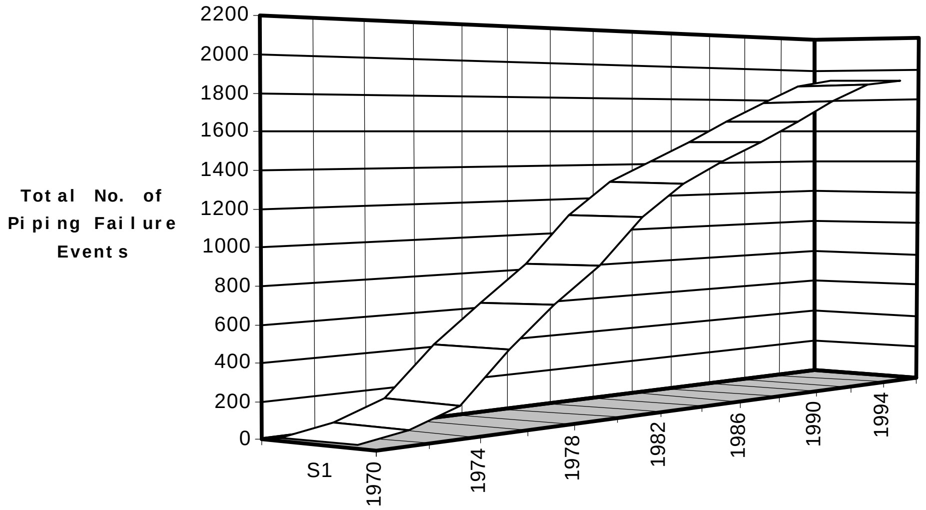


Figure 2-1: *Accumulated Pipe Failure Event Data As Documented by SKI's Relational Database - Commercial Nuclear Power Plant Data.*

Phase 2: Piping Failure Rate Estimation. The objective of this task was to develop a framework for failure rate estimation, including statistical uncertainties, that relies on operating experience rather than fracture mechanics. The analysis framework should recognize that the operating experience comes in the form of:

- Observed leaks or ruptures (i.e., degraded failures and complete failures) requiring delayed or prompt repairs.

- Inspection reports that indicate wall thinning due to erosion or corrosion (i.e., incipient failures) or cracking. Leak-before-break phenomena should be addressed.

The issue of the appropriate piping component boundary definition and unit of piping failure rate should be addressed. The unit of failure rate could be "[failure/hour.pipe segment]" or "[failure/hour.m.piping]" depending on application. Choice of unit has an important implication for piping reliability analysis and quantification. Also, intended application determines the component boundary definition.

Phase 3: Piping System Reliability Analysis. Analysis of piping reliability should be based on recognition of the key reliability influence factors and knowledge of piping system design. The analysis should account for piping geometry in terms of types and number of pipe sections; e.g., elbows, tees, straights. Phase 3 is directed at an analysis procedure building on insights from data analysis.

Phase 4: Application of Piping System Reliability Analysis Procedure. The results of Phase 3 will be applied to a piping line number in a Swedish BWR or PWR, or both. The scope includes LOCA frequency estimation as a complement to the Nordic NKS/RAK project, and comparison of PSA and PFM approaches.

2.4 Summary

SKI has commissioned a R&D project on piping system component reliability to: (i) develop a worldwide piping failure event database, (ii) establish a consolidated perspective on piping system reliability as it relates to PSA, (iii) provide a data-driven and systems-oriented analysis structure compatible with the PSA methodology, and (iv) test the analysis structure via pilot applications. Phase 2 results are documented in four volumes:

- Volume 1 (SKI Report 95:58), this report.
- Volume 2 (SKI Report 95:59. PSA LOCA Data Base. Review of Methods for LOCA Evaluation. The scope of the review included about 60 PSA studies. Unique deviations from the WASH-1400 practice of categorizing LOCAs and estimating their frequencies are presented. A detailed overview of LOCA categories and the passive component failures contributing to these categories.
- Volume 3 (SKI Report 95:60). Piping Reliability - A Bibliography. This bibliography includes over 800 technical reports, papers, and conference papers. Computerized literature searches were performed using the International Nuclear Information System (INIS), UN International Labor, Occupational Safety and Health data base (CISDOC), U.S. National Institute of Occupational Safety and Health data base (NIOSHTIC), and UK Health and Safety Executive's Library and Information data base (HSELINE). Key words such as "pipe failure" and "pipe rupture" were used.
- Volume 4 (SKI Report 95:61). SLAP - SKI's Worldwide Piping Failure Event Data Base. Includes printouts of failure reports classified as "public domain" information, not undergoing additional investigations. A large portion of event reports remains subject to interpretation and classification by project team. The report includes graphical presentation of the worldwide operating experience with piping system components. The report also includes an overview of fundamental data analysis considerations.

3: PIPING SYSTEM COMPONENT RELIABILITY & NUCLEAR SAFETY

3.0 Overview

This section addresses piping system component reliability and its relevance to PSA. Unique analytical considerations are addressed. Estimation of piping reliability using traditional reliability engineering and statistical analysis principles is complex. Four fundamental piping reliability analysis considerations are:

- ***Reliability influence factors*** affecting passive components are different from those affecting active components. Testing and preventive maintenance measures for primary system piping are complicated by lack of accessibility. Evaluation of metallurgical survey results could require considerable interpretation.

- The ***amount*** of passive components in a nuclear power plant is very large compared with active components. There is no easy way of grouping passive component failures according to cause-and-effect. The cause-and-effect of piping failures tends to be highly location dependent. Detailed qualitative reliability evaluations normally should precede attempts to quantify piping failure rates or failure probabilities.

- No generally applicable passive ***component boundary definition*** approach exists. Depending on PSA application needs, type of passive component, predominant reliability influence factor(s), and location in plant, a boundary definition could include, say, a single piping system component section (elbow, straight, weld, tee) or multiple sections.

- A prevailing ***mind set*** among PSA analysts has been that contributions to plant risk by passive component failures are negligible. For a long time, PSA guidelines, databases, and analysis practices have almost entirely focused on active component failures. Also, in relative terms piping failures are rarely experienced. It is therefore easy to overlook potential incident scenarios involving piping component failures.

As nuclear power plants age the topic of structural reliability could become more important. PSA studies should include explicit consideration of risk-significant piping systems, that allow evaluation of importance of small leakages, crack indications and effectiveness of NDE.

3.1 Pipe Failure Rate Estimation Approaches

Piping reliability estimation is complicated by an absence of complete, "pedigreed" failure data. A primary reason is lack of uniform failure event reporting requirements. Investigating passive component failures is a difficult undertaking. Extensive engineering analyses and metallurgical surveys could be required to correctly interpret available failure event data.

Over the years two general approaches to the estimation process have evolved. They are: (i) direct estimation using statistics of historical piping failure event data, and (ii) indirect estimation using probabilistic analysis of the failure phenomena of consideration. The essence of PSA includes application of historical and/or predictive techniques to arrive at the spectrum of unsafe event states versus their impact on plant operations. Both piping reliability estimation approaches fit the general PSA structure.

An advantage of direct estimation methods lies in the compatibility with PSA methodology and modeling approaches. Also, the direct estimation methods can be validated relatively easily. A structure for direct estimation is shown in Figure 3-1. A couple of variations on the direct estimation approach exist:

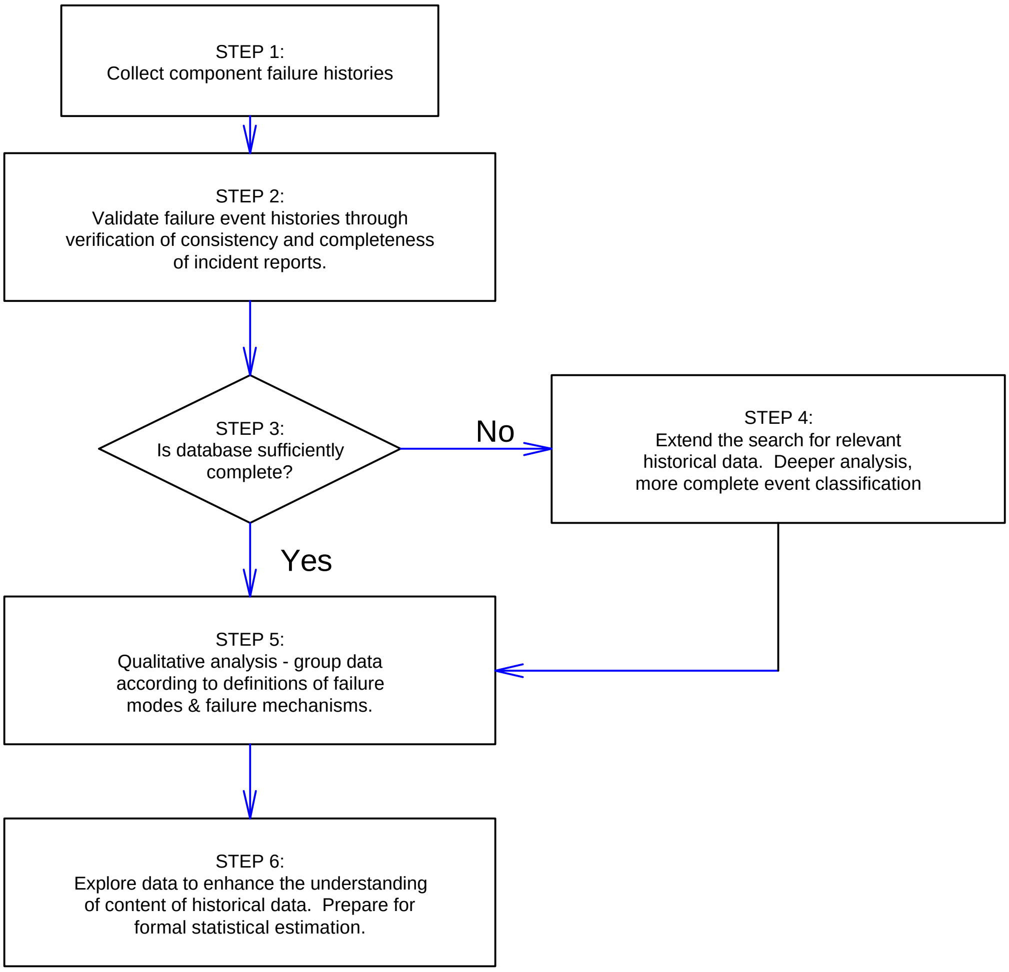


Figure 3-1: *Structure of Direct Estimation Strategy.*

- 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.

An advantage of indirect estimation methods is that they do not rely on access to extensive historical failure event data. Instead, indirect methods use statistics of material properties and loads which are more readily available. Experience data could be used to validate the results. Intimate knowledge of failure modes and failure mechanism is a requirement. Indirect estimation methods are favored by structural engineers and PFM analysts.

Whereas direct estimation methods tend to be relatively simple and transparent, indirect methods often utilize computation intense "black-box" approaches not directly compatible with PSA methodology and today's highly integrated computer codes for PSA. A further drawback of indirect methods could be the cost of carrying out necessary calculations, including validation of results.

Regardless of estimation technique, validity of results relies on detailed knowledge of <u>why</u> and <u>how</u> piping components fail. A fundamental aspect of piping reliability is access to comprehensive historical failure event data collections that address the possible range of reliability influence factors. Direct estimation should not be performed without first developing a detailed understanding of the failure modes and failure mechanisms of concern. Also, prior to selection of statistical parameter estimation approach, planned applications should be acknowledged. The remainder of the report follows the "direct estimation structure" of Figure 3-1.

A particular concern when addressing piping component reliability is the appropriate failure event population groupings. As an example, LOCA-sensitive piping should not be pooled with LOCA-insensitive piping to enhance population numbers. 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.

3.2 Pipe Failure Modes & Failure Mechanisms

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 significant 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 the 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.

  Most of the piping failure events are captured by other information systems; e.g., NSSS owners groups information bulletins, NEA/IRS, IAEA-INIS, inspection reports and workorder 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-INIS is considered "final", and therefore not subjected to updates or revisions. These two databases do not reflect on the detailed information typically available to utilities and regulatory agencies.

- On a system-by-system level, piping failures are rare events in comparison with active component failures. This forces PSA analysts to devote considerable time to interpreting limited amounts of raw data.

- Piping reliability is determined by many different influence factors. There are inherent, phenomenological factors, and operational and organizational influence factors. Piping components of like metallurgy, dimensions and application could exhibit widely different reliability characteristics in two similar plants because of unique operational philosophies or, say, inspection practices.

  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.

- 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).

Looking at the operating experience with piping systems (Section 4) 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.

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. 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 3-2) :

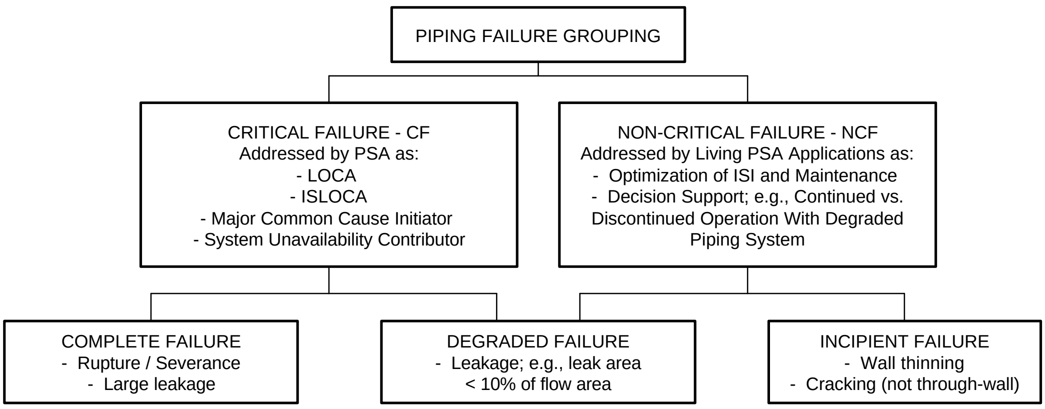


Figure 3-2: *Example of Piping System Component Failure Grouping.*

■ 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 is sometimes used to characterize the failure.

■ 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.

Often the incipient failures are classified simply as "failures." Sometimes these events have been counted towards the failure rate estimates used in PSA. 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, a significant amount of incipient or degraded failures are detected during major maintenance outages or refueling outages and 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.

3.3 Piping Reliability Influence Factors

From the PSA perspective, piping failures have the effect on plant risk as initiating events or on-demand failures (Figure 3-3). Whether a specific failure manifests itself as an incident initiator or a system disabling event depends on factors such as:

■ Location in plant; e.g., part of primary system pressure boundary, part of safety system (normally in standby), or part of balance-of-plant pressure boundary.

■ Failure mechanism; e.g., certain failure mechanisms could require a trigger event such as a pressure transient or water hammer for an incipient failure to transfer to complete failure. Other mechanisms could feasibly propagate into a full pipe break more-or-less spontaneously.

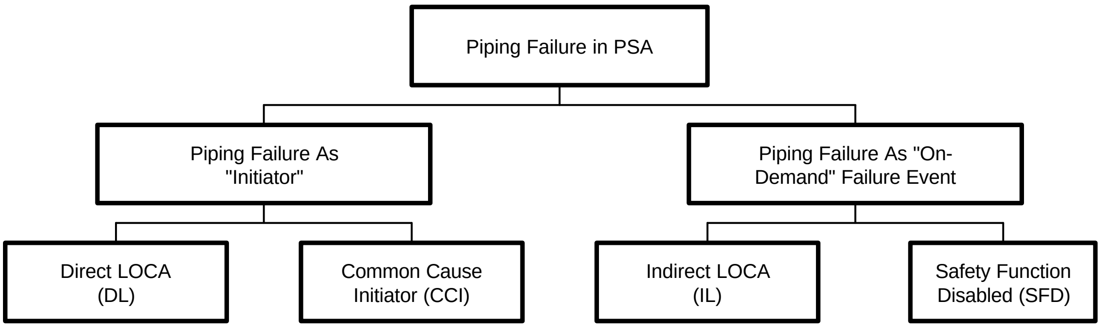


Figure 3-3: *Piping Failure Categories for Consideration in PSA Models.*

The methods for estimating piping failure statistics from operating experience should acknowledge a classification scheme such as shown in Figure 3-3. Following are comments on the piping failure categories:

- "Indication" and "leakages" could be categorized as "On-Demand" candidates. As an example, a pressure transient caused by system actuation or shutdown could cause degraded piping to rupture, and lead to consequential (indirect) LOCA, or disable a vital safety function.

- When addressing potential effects of piping failure on plant response a distinction should be made between isolateable and non-isolateable LOCAs ("DL"). Also, distinction should be made between piping failures within and outside the make-up capability of ECCS.

- CCI-events cover a wide range of potentially very important piping failures. Among utility systems, the obvious would be piping failures in CCWS, SWS, IAS, or oil lubricating system. Some piping failures could result in internal flooding events that disable vital safety functions. Steam system piping failures could severely impact motor control center (MCC) functions, pump motor operability, etc. Examples exist where a piping failure potentially could constitute a single failure of ECCS (e.g., HPIS, LPIS and CSS). Pipe failure in oil lubricating system could result in a fire hazard and extensive fires; e.g., turbine building fire as witnessed by a recent incident in Forsmark-3 in 1995[3-1].

  Dynamic effects (e.g., pipe whips, steam jets) of one pipe failure could cause failure of adjacent, smaller-diameter piping. Based on operating experience, CCI-effects constitute a prime reason why piping failures could cause turbine or/and reactor trip. The operating experience also indicates that few pipe failures have direct, immediate effects plant safety functions.

Derivation of piping reliability estimates for input to PSA models also should be done against a background of valid incident theory that explains how piping fails and what the consequences might be. A first event tree below addresses a screening approach for initiating event identification and categorization; Figures 3-4 and 3-5. A pipe failure could result in a leakage or rupture, with or without dynamic effect(s) on adjacent piping system(s). The effect of a failure could be benign (i.e., easily mitigatable), or serious (i.e., challenging the safety barriers).

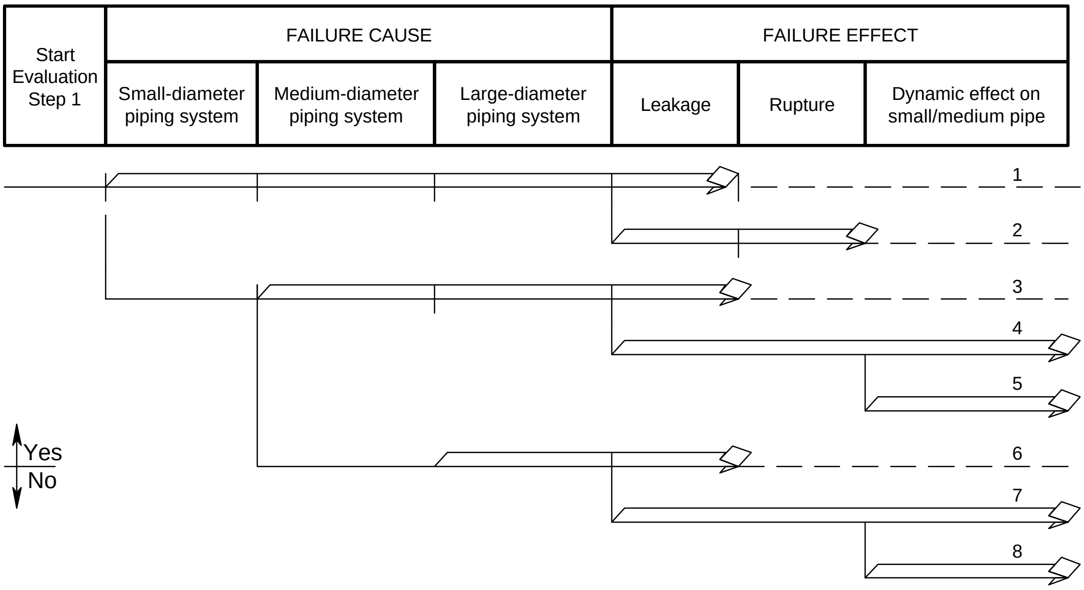


Figure 3-4: *Piping Failure as Initiating Event - Failure Cause & Effect.*

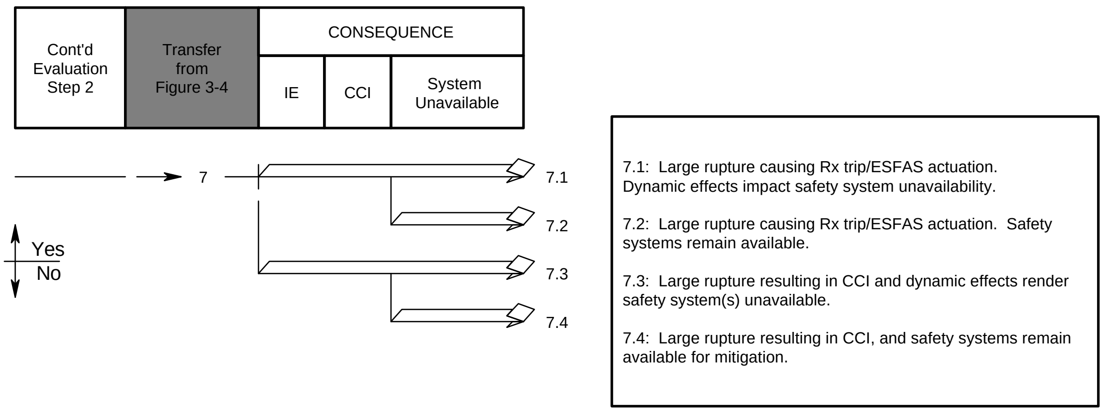


Figure 3-5: *Potential Consequences of Piping Failure - An Example.*

Initiating event types depend on how and where a piping failure occurs. So can dynamic effects of a large-diameter pipe failure result in failure of small-diameter and medium-diameter piping. While initiating event frequency estimation for the large LOCA event itself could be based on direct estimation, the consequential medium and small LOCA events would require additional engineering analyses, including PFM-modeling. Similarly, dynamic effects of a medium-diameter pipe failure could result in failure of adjacent small-diameter piping. Finally, a small-diameter pipe failure would not normally be expected to impact adjacent medium- and large-diameter piping systems.

A conceptual, event tree based plant model is shown in Figure 3-6. Given a sufficiently detailed initiating event categorization, the "plant model" asks questions about how a loss of coolant event is terminated (e.g., isolated by closing of valves) or mitigated (e.g., actuation of coolant make-up function).

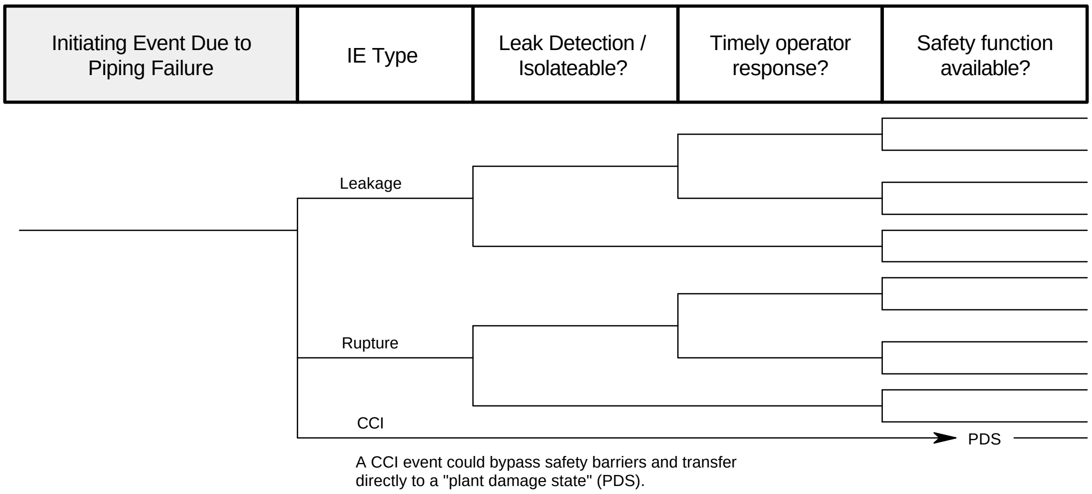


Figure 3-6: *Anatomy of Piping Failure Incidents - Conceptual Plant Model.*

Piping failures could be conditional events; i.e., they require a trigger event (such as a water hammer) challenging the strength of the pressure boundary component. The likelihood of such a failure is a function of failure mechanism (i.e., symptom of degradation) and the degree by which the strength has deteriorated, and plant status. Examples of conditional events are steam piping failures through erosion-corrosion damage combined with a hydraulic pressure transient. Other piping failures could occur spontaneously; i.e., a piping component could have degraded to the point of failure through exposure to the normal heating and cooling cycles, and anticipated plant transients, and without presence of an abnormal plant state or state transition. The "conditional events" cover a wide range of LOCA-sensitive and non-LOCA-sensitive piping failures. If the failure is self revealing (i.e., detectable) and isolateable, the incident control function would normally consist of valve closure by an operator (either remote or local isolation). The incident barrier function would normally be a safety system for coolant makeup, combined with containment (e.g., a bund) that prevents flooding. The barrier function could feasibly be disabled by the piping failure, either directly or indirectly (i.e., through the potential common cause effects of a piping failure). A common cause initiating event (CCI) could render vital safety equipment unavailable thus making mitigation difficult; e.g., water or steam from failed piping could spray on electrical equipment such as motor control centers (MCCs), pump motors.

Definition of initiating events (IE) relies on PSA analysts' understanding of plant design bases and available operating experience. Information contained in Final Safety Analysis Reports (FSARs) and Technical Specifications (TS) is usually input to IE-groupings. In addition, already completed and "certified" PSAs guide analysts in making assumptions about events and safety functions to be included by system and plant models. Validity of PSA results depends on how plant safety principles (as documented in FSAR and TS) and PSA precedents have been interpreted and modified by PSA analysts. While TS documents have been subjected to frequent updates and enhancements reflecting on operating experience, engineering analyses and feedback from PSA applications, FSAR documents often have remained relatively static, reflecting on state-of-knowledge relevant perhaps twenty years ago (when the plant was constructed and commisioned). As a result, inconsistencies between the two documents have been known to exist. Validation of IE-grouping through reviews of operating experience is always important.

3.4 Human Factors & Human Reliability Considerations

So far we have addressed the failure modes and failure mechanisms of piping failure; 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; c.f. Lydell[3-2]. The situation is no different for piping failures.

Human errors are either ***latent*** or ***active***; c.f. Reason[3-3] and Embrey et al[3-4]. 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[3-5]. Another example of latent human error affecting piping reliability is the maintenance and ISI-policy that does not acknowledge existing, generic operating experience with a particular type of piping system. By contrast, effects of an active human error are felt almost immediately; e.g., water hammer due to improper post-maintenance restoration of a piping system.

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[3-6]. 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).

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[3-7]

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[3-8]. 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.

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.

Looking at the "anatomy of piping failure incidents" in Figures 3-4 through 3-6, it is clear that an important human reliability consideration is detectability of a piping failure. A large portion of piping failures are detected by plant personnel performing shiftly walk-throughs 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, and reliability and applicability of leak detection systems. The further away from RCS, the more likely is prompt detection.

3.5 Pipe Reliability Studies

The PSA practice remains influenced by the twenty year old WASH-1400. According to WASH-1400, piping failures are rare events relative to active component failures. Therefore, explicit modeling of piping failures has not been viewed as warranted. Numerous studies of operating experience with piping system components have been pursued since the mid-sixties. Yet, WASH-1400 has remained the primary data source. Section 3.5 summarizes results from a selection of these studies.

3.5.1 Published Failure Statistics (1964-1995)

No generally recognized, validated and PSA-oriented source of piping failure statistics exists. Several attempts have been made to update the information included by WASH-1400, Appendix III, published in 1975[3-9].

Existing technical approaches range from application of limited operating experience combined with expert judgment (EJ), the "Thomas elemental approach" (TEA), integral statistical estimation (ISE), to probabilistic fracture mechanics (PFM). For PSA the Reactor Safety Study (RSS) of 1975 has remained a primary data source of failure statistics including failure probabilities. Practitioners have often considered validation by reference to RSS as sufficient. PSAs seldom explicitly address reliability of passive equipment. While notable R&D efforts have been directed to the general topic "reactor primary component reliability", no systematic program has been instituted for tracking operating experience.

Also, no consensus statistical analysis structure (compatible with today's PSA methodology) has yet been approved for failure rate estimation based on operating experience.
The basis for the reliability estimates documented in RSS originated from analysis of limited commercial nuclear power operating experience and analyses of non-nuclear process piping (primarily fossil power plants). Preceding RSS by about ten years, General Electric (GE), under contract with the U.S. Atomic Energy Commission, performed the "Reactor Primary Coolant System Rupture Study" (GEAP-4574)[3-10]. This study surveyed available experience with steam plant piping and provided frequencies for the failure modes "leaks" and "severance" taking into consideration the impact of UT on overall reliability; Table 3-1.

FAILURE MODE	FAILURE RATE [Events/Plant.Year]	SOURCE
"General Failure" - Leakage Severance Severe Service Failure	4.4E-02 1.9E-03 4.4E-04	GEAP-4527 (1964); Conventional utility industry steam piping. About 9000 plant-years of experience.
Leakage - Without UT Severance - Without UT Leakage - With UT Severance - With UT	2.6E-01 4.0E-03 1.3E-01 1.5E-03	GEAP-10207-23 (1970); Steam piping in conventional power plant and NPP.
Leakage Severance	6.8E-01 1.5E-02	ORNL-TM-3425 (1970); Oak Ridge National Laboratory. Review of NPP experience (75 reactor-years) with interpretations and additional analysis by Holt [3-11]. High failure rates attributed to human error/ design error/construction error. According to the report by Oak Ridge, about 57% of all LERs attributed to human error.

Table 3-1: *Early Pipe Failure Rate Estimates.*

Best estimate (maximum likelihood estimates) were obtained by taking the total number of leak (severance) events over the total number of plant years. The then available operating experience did not allow for detailed classification of data, nor were systematic data exploration and reductions performed. Uncertainties in derived estimates were recognized as significant. GEAP-4574 was a key information source used by RSS.

At the time of publication of the RSS in 1975 only about 150 reactor years of operation had transpired and limited experience data were available for estimating pipe break frequencies. Since 1975 several studies have been conducted to update the pipe failure data. Despite these more recent efforts, the RSS-data have remained a primary source for PSAs.

3.5.2 Pipe Failure Rates by WASH-1400

As part of the WASH-1400 effort a limited evaluation of nuclear pipe reliability, based on actual failures in nuclear systems related to the operating period of nuclear systems. The emphasis was on the derivation of order-of-magnitude LOCA frequencies for input to event tree analysis (Table 3-2) and pipe failure rates for input to system fault trees (Table 3-3). WASH-1400 examined several different sources to obtain failure rates for small-diameter and large-diameter pipe. The reason for using several data sources was the interest in pipe ruptures (complete pipe severances) resulting in reactor coolant loss, and none had occurred in the 150 U.S. commercial nuclear reactor operating years considered by the study. Therefore, other pipe failure data sources were sought for extrapolating pipe failure rates for use in the RSS.

LOCA CLASS	INITIATING EVENT FREQUENCY [1/Year]	
	Median	Range (90%)
Small	1.0E-3	1.0E-4 - 1.0E-2
Medium	3.0E-4	3.0E-5 - 3.0E-3
Large	1.0E-4	1.0E-5 - 1.0E-3

Table 3-2: *LOCA Frequencies in WASH-1400*[3-9].

PIPE SIZE [DN, mm]	FAILURE RATE, RUPTURE [1/hr.m]	
	Median	Range (90%)
< 75	1.0E-9	3.3E-10 - 3.0E-8
> 75	1.0E-10	3.3E-10 - 3.0E-9

Table 3-3: *Pipe Failure Rates in WASH-1400*[3-9].

Several different means of extrapolating the data were devised because the data were given in different forms. Details such as leak rates, pipe diameter, cause of failure, system in which the failure occurred, and other pertinent information were not supplied. As a result, weighting factors based on "average plant characteristics" were used to relate total plant piping to LOCA-sensitive piping and to large- and small-diameter piping and complete severance to large pipe. LOCA-sensitive piping was defined as:

- LOCA-sensitive piping; 10% of total piping in the reported data base.

- LOCA-sensitive small piping (≤ DN 100); 4.7% of total piping in the reported data base, 10% of small piping.

- LOCA-sensitive large piping (≥ DN 100); 5.3% of total piping in the reported data base, 10% of large piping.

A criticism against the WASH-1400 was that the data base on significant pipe failures only included 11 data entries on "significant events from U.S. nuclear industry; c.f. Holt[3-11]. Therefore the statistical uncertainties of the failure rate estimates and LOCA frequencies were considerable. As a further criticism, several inconsistencies exist in the failure rate estimation and interpretation of estimates within WASH-1400. In Appendix III the failure rates were calculated so as to provide estimates having dimension [1/hr.feet], while in the systems analyses the same failure rates were assumed having the dimension [1/hr.section]. Although inconsistently applied, in WASH-1400, a pipe section was assumed to correspond to about 12 feet of piping[3-12]. For small-diameter piping (≤ 75 mm diameter), the failure rate was derived from:

- In 1972 about 150 reactor-years of U.S. NPP experience were available. During the period 1960-1972, eleven significant pipe failures were recorded. They all occurred in small-diameter piping. Based on this information a point estimates was calculated from:

  $\lambda = 11/(150 \times 8760) = 8.37 \cdot 10^{-6}$/hr.plant.

  In Appendix XI of WASH-1400 ("Comments on the Draft Report", page 14-3) information is given on the amount of LOCA-sensitive piping in a typical commercial, U.S. nuclear power plant:

  "..... 5% or 8,500 feet of piping is large LOCA-sensitive ..."

  This information would imply the total amount of piping to be on the order of 170,000 feet. On page III-75 of Appendix III it is stated that 4.7% of total plant piping is small LOCA-sensitive (i.e., about 7,990 feet). Therefore, the failure rate of small-diameter piping is about:

  $\lambda = 8.37 \cdot 10^{-6}/7{,}990 = 1.05 \cdot 10^{-9} \approx 1.0 \cdot 10^{-9}$/hr.feet.

  In the fault tree models this failure rate is interpreted as being valid for each section of piping. While there is inconsistencies within WASH-1400, there are also inconsistencies in how later piping reliability studies have interpreted WASH-1400. As we shall see, the interpretations of the above numerical information not only varied within WASH-1400, but among subsequent piping reliability studies.

3.5.3 Pipe Failure Rates by PNL (1976)

After the publication of WASH-1400 in 1975, Battelle Pacific Northwest Laboratories (PNL) performed an assessment of piping reliability based on available U.S. LWR operating experience and non-nuclear operating experience[3-13,14]; Table 3-4. Differences between WASH-1400 and PNL results are due to how limited failure data were interpreted. The study by PNL addressed the role of periodic inspection, and addressed failures due to intergranular stress-corrosion cracking (IGSCC). Among the conclusions by PNL were:

- The failure probabilities for larger sizes of nuclear piping were considered to be in the range of 1.0E-4 to 1.0E-6 per reactor year (exclusive of IGSCC).
- Smaller pipe sizes, of lesser safety significance, have much higher failure rates.
- In BWRs, IGSCC can cause failure rates much higher than 1.0E-4 (e.g., 1.0E-2) in piping DN 100 to DN 250.
- Catastrophic failures would appear more likely from operator error or design and construction errors (water hammer, improper handling of dynamic loads, undetected fabrication defects) rather than conventional flaw initiation and growth by fatigue.

FAILURE RATE [1/hr.m]	
BWR	**PWR**
4.9E-9	5.3E-9
Note: The failure rates are in terms of failures per m of piping. According to the PNL-study, a BWR contains 94,500 m of piping, and a PWR contains 84,000 m of piping; 317,000 feet and 280,000 feet, respectively.	

Table 3-4: *Pipe Failure Rates in PNL Study (DN > 100).*

3.5.4 Pipe Failure Rates by AECL (1981)

The Atomic Energy of Canada Limited (AECL) performed a study[3-15] of U.S. LWR piping operating experience for the period 1959 through 1978, representing 409 reactor-years of experience. The study was initiated in support of the analysis of the consequences of pipe rupture in the Primary Heat Transport System (PHTS) for CANDU power stations.

Another objective was to establish whether the additional operating experience that had accumulated since publication of WASH-1400 warranted new pipe failure rates to be used in PSA applications.

The pipe failure events were classified according to: (i) severance, (ii) leak, and (ii) defect. Of the total of 840 failure events considered by the study, 87 pipe failures were interpreted to be severances (8 events in small-diameter primary system piping). Table 3-5 summarizes failure rate estimates for primary system pipe severances.

Statistical analysis was limited to estimation of confidence limits for failure rates using the Chi-square distribution. Because of uncertainties in the pipe failure event data base and assumptions in interpretation of the data, the order-of-magnitude failure rate estimates by WASH-1400 were viewed by the AECL study as representative of "true" failure rates.

PIPE SIZE	FAILURE RATE, RUPTURE UPPER LIMIT AT 95% CONFIDENCE [1/hr.plant]
DN ≤ 25	4.4E-6
25 < DN < 150	8.3E-7
DN ≥ 150	8.3E-7

Table 3-5: *Pipe Failure Rates in AECL Study (1981).*

3.5.5 Pipe Failure Rates by Thomas (1981)

In 1981 H.M. Thomas of Rolls Royce & Associates Ltd. published a modeling system for interpretation of piping failure data, and for "adjusting" generic industry data to plant-specific data[3-16]. Among reliability influence factors acknowledged in updating generic data were: design learning curve, pipe diameter, plant age, fracture toughness, pipe length, number of cycles, parent material versus weld material, fatigue stress, crack dimensions, and wall thickness. On the subject of pipe length Thomas states on page 103[3-16]:

- *"... It is known that a typical [nuclear power] plant contains about 16,500 feet of pipe less than 4 inch diameter and about 18,500 feet of pipe greater than 4 inch diameter, making a total of 35,000 feet ..."*

Thomas references WASH-1400, Appendix III. There is discrepancy between WASH-1400 and the Thomas paper, however. Let us speculate how the information on pipe length was developed. Some insights can be gleaned by assuming that Thomas arrived at a number of 350,000 feet being the total length of piping in a typical nuclear power plant. By multiplying this length by 4.7% and 5.3%, respectively, we would (consistent with WASH-1400) get the total lenght of small-diameter, LOCA-sensitive piping and large-diameter, LOCA sensitive piping, respectively; i.e., together about 35,000 feet of pipe. It is feasible that Thomas was influenced by the paper of Spencer Bush published in 1975[3-13] in which a typical BWR is stated as having 315,000 feet of (LOCA-insensitive) piping. Under the set of assumptions there would be consistency between Thomas and Bush; i.e., 315,000 + 35,000 = 350,000 feet)[3-17].

3.5.6 Pipe Failure Rates by Risø (1982)

Within the framework of the SÄK-1 (Probabilistic Risk Assessment and Licensing) project sponsored by the Nordic Liaison Committee for Atomic Energy (NKA), Risø performed the "Pipe Failure Study"[3-18,19]. Derived failure rates were based on Swedish and Finnish nuclear plant operating experience for the period 1975-1981, corresponding to 43 reactor-years. A total of 62 pipe failures were recorded in Swedish plants for the study period, of which 2 events represented crack or rupture. A summary of the pipe failure rates is given in Table 3-6.

PIPE RUPTURE SIZE	FAILURE RATE, RUPTURE (90% Range) [1/hr]	
	Water Pipe	Steam Pipe
Small	6.63E-5 - 1.17E-4	6.96E-6 - 2.79E-5
Medium	8.68E-6 - 3.15E-5	9.13E-7 - 1.26E-5
Large	9.13E-7 - 1.26E-5	≤ 6.16E-6

Table 3-6: *Pipe Failure Rates in Risø Study.*

The derived failure rates are based on instances of pipe degradations requiring repair, and not only actual breaks or ruptures. Hence, an application of the failure rates would require additional interpretations and conversions to be compatible with the data needs of PSAs; i.e., critical failures.

3.5.7 Pipe Failure Rates by AECL (1984)

As a continuation of the study by AECL in 1981 (Section 3.5.4), an assessment of the piping system component reliability in CANDU plants was published in 1984[3-20]. Failure event data from Pickering-A and Bruce-A for the period 1971-1981 was analyzed using an approach similar to AECL (1981) study. A total of 158 failure events were recorded for the study period. Of these, 6 events were pipe severances in total plant. Only one primarys system severance was reported. Table 3-7 summarizes derived pipe failure rates for CANDU plants.

A key conclusion was that because of the shorter operating history of CANDU plants, the derived failure rates bounded the failure rates by WASH-1400. The AECL (1984) study also addressed failures in nozzles, tubes, valve bodies and bonnets, pump casings and covers, and flanges.

PIPE SIZE	FAILURE RATE, RUPTURE UPPER LIMIT AT 95% CONFIDENCE [1/hr.plant]
DN ≤ 25	1.2E-5
25 < DN < 150	6.4E-6
DN ≥ 150	6.4E-6

Table 3-7: *Pipe Failure Rates in AECL Study (1981).*

3.5.8 Pipe Failure Rates by EG&G Idaho, Inc. (1987)

Objective of the EG&G-study was to update the failure rate estimates of WASH-1400 by utilizing the accumulated U.S. nuclear operating experience available as of December 1984[3-21]. About 800 reactor years of operation were considered. Derived LOCA frequencies and pipe failure rates are shown in Tables 3-8 and 3-9, respectively. Relative to WASH-1400 an additional 650 reactor years were accounted for to improve the uncertainties of the pipe failure rates. Whereas RSS accounted for a total of eleven (11) significant pipe failures, the EG&G-study identified twenty (20) significant pipe failure events for input to failure rate estimation.

LOCA CLASS	INITIATING EVENT FREQUENCY [1/Year]	
	Median	Range (90%)
Leak rate > 3 kg/s	3.0E-4	0 - 3.8E-3

Table 3-8: *LOCA Frequencies in EGG-2421.*

In the EG&G-study LOCA-sensitive piping was defined as piping in which a pipe break results in a LOCA. Non-LOCA-sensitive piping was defined as piping associated with systems that would be used to help mitigate a core damage sequence. Failure criteria were established for the two piping categories to define the failure data to be collected. For LOCA-sensitive piping, failure was defined as a leak rate of at least 3 kg/s for PWRs and 30 kg/s for BWRs. These rates are the normal reactor coolant makeup system capacity for each plant type. For non-LOCA-sensitive systems, several factors were considered in the definition of failure. One factor considered was whether one could determine the leak rate necessary to disable a system from performing its intended function. Since the leak rate value is system and location dependent, the data were instead placed in two discrete categories (> 0.06 kg/s and > 1 kg/s). These leak rate categories were selected because the few actual known leak rates reported occurred roughly in the range 0.06 - 1 kg/s.

PIPE RUPTURE SIZE [mm]	FAILURE RATE [1/hr]		
	5th	Median	95th
BWR			
12 - 50	3.0E-7	1.1E-6	2.8E-6
50 - 150	1.3E-7	7.3E-7	2.3E-6
> 150	7.3E-7	1.8E-6	3.8E-6
PWR			
12 - 50	8.0E-8	4.7-7	1.5E-6
50 - 150	3.2E-7	9.5E-7	2.2E-6
> 150	1.9E-7	7.1E-7	1.8E-6

Figure 3-9: *Pipe Failure Rates in EG&G-Study (1987) - Non-LOCA-Sensitive and LOCA-Sensitive Piping.*

3.5.9 Pipe Failure Rates by GRS (1987)

In support of the Phase B of the German Risk Study, GRS sponsored R&D on pipe reliability[3-22]. This R&D was sponsored in recognition of the significant limitations of the available pipe reliability estimation approaches, and the significant limitations in the approaches to LOCA frequency estimation practiced in PSA projects.

GRS elected to apply two general analysis approaches: (i) statistical evaluation of operating experience, and (ii) probabilistic fracture mechanics studies. The former approach was applied to small-diameter piping for which failure experience existed, while the latter approach supported analysis of piping for which some experimental data existed together with insights from the German NDE experience. Table 3-10 summarizes pipe failure probabilities by GRS. Reliability influencing factors were recognized in the work. According to GRS:

- The worldwide operating experience with LWRs is of limited use as a data source. Observed failure mechanisms are partly design dependent. Problems with pooling of data.

- The available operating experience with German NPPs showed only a small number of leakage events. Therefore the statistical uncertainty bands were considerable.

Rather than using equivalent leakage/rupture sizes, pipe failure data were estimated for three categories of piping: (i) ≤ DN 25, (ii) > DN 25 - < DN 250, and (iii) ≥ DN 250. Statistical analysis of operating experience was used for ≤ DN 25, while probabilistic fracture mechanics studies were used for the large nominal diameters; ≥ DN 250. For the range > DN 25 to < DN 250 insights from operating experience was applied in a qualitative sense together with experimental data and LBB-reasoning.

PIPE FAILURE CLASS [Break Size]	FAILURE PROBABILITY [Mean]
DN 25	1.7E-03
DN 50	1.7E-04
DN 80	5.7E-05
DN 100	9.6E-06
DN 150	1.4E-05
DN 250[(a)]	< 1.0E-07
≥ DN 300[(a)]	< 1.0E-07
Break (DEGB) - > DN 250[(b)]	< 1.2E-10
Leakage - > DN 250[(b)]	< 2.0E-07

Notes: (a). Evaluated using probabilistic fracture mechanics. Stated value interpreted as upper bound.
(b). From NUREG/CR-3660-VI [3-23]. Stated values are the upper bounds. The DEGB is induced by fatigue crack growth. The leakage is assumed to result from a through-wall crack.

Table 3-10: *Pipe Failure Probabilities in GRS-Study (1987). PWR Piping Inside Containment.*

Relative to data on BWR piping, the German eighties' view was that the worldwide experience was unapplicable. Because of the types of materials used in backfitting all BWRs with new live steam and feedwater piping within the containment about 15 years ago, the failure potential due to IGSCC has been viewed as eliminated[3-24,25].

3.5.10 Pipe Failure Rates by EG&G Idaho, Inc. (1991)

Building on earlier work (Section 3.5.8) EG&G Idaho, Inc., under contract with the U.S. Department of Energy, developed an updated, more comprehensive data source for external leakage and rupture events for piping and piping components such as valves, flanges, fittings[3-26]. This new data source was developed to support internal flooding risk analyses; Table 3-11.

Licensee Event Reports (LERs) contained in Nuclear Power Experience (NPE)[3-27] were searched for leakage and rupture events. Extracted failure reports covered the period 1960-1990. Some of the qualitative insights from the data analysis were:

- There appeared to be no significant difference in external leakage or rupture frequencies between piping with diameters < DN 75 and larger piping.

- There appeared to be no significant difference between PWR and BWR component external leakage and rupture frequencies.

- It was possible to distinguish between external rupture frequencies for components in primary coolant systems and external rupture frequencies for components in other systems. The difference is probably a result of better inspection and leak detection methods for PCS components. No significant difference noted in external leakage frequencies between the two component classes, however.

- External rupture frequencies were found to generally be factors 25 or 100 times lower than external leakage frequencies and are dependent on the type of component and whether the component is in the primary coolant systems.

PIPING SYSTEM COMPONENT	RUPTURE PROBABILITY[a] [Mean]
Non-RCS[b]:	
- Piping (including elbows)	3.3E-03
- Valve, pump, heat exchanger, tank	5.2E-02
- Flange	1.0E-02
RCS[c]:	
- Piping (including elbows)	8.0E-03
- Valve, pump, flange, heat exchanger, tank	9.0E-03

Notes: (a). Conditional (given an external leakage or rupture event) mean rupture probability. In deriving the probabilities, the ratio of external rupture events to external leakage and rupture events was determined. Leakage rate > 3 kg/s.
(b). Non primary system components.
(c). Primary system components.

Table 3-11: *Piping Component Failure Probabilities in EG&G-Study (1991).*

Based on derived leakage frequencies a rupture frequency was estimated by first calculating a rupture probability using Bayesian statistics. For piping the external rupture probability given that an external leakage or rupture has occurred was given as 0.04 for non-PCS piping and 0.01 for PCS piping. Figure 3-12 summarizes the pipe failure rates.

PIPE FAILURE MODE	MEAN FAILURE RATE [1/hr.m]
Leakage (PCS & Non-PCS)[1]	1.0E-08
Rupture (PCS)	1.0E-10
Rupture (Non-PCS)	4.0E-10

Note: (1). Leakage defined as $\leq$ 3 l/s / Rupture defined as > 3 l/s or complete severance.

Figure 3-12: *Pipe Failure Rates in EG&G Study (1991).*

3.5.11 Pipe Failue Rates by EPRI (1990-1993)

Originally undertaken for Northeast Utilities Service Company[3-28], and later co-sponsored by EPRI, Jamali[3-29] developed a methodology and data base for pipe failure rate estimates. A first report documenting results was published in 1990, and to allow for wider access EPRI later published enhanced and updated versions of this report in 1992 and 1993, respectively[3-30,31]. The EPRI reports have limited distribution, available only to EPRI member utilities and affiliates.

The EPRI-studies were undertaken to provide a U.S. nuclear plant pipe failure data base reflecting the additional experience generated since WASH-1400 was published. The principal sources of pipe failure information were Licensee Event Reports (LERs), Nuclear Power Experience (NPE) published by S.M. Stoller Corporation[3-27], and the Nuclear Plant Reliability Data System (NPRD) operated by the Institute of Nuclear Power Operations (INPO).

For estimation of pipe failure rates from operating experience a new "EPRI methodology" was developed. A parameter referred to as "failure severity code" was introduced as key ingredient of the methodology. This parameter accounts for the fact that the effective break area can be significantly smaller than the area calculated using pipe inner diameter. It was used to estimate conditional probability of having a given effective break size for a given pipe size. The EPRI methodology also accounts for factors that can be quantified from the data base and that may significantly affect the values of the failure rates. These include the nuclear steam system supplier (NSSS), system type, pipe size, and plant age. Variance analysis (ANOVA) techniques were used to estimate the effect of system types on leakage failure rates. Key features of the EPRI methodology are summarized below:

- Piping component boundary definition. A pipe section is a segment of piping, between major discontinuities, such as valves, pumps, reducers, tees, etc. as defined by WASH-1400. While the EPRI reports do not give specific guidance on how to apply this definition, the reports include typical pipe section counts for BWRs and PWRs.

- Pipe failure attributes. These are factors believed to significantly impact pipe failure rate. The EPRI methodology explicitly accounts for failure mode, pipe size, system type, and time (i.e., age). Four size categories were used; $13 \leq ND < 50"$, $50" \leq ND < 150$, $150 \leq ND$, and "unknown size".

- Pipe failure mode definitions. Three failure modes were considered:

    - Cracking; failures with no seepage of process fluid to the outside of the pressure boundary.

    - Leakage; loss of fluid in amounts of less than 50 gpm (3 kg/s).

    - Rupture; major piping breakage is classified as rupture regardless of leak rate.

- Failure severity codes. For estimation of time-independent and time-dependent parts of the failure rate equation.

Tables 3-13 and 3-14 summarize derived LOCA frequencies and failure rates by the interim (1992) EPRI-study. A final report published in 1993 included an updated list of pipe rupture events considered for input to statistical analysis; 105 events in 1993 versus 41 events in 1992.

EPRI adopted the WASH-1400 definition of pipe section; i.e., a segment of piping between major discontinuities such as valves, pumps, reducers, etc. Pipe section counts are provided for typical U.S. BWRs and PWRs, and these counts are consistent with WASH-1400.

LOCA CATEGORY	INITIATING EVENT FREQUENCY (Median)		
	EPRI-BWR	EPRI-PWR	WASH-1400
Small	1.8E-3	1.0E-3	1.0E-3
Medium	2.8E-4	3.2E-4	3.0E-4
Large	3.0E-4	1.4E-4	1.0E-4

Table 3-13: *LOCA Frequencies in EPRI-Study (1992).*

PIPE SIZE - INNER DIAMETER (ID) [mm]	FAILURE RATE [1/hr.section]	
	EPRI	WASH-1400
$12 \leq ID < 50$	6.0E-10	3.6E-9
$50 \leq ID < 75$	3.0E-10	3.6E-9
$75 \leq ID < 150$	3.0E-10	3.6E-10
$ID \geq 150$	7.0E-10	3.6E-10

Table 3-14: *Pipe Failure Rates in EPRI-Study (1992).*

3.6 Summary

The PSA-treatment of piping system component failures is largely influenced by data and modeling concepts developed by WASH-1400. Since the mid-seventies several R&D projects have attempted to update the failure event database developed in WASH-1400. Failure rate estimates resulting from these efforts have large statistical uncertainty bands. The uncertainties are the result of incomplete data and difficulties in interpreting existing data. Each effort has highlighted the difficulties involved in interpreting and analyzing pipe failure data. Large LOCA frequencies based on interpretation of operating experience continue to differ by about four-order-of-magnitudes relative to PFM-results.

4: OPERATING EXPERIENCE WITH PIPING SYSTEM COMPONENTS

4.0 Overview

A basis is developed for a data-driven, systems-oriented framework for including piping system component failures in existing PSA model structures. A two-tier approach was taken to meet this project objective. First, the worldwide operating experience with piping system components was reviewed to better understand why and how piping fails. Second, insights from *review of about 60 PSA studies* (Section 5) were used to define desirable features of a framework for PSA-treatment of passive component failures. Section 4 addresses insights from reviews of operating experience involving piping failures; i.e., leakages and ruptures in straights. elbows, tees, or reducers challenging NPP barrier functions.

Desirable features of a structured approach to piping reliability analysis includes access to validated failure event data, and a logical basis for data interpretation. Beginning with a description of available operating experience, Section 4 addresses the pipe failure modes, failure mechanisms, and failure influence factors requiring consideration by reliability data analysts.

4.1 SKI's Worldwide Piping Failure Event Data Base

A main resource for direct estimation of piping failure rates should be historical data, including findings of incident investigations, precursor event information, and state-of-knowledge in piping reliability. The validity of results from direct estimation is a function of the validity (e.g., completeness) of data, and the ability to explore the database content. Unless a piping failure has direct impact on normal plant operation, discretionary reporting normally is deemed sufficient by regulators and plant operators. This practice has important implications for analyses of failure statistics, however.

Statistical uncertainties from incomplete data could be substantial. This is especially true for piping failures. Regulatory reporting requirements, industry policies regarding sharing of operating experience, and data base maintenance approaches influence data quality and completeness. Distinguishing features of different data collections are found in the amount and quality of information attached to each event record. The current version of SKI's piping failure event database (SLAP, included in Volume 4 of this report) currently includes about 2,300 piping failure event records. Substantial number of failure reports await processing. Data classification by project team is based on available event descriptions and plant design information. The database content consists of *primary* and *auxiliary* records:

- Primary failure data: Nordic and U.S. operating experience including all public domain information such as U.S. LERs, Swedish ROs, special incident investigation reports prepared by regulators. In addition, proprietary failure event data sets were made available to the project by electric utility organizations; e.g., APS, IVO, KSU. Included among the "primary failure data" are important calibration data sets consisting of detailed failure event reports, including results from UT-surveys and metallurgical analyses.

As defined here, "primary" relates to the statistical estimation process. Industry-wide, generic (or prior) piping failure rate distributions were generated based on the failure information for which a "reasonable" and "verifiable" level of assurance of relevance and completeness existed. The entire Swedish RO database (STAGBAS) and the entire U.S. LER database were surveyed. The U.S. data is of interest for two reasons: (i) NPP designs and operating conditions are compatible with the Swedish situation, and (ii) U.S. LER data sets have been subject to previous data analysis efforts enabling comparisons between data interpretations to strengthen data quality.

U.S. SCSS LER DATABASE
1980 - April 1995

- **Leakage from or in any primary system: 644 LERs**
- **Leakage from or in any high pressure safety system: 534 LERs**
- **Leakage from, or failure to close, primary system pressure relief valve: 65 LERs**
- **Leakage from or in low pressure safety system: 161 LERs**
- **Leakage from or in main steam systems (BWRs): 21 LERs**

Courtesy of: A.E. Cross (Oak Ridge National Laboratory, Oak Ridge, TN, USA). **Data search performed at requests by R. Nyman (SKI) and U.S.NRC.**

- Auxiliary failure data: European, Russian, and Asian piping failure events in NPPs primarily extracted from NEA-IRS and IAEA-INES/ERF and included in SLAP to enhance the library of piping failure modes and mechanisms. Specifically for failures in carbon steel piping, chemical, petrochemical and petroleum industry data also was included in SLAP. Reason for including auxiliary failure data was to enhance the "interpretive power" of the database, and demonstrate the need to consider chemical industry data. In chemical plant risk analysis (QRA) the need for good failure data on piping system components is greater than in PSA[4-1,2].

SLAP is a relational data base designed in MS-Access®. Each failure event record consists of 40 data fields that address failure symptoms and underlying causes, impact on system(s) and plant, brief event chronologies, failure location, metallurgy, operating/process conditions; i.e., *piping system reliability attributes*. Each event has a unique identification for tracking/sorting purposes, and for QA/QC purposes. It is a living database maintained and updated by SKI. Summary reports will be generated to coincide with future updates of the T-Book and IE-Book (see Section 2). Detailed description of the database design and content appears in Volume 4 (SKI Technical Report 95:61).

Many studies have derived piping failure statistics from available operating experience; c.f. Table 4-1. The failure information supporting statistical analyses has been divided into leakage versus rupture (severance) categories, and RCS versus non-RCS categories. The failure information has also been categorized according to pipe size (e.g., ≤ DN25, 25 < DN ≤ 150, and > DN150). WASH-1400 remains the most widely used data source. In part because the data was converted into LOCA frequencies that have been viewed as acceptable; see Sections 5 and 6.

STUDY	FEATURES	
	COVERAGE	**ANALYSIS APPROACH**
WASH-1400 (1975)	150 reactor-years operating experience amended by about 400 piping failure case studies from fossil power plants.	Pooling of data sources and MLEs.
PNL (1976)	11 piping failures in U.S. plants.	Same as WASH-1400.
EG&G (1987)	800 reactor-years operating experience	Distinction between LOCA-sensitive and non-LOCA sensitive piping. Experience data and subjective data combined using Bayesian statistics.
EG&G (1991)	Based on search of LERs and Stoller Corp.'s Nuclear Power Experience for period 1960-1990 (total of 1,269 reactor years)	Bayesian statistics; see EG&G (1987)
EPRI (1992)	U.S. NPP operating experience up to mid-November 1986 corresponding to 1,000 reactor-years .	Analysis of variance (ANOVA).

Table 4-1: *Some U.S. Piping Reliability Studies 1975-1992; See Also Section 3.5.*

Incompleteness of historical data has stemmed from insufficient number of failure events in the data bases to facilitate meaningful statistics, or from insufficiently detailed failure event descriptions to allow appropriate distinctions between failure modes. In some instances lack of detailed failure mode definitions have led to event populations that included failures of such piping components as flange gaskets, leaking relief valves, hydraulic hoses, as well as failures of piping sections. The "pedigree" of published piping failure rate estimates varies significantly.

DATA SOURCES USED IN DEVELOPING SLAP

NPPr:	**U.S. LERs + Selected NUREGs** **Swedish RO + TUD data** **SKI/RA-010/94: Survey of Nuclear Network (INPO) Re. Piping Failures.** **SKI/RA-04/95:Weld Repairs in Swedish NPPs** **NEA-IRS + IAEA-INIS + NPE** **Proprietary data supplied by utilities**
CPIr:	**UK MHIDAS, U.S. NTSB** **Marsh & McLennan annual reports on "Large Property Damage Losses in the Hydrocarbon-Chemical Industries"** **Proprietary U.S. oil refinery data.**

An overview of SKI's data base content is given by Tables 4-2 and 4-3, and Figures 4-1 through 4-7. Except for category denoted as "Other", the failures are "cracks/indications" in either the piping base material or weldments discovered by special inspections during maintenance/refueling outages. Similarly, "leakage" is either a through-wall crack or opening resulting in a visible or measurable loss of process medium (e.g., 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. As an example, leakage in large-diameter piping could have the same impact on plant response as rupture of small-diameter piping.

EVENT TYPE	NO. OF RECORDS		
	NPP	CPI	COMMENTS
Crack / Indication / Distortion	237	12	Events resulting in repair or replacement, and possibly design modification
Leakage	1423	85	Includes the range from pin-hole leaks to major leakages
Rupture / Severance	295	221	Events of catastrophic nature w/o prior warning.
Other	35	--	Includes significant RCS leaks due to other than piping failures.
NPP = Nuclear Power Plant / CPI = Chemical Process Industry			

Table 4-2: *Overview(i) of Piping Failure Event Content in SLAP - For Details, See Volume 4 (SKI Technical Report 95:61).*

PLANT TYPE	NO. OF RECORDS	EVENT TYPE		
		CRACK / INDICATION	LEAKAGE	RUPTURE
ABB-BWR	47	25	14	5
GE-BWR	623	54	449	89
BW-PWR	148	4	116	16
CE-PWR	321	15	259	37
WE-PWR	631	43	451	82
WWER-PWR	46	3	30	11
RBMK	47	2	29	15

Table 4-3: *Overview(ii) of Content in SLAP - For Details, See Volume 4 (SKI Technical Report 95:61)*[4-3].

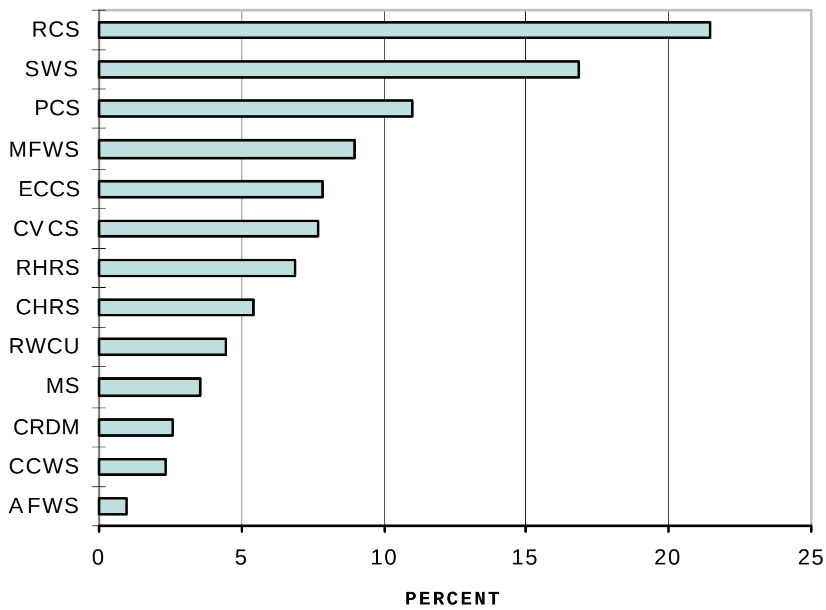


Figure 4-1: *Pipe Failure Events Categorized by System - For Details, See Volume 4 (SKI Technical Report 95:61).*

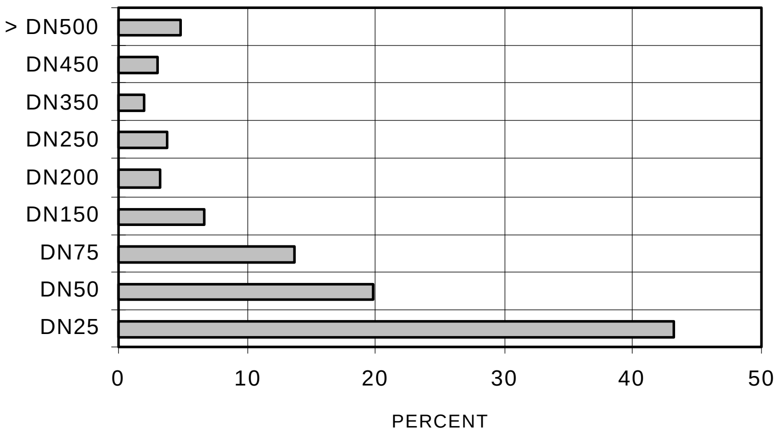


Figure 4-2: *Pipe Failure Events Categorized by Pipe Diameter - For Details, See Volume 4 (SKI Technical Report 95:61).*

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. In Figures 4-3 through 4-7 examples of apparent causes (or symptoms) of piping failures are summarized. The "No Cause Given" represents failure events currently undergoing evaluations to determine apparent and underlying root causes. In line with published information on "human error contributions" to piping failures (c.f. Hurst et al[4-4] and Section 3.4), the proportion of "human errors" in SLAP is considerable. A preliminary breakdown of broad human error categories is given in Figure 4-4. Most events are caused by latent human errors such as design deficiencies and/or procedural deficiencies. Underlying causes of many water hammer events are active human errors during commissioning of systems following maintenance outages; e.g., start-up procedure not followed.

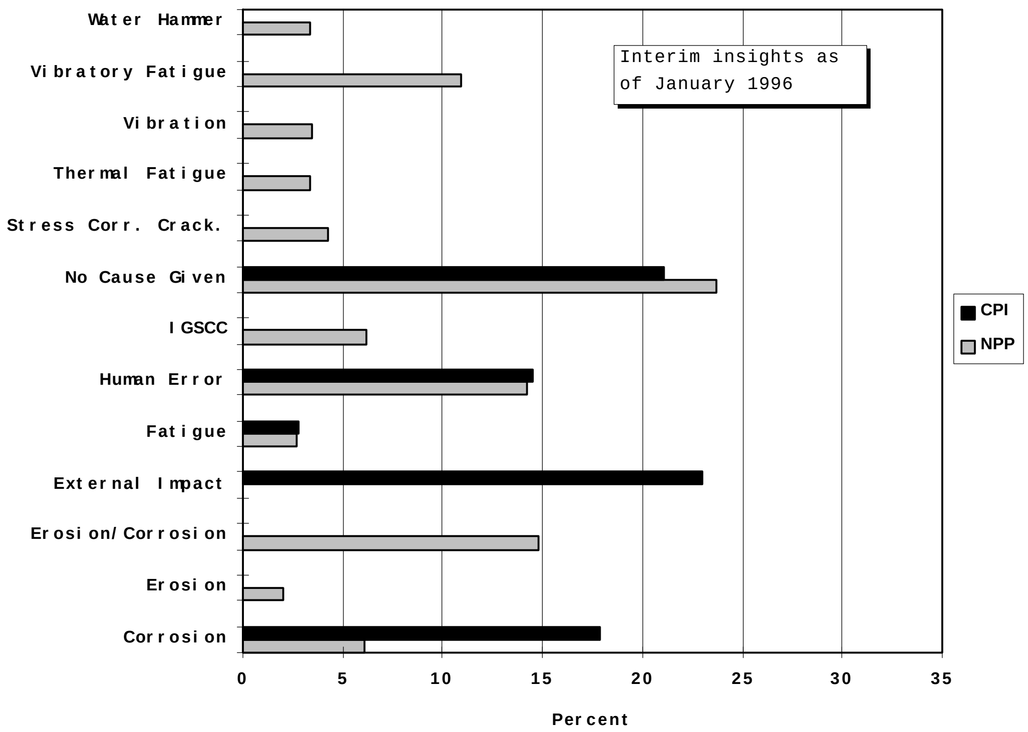


Figure 4-3: *Pipe Failure by Apparent Cause (Nuclear Industry vs. Chemical Industry Data) - For Details, See Volume 4 (SKI Technical Report 95:61).*

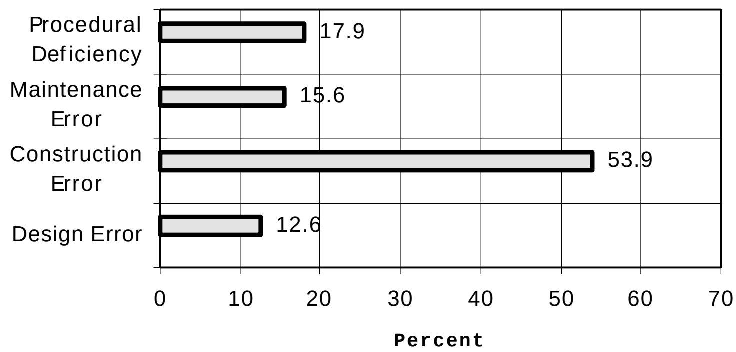


Figure 4-4: *Underlying Causes of Piping Failures (Nuclear Industry Data) - For Details, See Volume 4 (SKI Technical Report 95:61).*

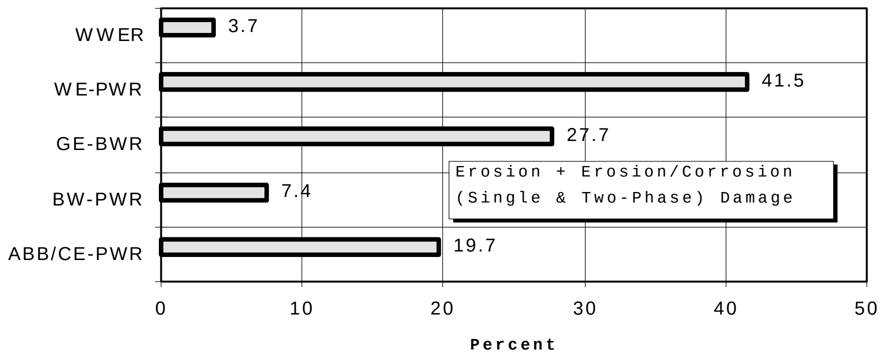


Figure 4-5: *Example of Distribution of Data Records by NSSS Vendor and Failure Mechanism.*

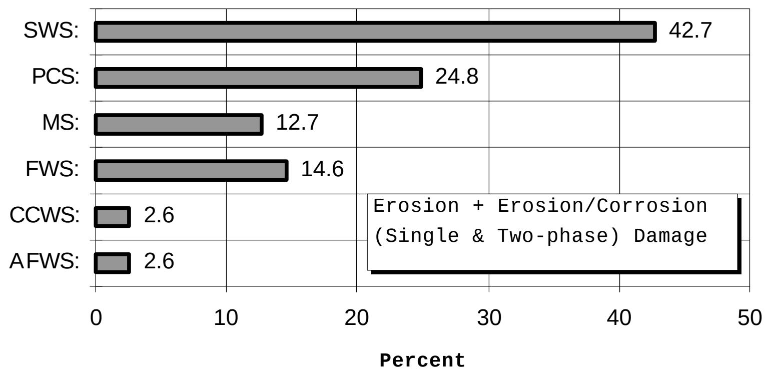


Figure 4-6: *Example of Distribution of Data Records by System and Failure Mechanism.*

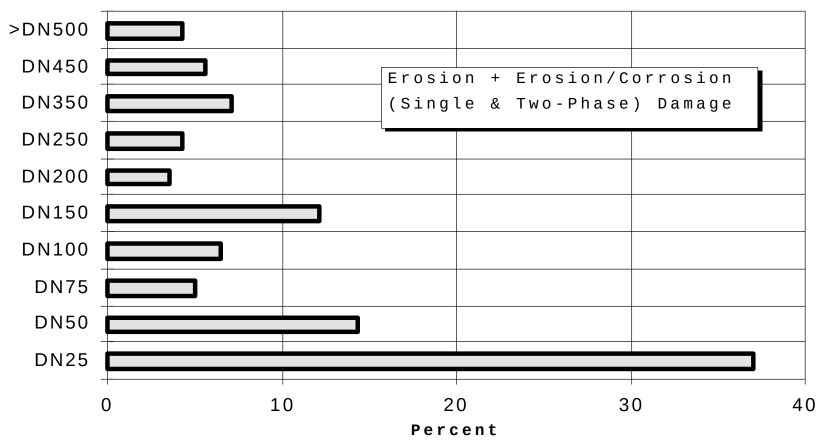


Figure 4-7: *Distribution of Data Records by Pipe Diameter and Failure Mechanism.*

In deriving pipe failure rates and failure probabilities from documented operating experience data completeness is important. Two kinds of "completeness" should be considered:

(1) Absolute completeness. Concerned with question: "Has all piping failure events been reported, and have all events been recorded in SLAP?" Absolute completeness focuses on quantity. Since no formal reporting requirements exist for piping components, only a small percentage of all piping failures get reported. Significant events (e.g., ruptures that cause reactor trip or rapid manual shutdown) are always reported. The reporting tends to be biased by specific industry and regulatory concerns. As an example, during the late seventies and early eighties intergranular stress corrosion cracking (IGSCC) was an ongoing concern. A large volume of IGSCC-events were reported during this time period, while other failure mechanisms did not get coverage by the reporting systems. Failure events not included by LER or RO systems reside in local workorder systems and inspection reports. The ratio of total number piping failures to number of "officially" reported piping failures gives an indication of the absolute completeness. Based on reviews of U.S. piping experience, Rodabaugh[4-5] gives as a "reasonable failure rate" about 1 event per reactor-year.

(2) Relative completeness. Concerned with question: "Has all relevant event information been captured for each record?" Relative completeness focuses on data quality. With the known difficulties of obtaining absolute completeness, meaningful statistical analyses remain feasible given sufficient background information is obtainable for each data record.

Background information is concerned with questions like: "How does piping fail?"; "Why does piping fail?"; "If certain failure modes and mechanisms were observed over a certain time period, why have no repeat failures occurred during, say, the past five years?" Valid statistical information is obtained through engineering-based data interpretations using historical data characterized by high relative completeness.

4.2 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 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:

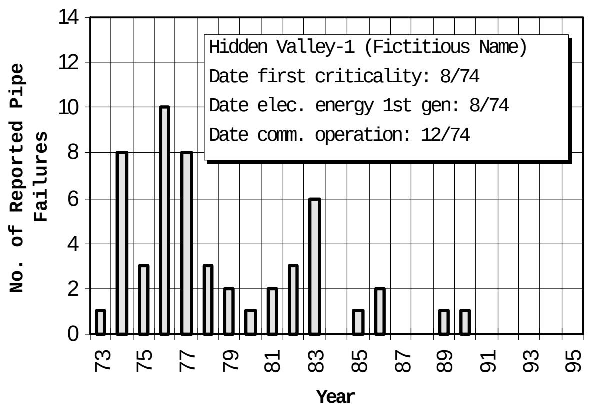
- Much of the available nuclear piping operating experience represents incipient and degraded failures. Questions arise regarding extrapolation of such information to be representative of complete piping failures. As an example, during the recent (1992-95) Oskarshamn-1 maintenance outage a drop-leakage was found in a non-isolateable RHR pipe section. What would be a reasonable PSA-type interpretation of this discovery? What is a reasonable PSA-type interpretation of crack indications? Should PSA only be concerned with observed, critical failures (e.g., large leakages and ruptures)?

- 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 consist of a complex interplay of different influences. A summary of piping failure mechanisms and failure influences is shown in Figure 4-8.

FAILURE MECHANISMS	
Examples of Failure Phenomena	**Examples of Operational / Organizational Influences**
Stress-induced corrosion cracking (SCC) Intergranular attack in weld heat affected zones (HAZ) Transgranular stress corrosion cracking Cracking in stagnant borated water Thermal fatigue cracks related to - Stratification of fluids - Leaking valve seats - Thermal sleeve failure Vibrational fatigue cracking Corrosion fatigue Cavitation erosion Erosion-corrosion (flow-assisted corrosion) Microbe-induced corrosion Corrosion due to leaking boric acid General corrosion Galvanic corrosion Fretting	**Improper overpressure protection Operation at loads or pressures exceeding design limits Excessive rates of heating or cooling (thermal shock) External impact / falling objects Improper or degraded supports Loose parts causing wear and impact damage Structural damage from maintenance Improper repairs / modifications Improper assembly / installation Improper design and fabrication Improper heat treatment (of bolting materials) Improper water chemistry specifi-cations Water hammer due to improperly drained systems / commissioned systems after maintenance**

Figure 4-8: *Example of Piping Failure Mechanisms (Adapted from ASME[4-6], and Törrönen, Aaltonen and Hänninen[4-7]).*

Pipe failure mechanisms are symptoms of underlying influence factors such as process phenomena (temperature, pressure), 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, relative to certain failure mechanisms may no longer be applicable because of subsequent improvements in operations or ISI-strategies. In pooling failure data it is important to apply consistent data selection criteria. Older data sets should not be dismissed based on unvalidated assumptions about their current relevance.



Example Pipe Failure Trend (from SLAP)

About 6% of failures in the data base represent repeat failures. That is, failures of a certain type have re-occurred in a system, or plant. Repeat failures reflect directly on organizational factors; i.e., insufficient feedback of operating experience within an organization. Also, 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 or testing activities could imply that a piping integrity deterioration remains undetected (or unattended) for several years in extreme cases.

Similar to repeat failures, construction errors reflect directly 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 are usually revealed early in plant life; e.g., pre-startup testing.

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 *whys* and *hows*. Data quality has little to do with statistical confidence levels. *It is a function of how well the estimates reflect the state-of-knowledge*. 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 (ageing 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*.

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. The predominant failure mechanisms are discussed in further detail below.
Examples of short-term failure mechanisms include: (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 their influence factors.

Erosion-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.

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)

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 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[4-8], cavitation-erosion incidents have occurred downstream of control valves in RHRS and CCWS of French standardized 900 MWe PWRs. According to Thoraval[4-9], 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[4-10] and Bush[4-11], among others. Most pipe vibratory fatigue problems have occurred in small-diameter piping (< 100 mm). Some failures have occurred in large-diameter 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[4-11], 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/Gs 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 cleanup water system. A first instance of such thermal fatigue cracking was discovered at Barsebäck-2 during the 1980 refueling outage. As explained by Nordgren[4-12], mixing tee problems have occurred after 20,000 to 40,000 hours of operation.

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[4-8,11]; see Volume 4 (SKI Technical Report 95:61) for details.

Stress corrosion cracking problems were first identified in the early sixties in the U.S. 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[4-13]. 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 and a corrosive environment. IGSCC is not a unique BWR problem. Instances of stress corrosion cracks have occurred in austenitic stainless steel piping containing relatively stagnant boric acid solutions; e.g., containment spray and RHRS lines.

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 be sensitized; i.e., precipitation of carbides during welding. 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. Finally, there must be relatively high tensile stresses in the material.

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

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.

4.3 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 system piping could be benign, a similarly sized leakage in another system piping 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. This section documents preliminary insights from exploring the SLAP database, and includes recommendations for future analysis directions.

4.3.1 Some Data Reduction Strategies

SLAP 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 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 unique reliability characteristics that differ substantially from stainless steel piping in the RCS. "Good" data exploration begins by searching for *relevant* information and to interpret and reduce the data against some model of failure:

- As a first step a set of data queries were developed to sort the event database and to perform preliminary validation of individual event descriptions. New information was added to data records as needed. These queries were done using MS-Access® functions (see Volume 4, SKI Technical Report 95:61.

- A first query in SLAP database 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.

- Next, a query was performed on [Plant-Type]-[Age]-[Event-Type]-[Cause]-[System-Affected].

The data queries were done against a preliminary grouping of failure modes and failure mechanisms; c.f. Volume 4 (SKI Technical Report 95:61). This grouping represented the piping failure analysis "super-structure". Failure mechanisms were separated according to piping material; carbon steel versus stainless steel (Figures 4-9 and 4-10). This grouping helped 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, respectively, are used (Figure 4-11). The failure mechanisms are also controllable. Changes in influence factors could have dramatic impact on reliability or 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 failure data 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 displayed in Figures 4-9 through 4-11 assist in interpreting piping failure event records. The "relationships" represent a framework for piping failure *pattern recognition*.

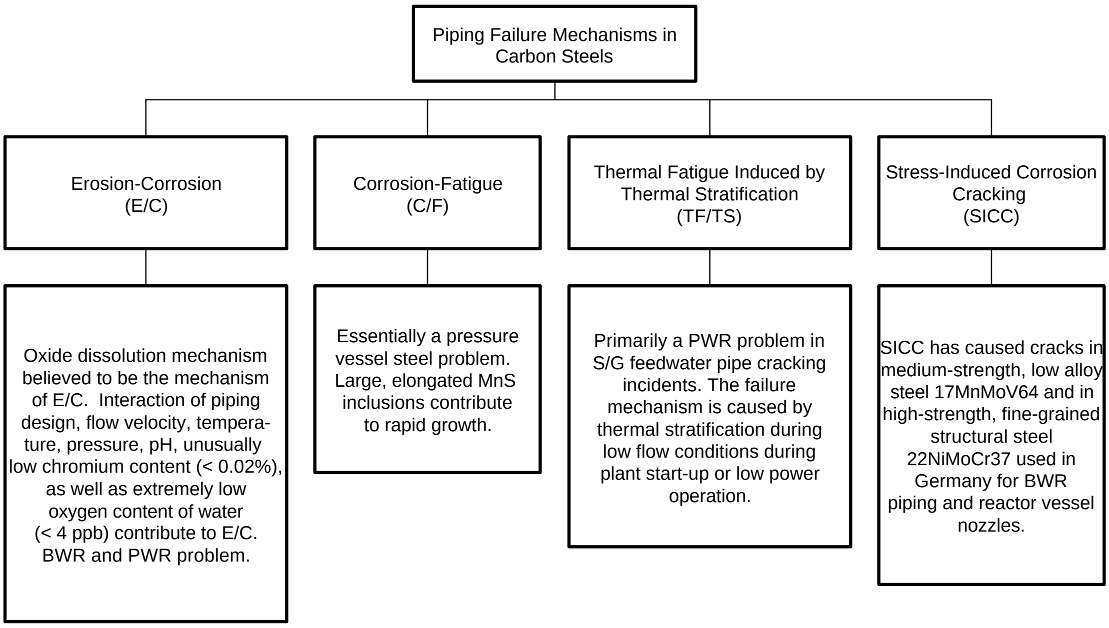


Figure 4-9: *Some Failure Mechanisms in Carbon Steel Piping.*

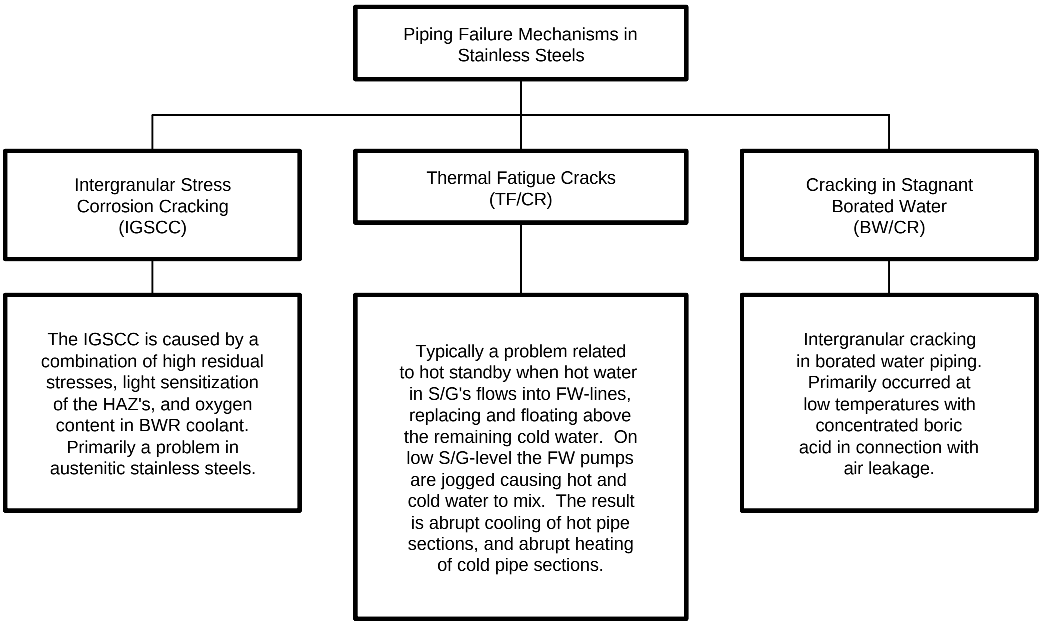


Figure 4-10: *Some Failure Mechanisms in Stainless Steel Piping.*

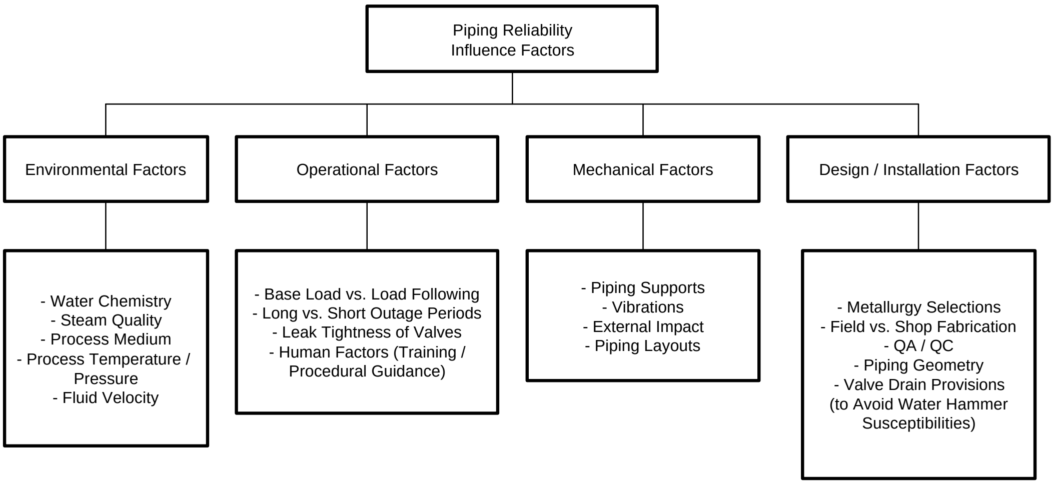


Figure 4-11. *Some Piping Reliability Influence Factors.*

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. Additional "rules-of-thumb" for interpreting piping failure event descriptions are given in Figure 4-12.

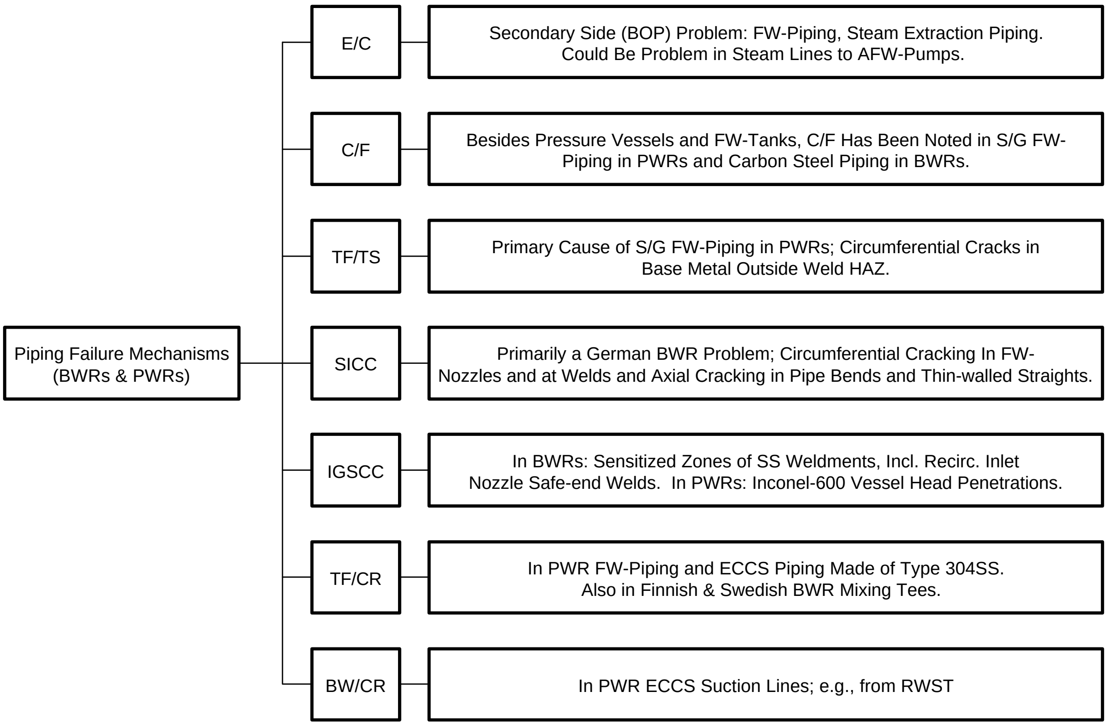


Figure 4-12: *Some Typical Failures in NPP-Piping.*

4.3.2 First Iteration Data Exploration - Some Insights

Based on above considerations the SLAP data records were grouped according to failure mode, failure mechanism, and plant system. Hazard plotting methodology[4-14,15,16,17] was selected for the purpose of graphically displaying the failure event data and to make decisions about how to best group the data before pursuing continued statistical analysis.

Hazard plots (or cumulative distribution function, CDF, plots) are used for display and interpretation purposes because they are simple and effective in presenting data. There are also pitfalls associated with hazard plots; e.g., validity of data might be obscured by the ease with which statistical parameters are derived from plots. As used here, time-to-failure was used as the "reliability indicator." In reality time might be a poor choice. Instead "number of transient cycles" or "number of startups and shutdowns" could be a more appropriate selection, describing assumed reliability influence factors. In a first example we demonstrate some features of hazard plot methodology. Figure 4-13 is a hazard plot for piping failures through rupture in U.S. GE-BWR plants. All "rupture" events were pooled regardless of failure mechanism and contributing cause of failure.

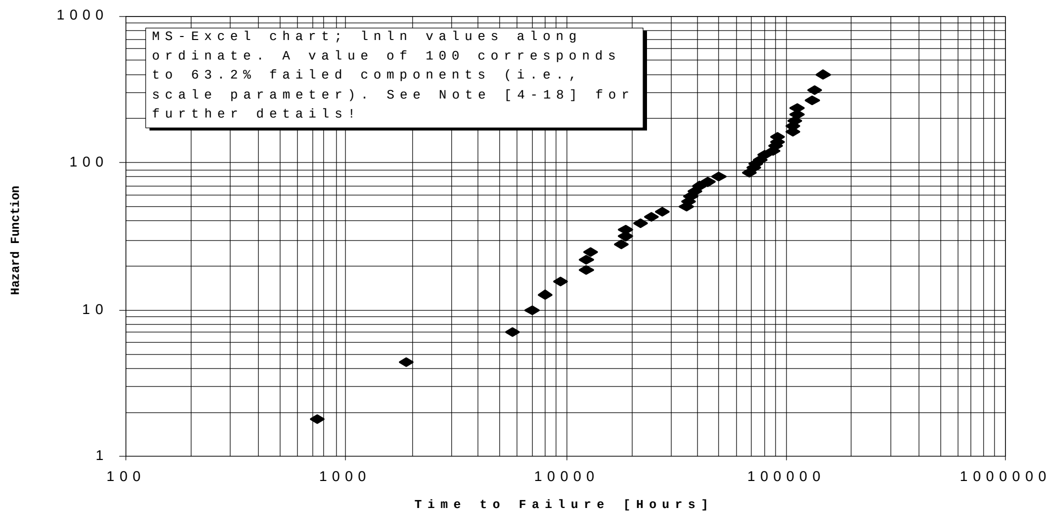


Figure 4-13: *Piping Rupture Events in U.S. GE-BWR Plants*[4-18].

Each point in the hazard plot corresponds to a database record as documented in Volume II. Almost all selected failure events displayed (39 events in total) occurred in BOP-systems; i.e., mostly LOCA-insensitive piping, see Volume 4 (SKI Technical Report 95:61) for additional information. The following failure mechanisms are represented in Figure 4-13:

- Vibratory fatigue.

- Erosion-corrosion.
- External impact through human error.

- Freezing (in condensate system piping).

Obviously, the information contained by displayed hazard plot provides overview-type (interim) information, possibly of nominal value to PSA practitioners. The plot demonstrates a substantial spread as a result of uncritical pooling of failure data. It is a plot of mixed distributions representing different failure mechanisms, such as early life failure, catstrophic failure, and (possibly) wearout failure.

More meaningful hazard plots are generated by recognizing predominant failure mechanism, metallurgy, dimensional factors, and other specific reliability influence factors. By grouping event data according to size (i.e., diameter), system, metallurgy, etc., the consistency in data analysis is enhanced. In Figure 4-14 the data reduction has been taken one step further - relative to Figure 4-13 - by only recognizing rupture events in carbon steel piping due to erosion-corrosion in U.S. GE-BWR plants.

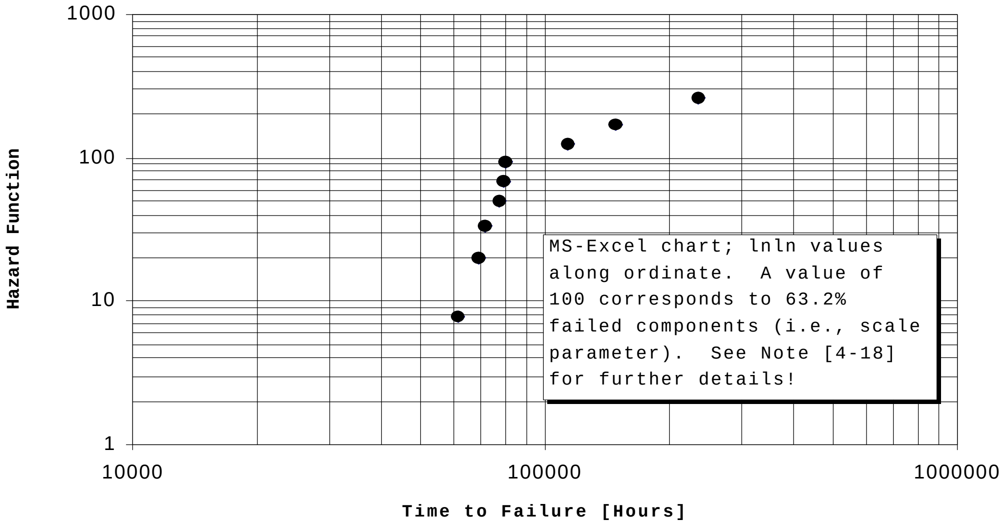


Figure 4-14: *Erosion-Corrosion Damage in Carbon Steel Piping in U.S. GE-BWR Plants - Failure by Rupture[4-18]*.

Within the group of erosion-corrosion damage, further data reduction should pursue additional reliability influence factors. Before, expanding the data reduction a general question of influence of NPP-type (i.e., BWR versus PWR) of susceptibility to erosion-corrosion damage is pursued. Figures 4-15 and 4-16 are equivalent to Figure 4-14 and address erosion-corrosion damage in U.S. PWR plants.

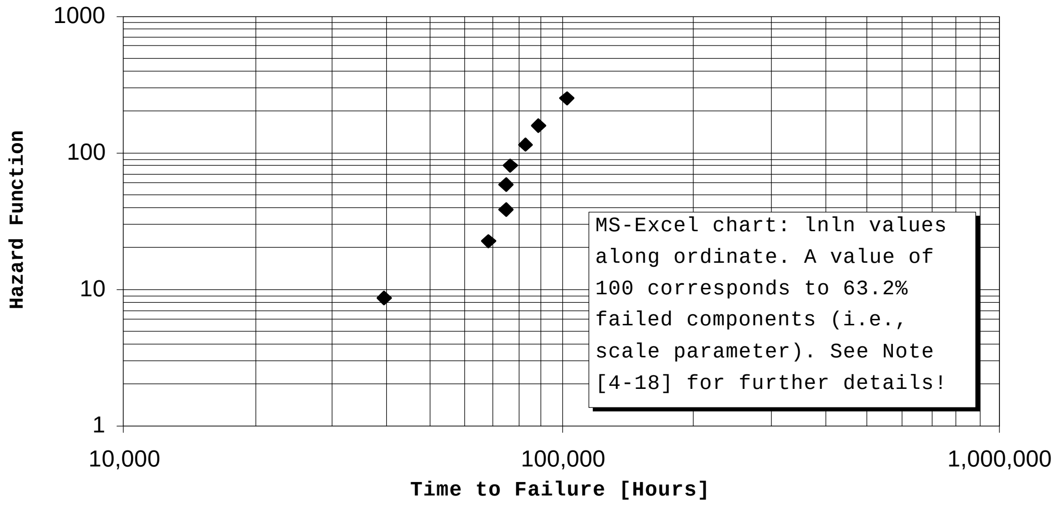


Figure 4-15: *Erosion-Corrosion Damage in Carbon Steel Piping in U.S. B&W and ABB-CE PWR Plants - Failure by Rupture[4-18]*.

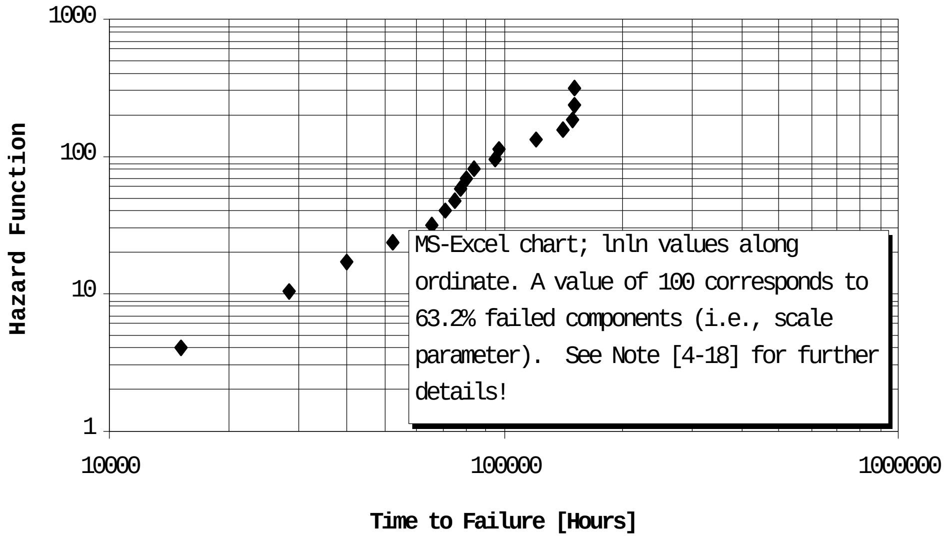


Figure 4-16: *Erosion-Corrosion Damage in Carbon Steel Piping in U.S. WE PWR Plants - Failure by Rupture[4-18].*

As expected, the incidence of erosion-corrosion failures is not linked to NSSS-vendor; the hazard plots show similar trends. Rather, it is a function of BOP piping system designs, operational influences, and ISI-practices. Erosion-corrosion 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[4-19]. It is therefore reasonable to develop a generic hazard plot by combining the above information; c.f. Figure 4-17.

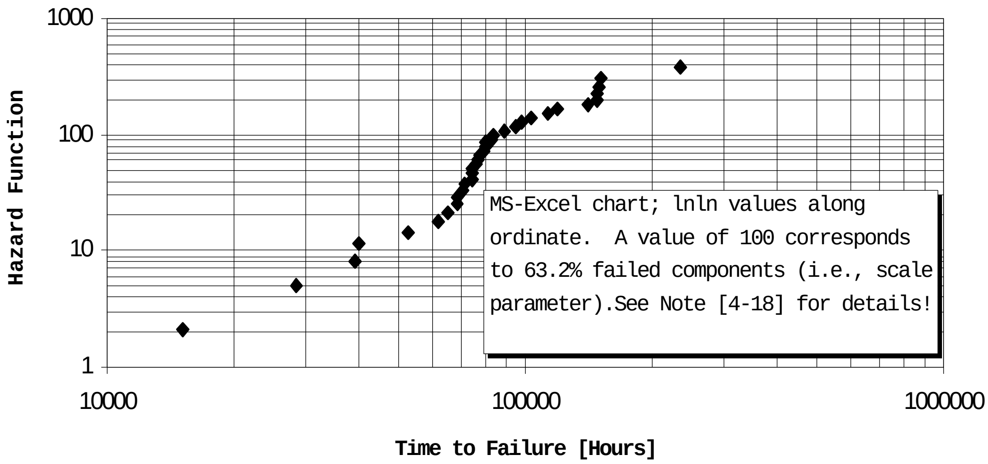


Figure 4-17: *Erosion-Corrosion Damage in Carbon Steel Piping in U.S. LWR Plants[4-18].*

The above failure information reflects on a total of 34 selected failure events where affected piping sections ruptured in a catastrophic way. While the generic information given by Figure 4-17could be used for statistical forecasting of piping reliability, such evaluations need to be foregone by additional data interpretations and possible re-groupings. Outliers in each of the previous hazard plots should be evaluated to ensure data homogeneity. In a next step the data in Figure 4-17 should be reviewed relative to information on failure location, piping size, and system information.

Erosion-corrosion damage typically occurs where turbulent and fast-flowing (e.g., > 45 m/s) water or wet (e.g., 5% moisture content) steam wears away the protective oxide film on the inside pipe surface. Locations particularly susceptible to wall thinning include the downstream section of the short radius surface on elbows, and straight sections immediately downstream of control valves. Almost all failures in the database have occurred near or at welds, immediately downstream of control valves, in reducers, or elbows; i.e., failure location and failure mechanism are correlated. *Piping geometry and design are important to erosion-corrosion susceptibility*. Therefore, extrapolating information contained in Figure 4-17 to a range of piping systems and types of piping sections must be foregone by further data explorations.

At least in principle, the information of the type presented above could be used to generate generic, or prior, failure distributions for the different groups of piping failures addressed in Section 4.3.1. The potential use of such prior distributions is displayed in Figure 4-18. The U.S. WE-PWR information on significant erosion-corrosion damage (Figure 4-16) was used to generate a prior distribution for Bayesian updating using failure data WE-PWRs operated in Sweden (0 significant failures); for details, see Volume 4 (SKI Technical Report 95:61).

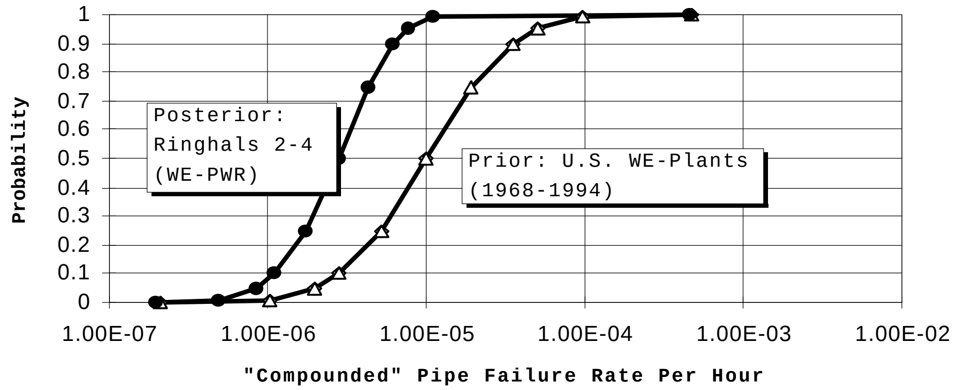


Figure 4-18: *Example of Posterior & Prior Piping Failure Distributions for Erosion-Corrosion Damage.*

At this stage of the data exploration it is already obvious that data quality very much is determined by data interpretations and groupings:

- 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[4-20,21] and some of the historical data may no longer be applicable.

While the efforts involved in interpreting the failure event data in SLAP is considerable, the efforts of interpreting the (preliminary) statistical insights are equally challenging:

- What is the meaning of the data parameters extracted from the hazard plots and Figure 4-18? Obviously, it is a failure rate having the dimension [1/hr-plant]. This leads to a subsequent set of questions:

- In the absence of a good piping reliability model there is an incompatibility problem between PSA requirements and pipe failure rates as derived above. Should the "compounded" failure rate be apportioned to individual piping sections (e.g., elbows, straights, tees), RSS-1400 type piping sections, or length of piping? Obviously, 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 ageing factors. This is particularly important where piping failure data are used for LOCA frequency calculations.

- Especially in older plants, piping systems are subjected to considerable reliability improvement activities. Especially in LOCA sensitive piping, selection of piping material of different metallurgy than the original is known to alleviate failure susceptibility or, possibly, eliminate certain failure mechanisms. A good example of reliability improvement would be Oskarshamn-1 where significant amounts of primary system piping were replaced during the recent, three-year maintenance outage.

Continued data exploration as for erosion-corrosion damage above will assist in identifying good data groupings and give directions for statistical analysis. In Section 6 we elaborate on the statistical estimation process.

4.4 Summary

Section 4 reviewed piping reliability influence factors, and addressed some unique piping failure analysis considerations. Statistical estimation of failure parameters must be foregone by careful interpretation of event data, as well as failure event groupings. The use of hazard plots demonstrated existence of multiple failure mechanisms in the data base. A statistical estimation process therfore needs to address mixed distribution models. In deriving generic and plant-specific 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*.

6: PIPE FAILURE RATE ESTIMATION - BASIC CONSIDERATIONS

6.0 Overview

Based on insights developed in Sections 3 through 5, treatment of piping system component reliability in PSA has been characterized by: (i) applications of order-of-magnitude, indiscriminate pipe failure rates, (ii) implicit rather than explicit modeling of piping systems, and (iii) LOCA assessments building on concepts and data used in WASH-1400. Pipe failure rates derived by WASH-1400, and many subsequent data analyses, generated "rough" estimates that did not distinguish between piping components (e.g., elbow, tee, weld), failures in base metal versus weldment material, or failure mechanisms. Yet, much of the PSA-treatment has been validated by reference to WASH-1400, and not always by acknowledging its assumptions and limitations.

In keeping with the general PSA philosophy of basing applications on plant-specific, validated data and models, the *PSA treatment of passive component failures is in need of improvement*. Considerable operating experience with piping system components now exists. A data-driven, systems-oriented analysis approach is proposed to directly utilize historical data. This approach is directed at giving risk-significant pipe sections unique identities in PSA models. The elements of this analysis approach are addressed in Section 6 together with generic (or prior) pipe failure rate distributions.

6.1 Data-Driven, Systems-Oriented Approach to Piping Reliability

A proposed analysis approach is based on PSA methodology requirements. That is, pipe failure rates and piping system models *should be fully compatible with structures for database, plant model and system models* developed using today's PC-based tools. Data on actual piping failures as well as precursor events should be input to the approach, and translate into plant-specific insights. In the context of dynamic PSA, the analysis approach should consider the impact on core damage frequency or system unavailability from continued operation with degraded piping components, and ISI-intervals. The failure of a piping system is described by failure contributions from different component types, failure modes and mechanisms, non-detection of faults, and different component failures:

$$Q_{PS} \propto \sum(\Sigma_i \Sigma_j q_{ji} \cdot p_{NON\text{-}DETECT})_{m,n,\ldots,p}$$

where Q_{PS} is the probability of a non-detected piping system failure that results in loss of system function or triggers an incident, q_{ji} is the probability of failure mechanism *i* resulting in mode j (e.g., leakage or rupture), and $p_{NON\text{-}DETECT}$ is the probability of non-detection. The piping system consists of component types *m,n,...,p* (e.g., elbow, straight, tee, flange, weld, valve body). Therefore, at the system level the failure probability is a function of predominant failure mechanism, detectability, and type of component. Data input to this conceptual system model should distinguish between failure mechanisms (*why failure occurs*), failure modes (*how failure occurs*), and failure location (*where failure occurs*).

A typical piping system consists of several discrete sections joined together by welds or flanges or both; Figure 6-1. System reliability is a function of types of components and number of components, as well as application.

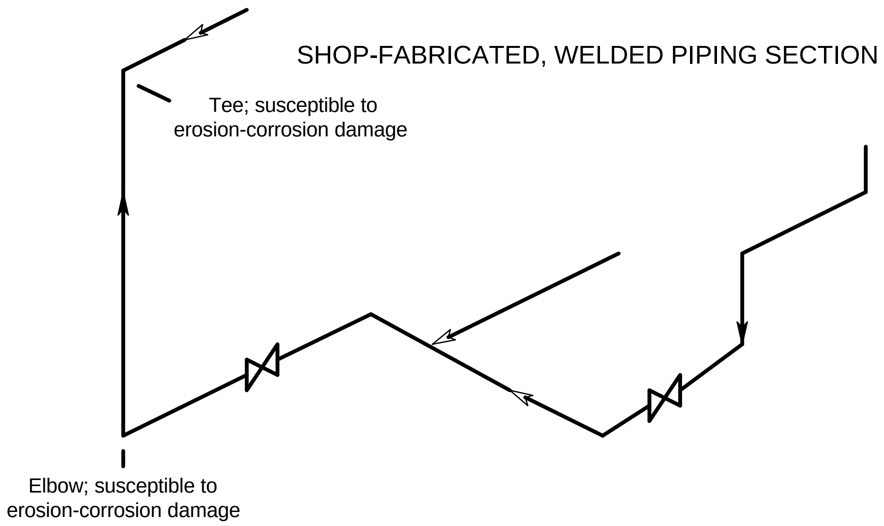


Figure 6-1: *Simplified Isometric Drawing for Piping System.*

TYPES OF PASSIVE COMPONENTS	
Piping:	**Elbow, Tee, Straight, Reducer, Expander**
Fittings:	**Flange, Forged Steel Threaded/ Socket Welded Coupling/Elbow/ Cross/Tee**
Tubing:	**For Heat Exchangers, Instrument Piping, Lubricating Oil Services, Steam Tracing**
Valves:	**Gate / Globe / Ball / Check, etc.**
Tank / Vessel:	**Pressurizer / CST / RWST, etc**

In determining piping system reliability a systems-oriented modeling concept should account for the number and type of piping components, and the failure rates input to the model should ideally differentiate between type, size and material. In developing an analysis structure the following topics should be addressed:

- Piping component boundary definition applied to failure rate estimation.

- Failure rate estimation process that accounts for different failure modes, failure mechanisms, and influence factors.

- Model of piping system for inclusion in PSA model structure. Based on screening approach to identify those piping systems that should be treated explicitly.

- Leak monitoring and leak-before-break (LBB) considerations for PSA. Leak detection systems do not address all possible locations in a plant. In many instances leak detection relies on operator input.

- Detectability of piping failures. Meaning of incipient and degraded failures to PSA modeling structure.

- Inspection methods and inspection intervals. The analysis structure should recognize the reliability of inspection methods, and the reliability improvement potential of inspection.

6.2 Piping Component Boundary Definition

Ideally the piping system model, as included in a PSA structure, should reflect on known failure susceptibilities. Available operating experience points to the location-dependency of failures. Leakages or ruptures occur in the weakest piping system component; e.g., elbows or tees thinned to the point of failure due to erosion-corrosion mechanisms, or welds cracked by vibratory fatigue. In some specific applications (e.g., risk significant systems) we may need a "microscopic" modeling approach, whereas other applications only require "order-of-magnitude" reliability estimates. The "microscopic" approach implies that all piping components are accounted for and analyzed according to relevant failure modes and failure mechanisms, ISI-history and maintenance history. An appropriate piping component boundary definition could be established through a screening step based on an structure as shown in Figure 6-2.

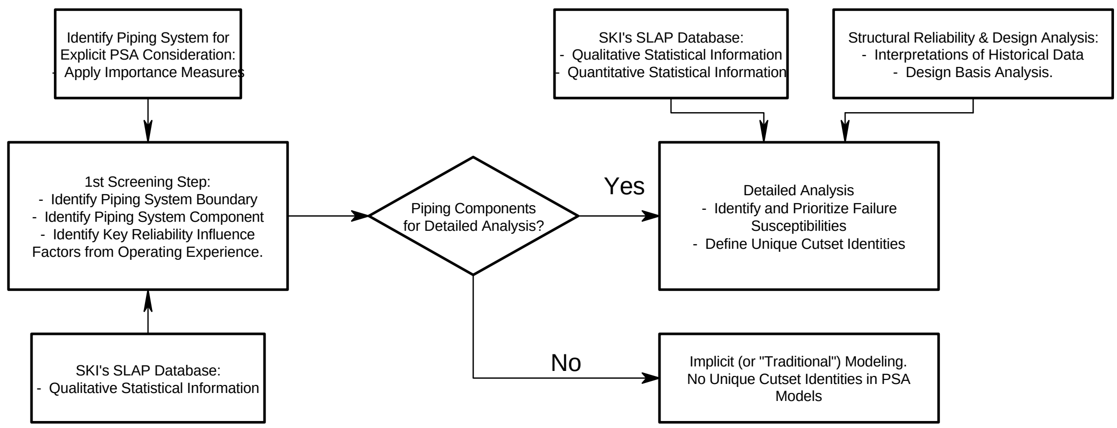


Figure 6-2: *Screening Approach to Piping System Component Reliability Analysis.*

For the "1st Screening Step" and "Detailed Analysis" it is suggested that qualitative analyses be documented using an influence matrix of the type shown in Figure 6-3. The matrix would be applied to those piping systems identified as important to PSA results. The columns of the matrix rely on input from metallurgical expertise, and inspections personnel. Qualitative ratings (e.g., "high", "medium", "low") would be translated into a nominal failure rate penalty factors or shape factors building on concepts of the Thomas Elemental Model[6-1]. Each column is accompanied by "evaluation rules." The information generated using the influence matrix comes from expert judgment. It allows for an integrated PSA + PFM perspective on piping reliability.

SYSTEM: _____________ **METALLURGY:** _________ **DIAMETER:** _________
PRESSURE: ____________ **TEMP.:** ____________ **MEDIUM:** __________
☐ **Operating History Known** ☐ **Failures Have Occurred at Other Plants**

<u>Failure Mechanism(s)</u>(2) ☐ **E/C** ☐ **C/F** ☐ **TF/TS** ☐ **TF/CR**
☐ **BW/CR** ☐ **IGSCC** ☐ **SICC** ☐ **Other;** ______________________

<u>Importance Measure(s) / Result Summary:</u>

Component Type / Count	Effect of Failure	Failure Influence(s)(2)					k-Factor(2)
		No. of Cycles	Access	Age	Size	ISI	
Straight							1.00
Elbow (45°)							
Elbow (90°)							
Elbow (135°)							
Tee							
Flange							
Reducer							
Expander							
Weld							
Valve							
Tube							

<u>Notes:</u> (1) As defined in Section 4.3.1
(2) Multiplier that accounts for failure susceptibility relative to straight section. Determined from review of failure records in SLAP, ISI-records. Conceptually building on the Thomas Elemental Model[6-1].

Figure 6-3: *Conceptual Piping Component Reliability Influence Matrix(i) - An Example.*

Determining a likelihood for a minor crack to propagate into a through-wall crack or guillotine break requires detailed assessment of the effectiveness and extent of in-service inspection and crack growth. For such assessments a matrix such as the one shown in Figure 6-4 could be applied as guide. Ten parameters are suggested for assessment by applying expert judgment solicitation, the results of which are entered into the ISI-column of the reliability influence matrix in Figure 6-3.

ASSESSMENT OF LIKELIHOOD OF CRACK GROWTH		
INFLUENCE	**COMMENT**	**EVALUATION RESULT**
Inspection	- Method - Interpretation of signals & images; difficulties / requirements - Environment; radiation, humidity, temperature, access (free space around piping. What are the stress levels on ISI-personnel?	
Flaw size	- Length/depth of fissure, and orientation	
Material	- Detailed description of metallurgy	
Geometry	- Inside diameter - Outside diameter - Wall thickness - Bending angle (for elbows)	
Heat & cold treatment	- Welding process - Heat and cold treatment in shop - Heat and cold treatment in plant - Repair history	
Flow/temp. pattern	- Mixing points - Steam quality	
Water chemistry	- pH-value - Conductivity - Content of oxygen/chloride/ sulphide - HWC or NWC	
Loads	- Pressure - Vibration - Dead weight	
Operating history	- Number of cold water injection - Number of water hammers - Number of reactor/turbine trips - Number of pressurizations	
Tests on specimens	- Material - Chemistry - Loads	

Figure 6-4: *Conceptual Piping Component Reliability Influence Matrix(ii) - An Example.*

General expert judgment considerations, such as those discussed by Vo et al[6-2], could be applied by the analysis team. Ultimately the results should be converted into a multiplier or adjustment factor that converts a nominal pipe failure rate into a plant- and location-specific failure rate.

6.3 Pipe Failure Rate Estimation Considerations

The dimension of pipe failure rate is either 1/hr.line, 1/hr.section or 1/hr.m depending on piping component boundary definition. That is, "failure per hour and line number", "failure per pipe section", or "failure per length of piping." All three failure rates can be estimated assuming that sufficient information exists on the piping system designs. Isometric drawings allow conversion of [1/hr.line] and [1/hr.m], respectively, [1/hr.section] under the assumption of all piping system components being equally failure prone. Viewed against operating experience (Section 4) and the quality of event reporting[6-3], such conversions are not trivial.

Depending on predominant failure mechanism and reliability influence factors, [1/hr.section] could be an appropriate dimension of pipe failure rate. According to Thomas[6-1] *pipe length by itself is a weak measure of reliability*. This is because the influence of welds, and with their adjacent heat affected zones and failure rates, is usually greater than the influence of length. Also, where a significant flow disturbance caused by discontinuities such as valves, pumps, reducers, or changes in flow direction, the failure rate is affected such that tees and elbows are more failure prone than straights. According to Bush[6-4], the *failure rate of tees and elbows could be at least twice that of straights*. The process of collecting and analyzing pipe failure data is complicated by such factors as:

- Strategies for data analysis. The results of data analysis are input to different applications. Therefore, the data analysis process must be sufficiently flexible to accommodate the application requirements (Figure 6-5).

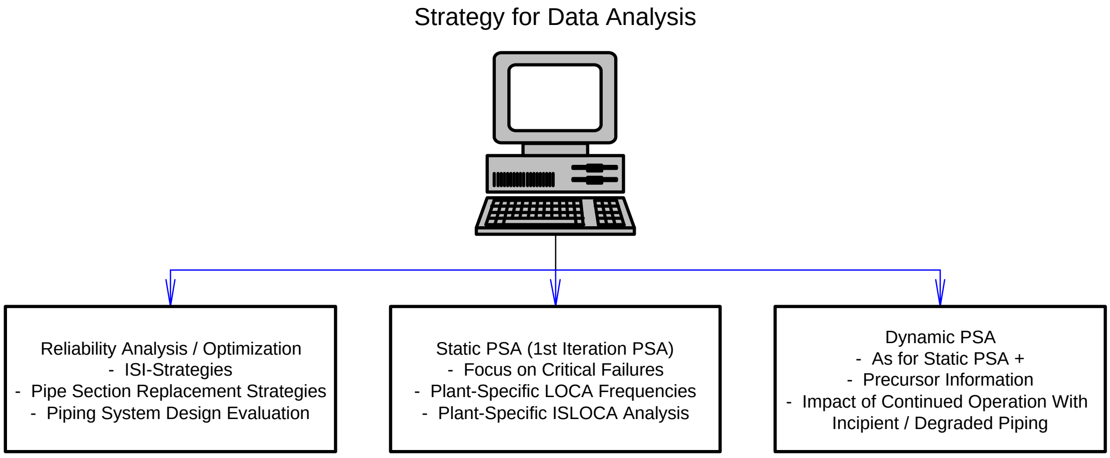


Figure 6-5: *Conceptual Data Analysis Strategy for Piping System Component Failures.*

- No uniform requirements exist for recording of piping system component failures. Existing licensee event reporting (LER) and reportable occurrence (RO) systems were not intended for piping failure events other than those causing forced plant shutdown. Most of piping failure events are captured by local workorder systems or inspections (ISI) records. Also, many precursor events are discovered during annual maintenance outages when regulatory (and other external) reporting requirements are relaxed. The data analysis process should distinguish between non-critical and critical failures (NCF versus CF).

- Compared with active component failures, pipe failures are relatively rare events. Therefore the PSA practitioner is always faced with limited failure populations. This is particularly so when deriving plant-specific failure data. While the worldwide experience (c.f. Section 4) includes hundreds of pipe rupture events, the plant-specific experience might be limited to, say, a few weld repairs and maybe one or two pipe section replacements during annual maintenance outages. According to Nordic experience data, the frequency of weld repair in stainless steel piping is on the order of 2-5 repairs/year[6-5]. How should such information be interpreted in view of PSA specifications?

- Pipe reliability is influenced by human factors. It is difficult to separate apparent and underlying root causes, and the reliability influence factors. According to our database, approximately 30% of all failure events are directly or indirectly caused by human factors issues. These tend to be very plant-specific (i.e., specific to the organizational structure or safety culture). Which of the failure events are not applicable to the plant-specific analysis?

- Causes of failure of primary system piping tend to be fundamentally different from secondary-side piping. Generic failure rate distributions should differentiate failure causes and failure modes.

- Causes of failures of large-diameter piping tend to be fundamentally different from small-diameter piping. Small-diameter piping could be very susceptible to vibrations, and external impact.

Lack of data homogeneity means that all basic failure modes must be considered, but to a varying degree. Incipient and degraded failures may have to be extrapolated to complete failures based on ISI-history and forecasting of reliability; e.g., at what time would an incipient failure propagate to complete failure? Using SKI's SLAP database, preliminary pipe failure rate "indicators" are given in Table 6-1.

Beyond providing information on the relative significance of different failure modes, estimates such as those in Table 6-1 are relatively meaningless. They don't account for impact of different reliability influence factors, or failure locations (e.g., elbow versus straight section). Should calendar time or operating time be used? Also, is time always a relevant parameter for failure rate estimation? In some cases number of cycles or demands could be a more relevant parameter.

FAILURE MODE	FAILURE RATE [1/hr.section]
Incipient	$1.5 \cdot 10^{-10}$
Degraded (e.g., leakage)	$8.8 \cdot 10^{-10}$
Complete (e.g., severance, rupture)	$1.8 \cdot 10^{-10}$

Table 6-1: *Global Maximum Likelihood Estimates of Pipe Failure Rates (Lower Bounds) -* ***Not Intended for Practical Application***[6-6] *- For Details, See Volume 4 (SKI Technical Report 95:61).*

6.4 Piping Reliability Analysis Considerations

A decision to include piping systems in PSA is based on assessments of the relative importance of system failures to plant safety and pipe failure contributions to system failure. That is, what are the potential consequences of a piping failure? As examples, "Can a piping failure result in a major common cause failure of several safety systems?; "In cases of major leakage or rupture can affected piping section be isolated to prevent further damage?" An existing PSA provides necessary information through application of suitable importance measures, and screening steps using the "Reliability Influence Matrices" (Figures 6-3 and 6-4).

Once piping system candidates for explicit modeling are identified, suitable piping component boundary definitions are applied. Such definitions should be based on available operating experience and knowledge about piping system designs. P&IDs and isometric drawings give good background information by showing where process flow splits and joins, number of piping sections (elbows, straights, tees), and piping geometry. In some applications it may be necessary to use boundary definitions that correspond with piping sections as shown in isometric drawings, in other applications it may be sufficient to define the boundary as being a WASH-1400 type piping section; i.e., "segment of piping between major discontinuities such as valves, pumps, reducers."

6.5 Leak-Before-Break (LBB) Concepts

Given steady-state operating conditions it is unlikely that an undetected leak would propagate to circumferential rupture, or that a detectable leak very abruptly will become a circumferential leak; i.e., allowing for no mitigative action. Under certain conditions, a system (or plant) transient could cause a crack to propagate to become a through-wall-crack causing leakage, or an elbow that has been thinned through erosion-corrosion to rupture.

PSA practitioners have applied leak-before-break (LBB) concepts to justify using low LOCA frequencies or low pipe failure rates. The underlying thought being that some leakages are self-revealing giving operators sufficient warning time to take corrective action. Research has been directed to the study of LBB phenomena[6-7,8,9,10]. The LBB entails the concept that, with a high degree of probability, failure of the pressure boundary of piping systems will be "signaled" by a detectable leak that provides ample time to shut down plant for leak repair.

In summary, the procedure for establishing a LBB-case for the primary coolant pipework consists of the following steps[6-11]:

- Identify those positions in the pipework at which the highest stresses occur in combination with poor material properties.

- Show by fatigue crack growth analysis that a defect which would be permitted by the acceptance criteria of Section XI of the ASME Code at each of these positions will not grow significantly during service.

- Postulate through-wall cracks of sufficient size to ensure their detection by way of the resulting leakage, then demonstrate that these cracks will be stable even when subjected to loads imposed by a safe-shutdown earthquake occurring during normal operation.

- Show that the pipework is not subjected to excessive/unusual loads or failure mechanisms such as erosion-corrosion damage or water hammer effects.

Detailed LBB methodology exists to support plant safety analysis including determining need for pipe whip restraints in case of LOCA. The methodology builds on a set of assumptions. The most important being that single cracks (e.g., welding cracks, fatigue cracks) are stable. The methodology is not applied to piping systems in which excessive or unusual loads or cracking mechanisms can be present because these phenomena adversely affect piping behavior. *While the LBB-methodology was never developed to directly interface with PSA methodology, some basic concepts regarding "signalling" of leaks should be acknowledged in the evaluation of piping systems for explicit inclusion in PSA.* Especially leak detection by human operators.

6.6 Detecting Piping Failures

How many incipient failures are identified through ISI, and what is the level of completeness in our database? Research has been directed at the reliability of ISI methods[6-12,13,14]. It is feasible that ISI misses a degradation because of complex piping geometry and/or lack of accessibility.

The PSA practitioner should consider questions like: "What if a significant incipient failure is not detected?"; "Should incipient failures be considered when deriving plant-specific

LOCA frequencies?"; "What is the significance of inspection intervals (e.g., inspection performed each refueling outage versus once every ten years)?" Several empirical correlations for probability of not detecting a defect ($p_{NON\text{-}DETECT}$) versus size of defect exist. Based on these the following correlation is proposed for consideration in PSA applications:

$$p_{NON\text{-}DETECT} = p_{BASE} + \exp(-k \cdot IC)$$

where

p_{BASE}	=	"Base-line" probability of not detecting a deteriorated piping segment under nominal (ideal) conditions. Interpreted as a human error probability (HEP).
k	=	1.2429; an assigned constant[6-15].
IC	=	Inspection Class; representing difficulty of finding a defect (Table 6-2, page 78) and inspection frequency.

A value of $3.0 \cdot 10^{-3}$ for p_{BASE} is used to represent the nominal inspections conditions. It is derived from the "Human Reliability Handbook"[6-16] in which it is taken to represent nominal (or "ideal") maintenance/inspections conditions. The proposed correlation is shown in Figure 6-6. The intended use of a reliability correlation for ISI is to enhance the proposed Reliability Influence Matrix by taking into account impacts of ISI, and acknowledging the ease or difficulty by which inspections are performed. Certain piping system are relatively easy to inspect using best available methods and have well documented failure histories. Such considerations should be factored into plant-specific pipe failure rate estimation.

Figure 6-6: *Probability of Non-Detection of Defect - Proposed Correlation.*

6.7 Summary

Pipe failure rate estimation should consider ultimate application; e.g., reliability optimization including piping system design evaluations, static PSA or dynamic PSA. In addition the estimation process must recognize piping component boundary definition, and reliability influence factors. Section 6 addresses piping reliability analysis considerations, and introduces a piping component "reliability influence matrix" for use by PSA practitioners in structuring explicit, plant-specific analyses. Interim, "global" pipe failure rates are presented.

INSPECTION CLASS (IC)	DESCRIPTION	$p_{NON\text{-}DETECT}$
1	Large diameter pipe; incomplete inspection history; no known pipe replacements. Access may be difficult Ultrasonic testing possible.	2.91E-1
2	Large diameter pipe, full inspection history available; pipe replacements known to have been performed. Ultrasonic testing possible.	8.63E-2
3	Medium diameter pipe; incomplete inspection history; no known pipe replacements. X-ray surveys challenging to perform due to the layout.	2.70E-2
4	Medium diameter pipe; full inspection history available; pipe replacements known to have been performed. X-ray surveys feasible for portion of pipe-run.	9.93E-3
5	Small diameter pipe; full inspection history available; history of previous pipe replacements; inspections ≤ 2 years. Full-length X-ray surveys feasible.	5.00E-3
6	Small diameter pipe; full inspection history available; history of numerous pipe replacements in the past; inspections ≤ 2 years; potential for external impacts; vibrations possible during normal unit operation. Full-length X-ray surveys can be performed.	3.58E-3

Table 6-2: *Interim Definition of Inspection Class (IC).*

7: CONCLUSIONS & RECOMMENDATIONS

7.0 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 database (Phase 1). This report documents Phase 2 results. Based on a two-tier approach, using insights from analysis of the failure database and review of over 60 PSA studies, Phase 2 identifies desirable features of a data-driven and systems-oriented piping system reliability analysis concept compatible with modern PSA methodology.

7.1 Conclusions

The pipe failure rates and LOCA frequencies generated by WASH-1400 were based on approximately 150 reactor-years experience with U.S. commercial nuclear power plants. Today (end of 1995) over 6,300 reactor-years of worldwide operating experience exists. In view of this, PSA practitioners question the applicability of the now twenty year old estimates of WASH-1400.

The SKI database includes about 2,300 piping failure event records (including about 300 piping failures in chemical process industry, CPI), with emphasis on Nordic and U.S. data. In evaluating the database content the following conclusions have been reached:

- A generic ("global"), *lower bound* pipe failure rate of about $2\cdot10^{-10}$/hr.section for rupture/severance is observed. This value is sensitive to data interpretations, and pipe section definition. By exploring the database it is seen that there is considerable plant-to-plant 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 continuities 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.

- 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 can 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.

- LOCA categorization and frequency estimation remain influenced by WASH-1400. Driving force behind the approach in WASH-1400 was to generate bounding-type analysis results that could be accommodated by analysis techniques and tools available in the early seventies. Progressive PSA projects in the nineties deviate considerably from WASH-1400, however, by identifying LOCA categories more in line with available operating experience and plant-specific LOCA response considerations. Instead of three LOCA categories due to pipe rupture (as in WASH-1400), current PSA projects consider more categories by accounting for hundreds (or more) potential LOCA locations. A conceptual, current LOCA classification structure is shown in Figure 7-1.

- Dynamic PSAs selectively consider impact of pipe failure on safety. This Phase 2 report identifies basic considerations of explicit modeling of piping systems in PSA.

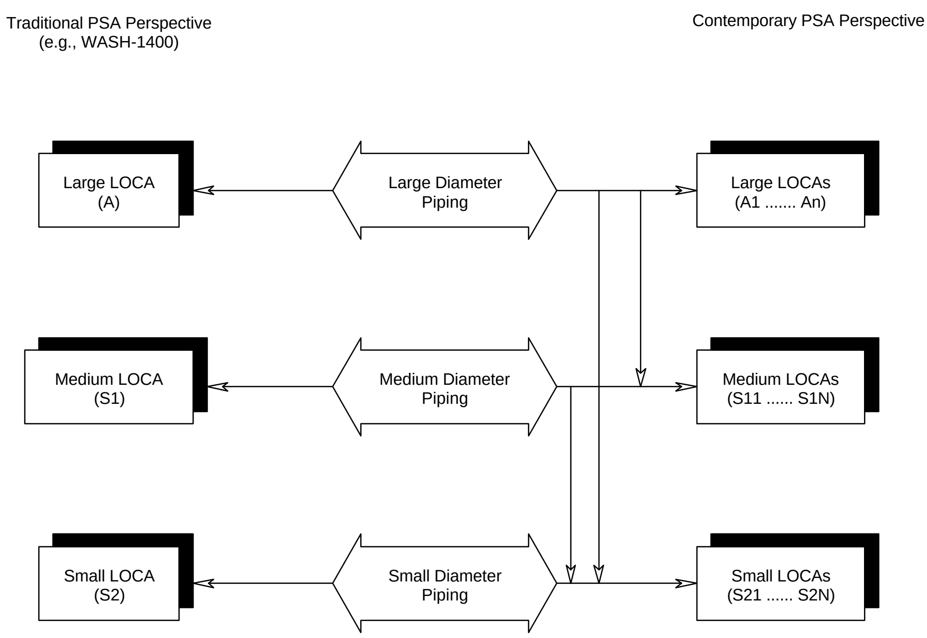


Figure 7-1: *Conceptual Structure for LOCA Classification.*

7.2 Recommendations

Phases 3 and 4 of the ongoing research will focus on database 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.
- Continued database work will include deeper analysis of repeat failures, and CCF and CCI effects of piping failures.
- Meaning of incipient failures and precursor events. An effort should be directed to how to acknowledge piping defects in extrapolations of failure data.
- Enhance, formalize and test the concept of "piping reliability influence matrix" by pilot applications. A systematic method for integrating piping reliability considerations in PSA should be constructed.
- Develop a structure for recording/documenting piping failure events, including enhancement of the current Swedish RO-system (equivalent to U.S. LER-system) to more effectively handle requirements for consistency and completeness.
- Enhance the exchange of international piping failure experience data, with emphasis on quality data.
- In preparation for Phases 3 & 4 of the research, the project team encourages comments on interim findings by recipients of this report.

As appropriate, the Phase 3 and 4 efforts will interact with ongoing and planned activities in the NKS/RAK-1 Nordic nuclear safety research program.

8: 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), <u>seismic</u> 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. <u>Flooding</u> 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.

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[1-3]. Galyean, W.J. and D.I. Gertman, 1992. *Assessment of ISLOCA Risk-Methodology and Application to a Babcock and Wilcox Nuclear Power Plant*, EGG-2608 (NUREG/CR-5604), EG&G Idaho, Inc., Idaho Falls (ID).

[1-4]. 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.

[1-5]. 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.

[1-6]. 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).

[1-7]. 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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[1-9]. ZPSA = Zion Probabilistic Safety Analysis, completed in September 1981 by PLG Inc., Westinghouse Electric Corporation, and Fauske & Associates, Inc. for Commonwealth Edison.

OPSA = Oconee PSA, a tutorial PSA cosponsored by the Nuclear Safety Analysis Center and Duke Power Company. OPSA was completed in June 1984, and published as NSAC-60 by the Electric Power Research Institute.

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.

[1-10]. 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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[2-4]. The reliability of various non-destructive testing (NDT) techniques has been one of thecontroversial problems of NDT. To evaluate the reliability of NDT-techniques, several research programs have included controlled experiments where qualified inspectors were asked to perform inspections of specimens containing artificial or real defects. As an example, the Plate Inspection Steering Committe (PISC) conducted a series of such experiments during the seventies and eighties.

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[2-16]. Stetkar, J. and R. van Otterlo, 1994. "Some Thoughts on the Use of PSA Experts and the Need to Break the Rules," in *Advances in Reliability Analysis and Probabilistic Safety Assessment*, IAEA-J4-TC-606.4, International Atomic Energy Agency, Vienna (Austria).

Section 3:

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[3-28]. Northeast Utilities was lead participant responsible for construction and operation of Millstone-1 (GE-BWR), Millstone-2 (ABB-CE-PER), and Millstone-3 (WE-PWR). The three Millstone units are located in Connecticut (USA) on the Long Island Sound.

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An underlying assumption of hzard plot applications is that failures are time-dependent. This may not always apply to piping systems.

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