OECD/NEA MULTI-LATERAL COOPERATION IN THE AREAS OF PIPING STRUCTURAL INTEGRITY & OPERATING EXPERIENCE

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ABSTRACT

Since 2002, the OECD Nuclear Energy Agency (NEA) has operated an event database project that collects operating experience data on passive metallic component degradation and failure; the "Component Operational Experience, Degradation and Ageing Programme" (CODAP). The scope of the database includes safety-related piping, reactor pressure vessel internals, support system piping, as well as non-safety piping whose degradation or failure can have significant operational impact. CODAP prepares topical reports to communicate insights and results from systematic analyses of the operating experience data. The Committee on the Safety of Nuclear Installations (CSNI) of the OECD NEA acts as an umbrella committee of the Project.

There is an abundance of operating experience data on piping pressure boundary performance in different operating environments. This experience spans seven decades of commercial nuclear power plant operations, from 1960 to date. Embedded in the data are technical details on the underlying causal factors of material degradation and failure as well as details on the technical and programmatic processes that have been implemented to prevent or mitigate recurrence of material degradation and failure. The objective of this paper is to highlight the role of operating experience in structural reliability analysis. Building and applying models of piping reliability is a complex undertaking. It requires an understanding not only of multiple engineering and science disciplines but also the contexts and requirements of different analysis regimes. Access to real data on pipe failure occurrences is essential to ensure realism and validity.

INTRODUCTION

Established in 2002, the Organization for Economic Co-operation and Development (OECD)/Nuclear Energy Agency (NEA) Component Operational Experience, Degradation & Ageing Program (CODAP) project has established an extensive database on the operating experience of metallic and certain non-metallic passive components. Details on the project's history, organizational structure, database structure, progress with data analysis, and data access rules are documented in OECD/NEA (2017), (2018), (2022), (2024). The CODAP project periodically prepares topical reports on the results of systematic evaluations of the international operating experience with piping and non-piping passive components. An overriding objective of these reports is to foster technical cooperation, to deepen the understanding of national differences in plant ageing management, and to preserve the institutional knowledge with respect to material degradation phenomena. To date the project has prepared eight such reports.

With an initial focus on piping components, project scope expansions have been made to also include material degradation of non-piping passive components such as reactor internals, and high-density polyethylene (HDPE) pipe degradation and failure. Through an international collaboration, the objective of the project steadfastly remains to encourage the exchange and analysis of operating experience data on material degradation and failures to promote a better understanding of underlying causes, failure prevention,

and impact on nuclear power plant operations and safety. The project is supported by several NEA member countries, and it has established a web-based database to securely facilitate the exchange of data and data analysis insights. The primary role of the CODAP database is to support applications, including: 1) development of data visualization tools, 2) evaluations of the effectiveness of in-service inspection, 3) data source for evaluating the effectiveness of ageing management programs, and 4) data source for failure statistics. A high-level summary of the piping operating experience (OE) as recorded in the CODAP database content is given in Figure 1.

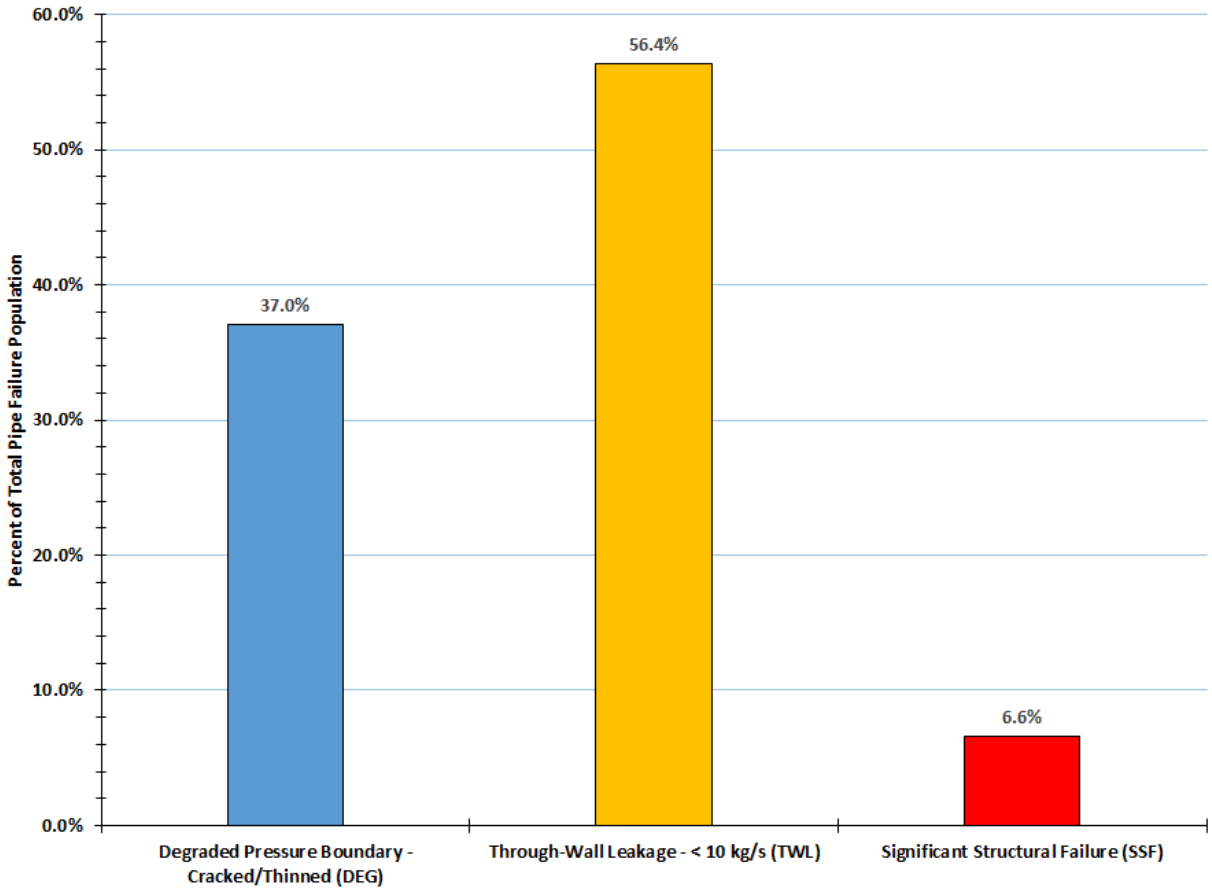


Figure 1. The Worldwide Piping Operating Experience.

In Figure 2 the OE data is organized by safety classification and type of failure, which is characterized as “degraded” (DEG), “through-wall leak” (TWL), or a “significant structural failure” (SSF). The latter type oftentimes is referred to as “pipe break” or “pipe rupture”. The TWL category covers minor leaks to significant leaks but less than 10 kg/s through pipe wall mass flow rate. National codes and standards provide precise definitions of what constitutes a “degraded condition”. Invariably, such a condition is a flaw in the base metal, weld metal or weld heat affected zone (HAZ) that is discovered during in-service inspection using visual and non-destructive examination techniques.

Two criteria must be met for a degraded (DEG) condition to be included in CODAP: 1) an operability determination for continued operation showing that a repair or replacement is required, and 2) a repair or replacement plan (RRP) to document the exact location within a piping system that is subjected to remediation. Embedded in each bar in the below bar chart (Figure 2) is an immense amount of technical information pertaining to operating environments, materials, pipe dimensions, in-service inspection, regulations, fabrication, welding processes, and nuclear power plant engineering and design.

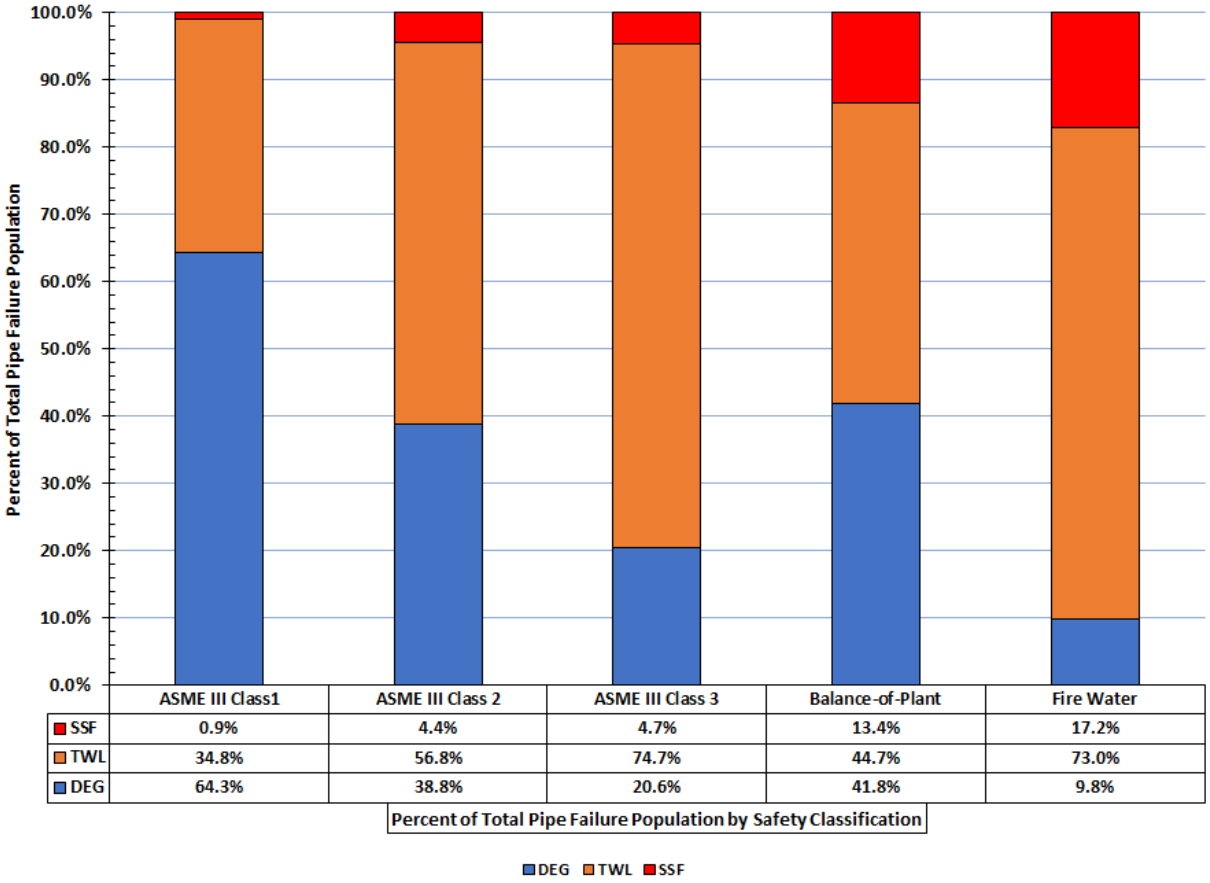


Figure 2. The Worldwide Piping Operating Experience State-of-Knowledge as of 2024.

SIGNIFICANT STRUCTURAL FAILURES

Significant structural failures are rare events. The above high-level OE is explored in more detail in this section. A "significant structural failure" (SSF) is a complete loss of structural integrity with a sudden, large release of process medium, e.g., 10 kg/s through-wall mass flow rate, or more, combined with spatial impacts. Of the total SSF event population of 900 events, only a small percentage has involved primary system piping that could not be isolated from the reactor pressure vessel. Furthermore, all those failures occurred in small-diameter piping systems within the primary pressure boundary.

Most of the SSFs have occurred in balance-of-plant (BOP) piping systems. It is a category of piping needed for energy conversion, and includes condensate, feedwater and various steam piping systems in the turbine building of a nuclear power plant. ASME safety class 3 includes "support system piping" important to safety, including component cooling, instrument air and essential service water. The fire water system piping is also an important safety system, and a piping pressure boundary breach can have a significant operational impact, including localized or global flooding of equipment areas within a nuclear power plant.

The term “failure” has many connotations. The many piping systems in a commercial nuclear power plant are made up of tens of thousands of weldments and tens of thousands of linear meters of piping. Furthermore, each nuclear power plant has on the order of sixty piping systems that are needed for chemistry control, heat transfer, power conversion, reactivity control, and various safety and support functions. Significant structural failures are rare events, and therein lies an analytical challenge in the assessment of pipe failure frequencies. The high-level OE is explored in more detail in Figure 3.

The pressurized water reactor (PWR) SSF experience is highlighted in Figure 4 (note the logarithmic scales). A primary cause of the SSF experience has been high-cycle fatigue. The operating experience is organized by nominal pipe size and the measured primary water through-wall mass flow rate in kg/s. The boiling water reactor (BWR) SSF experience is quite like that of PWRs. The term “perceptible leakage” means that a through-wall crack exists but without active at-power leakage.

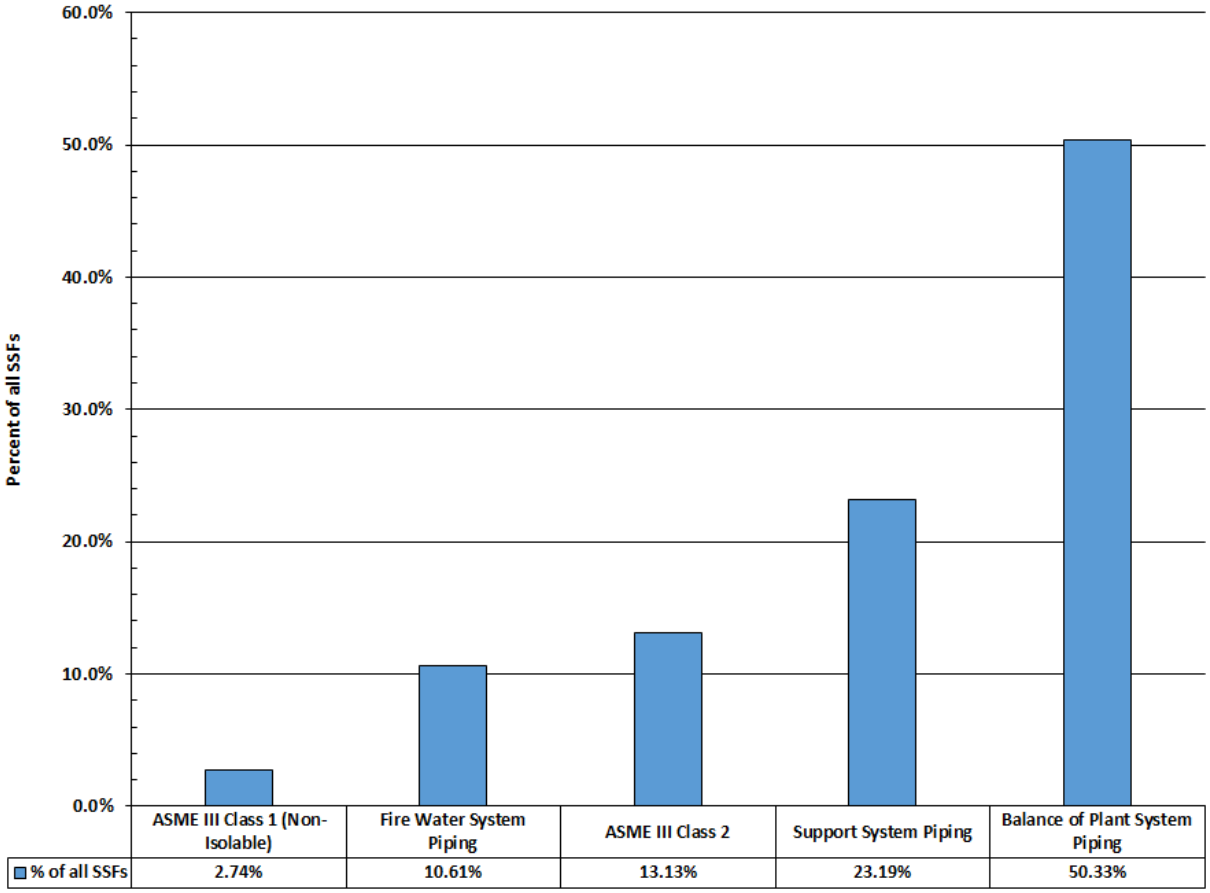


Figure 3. Significant Structural Failures by Piping System Category.

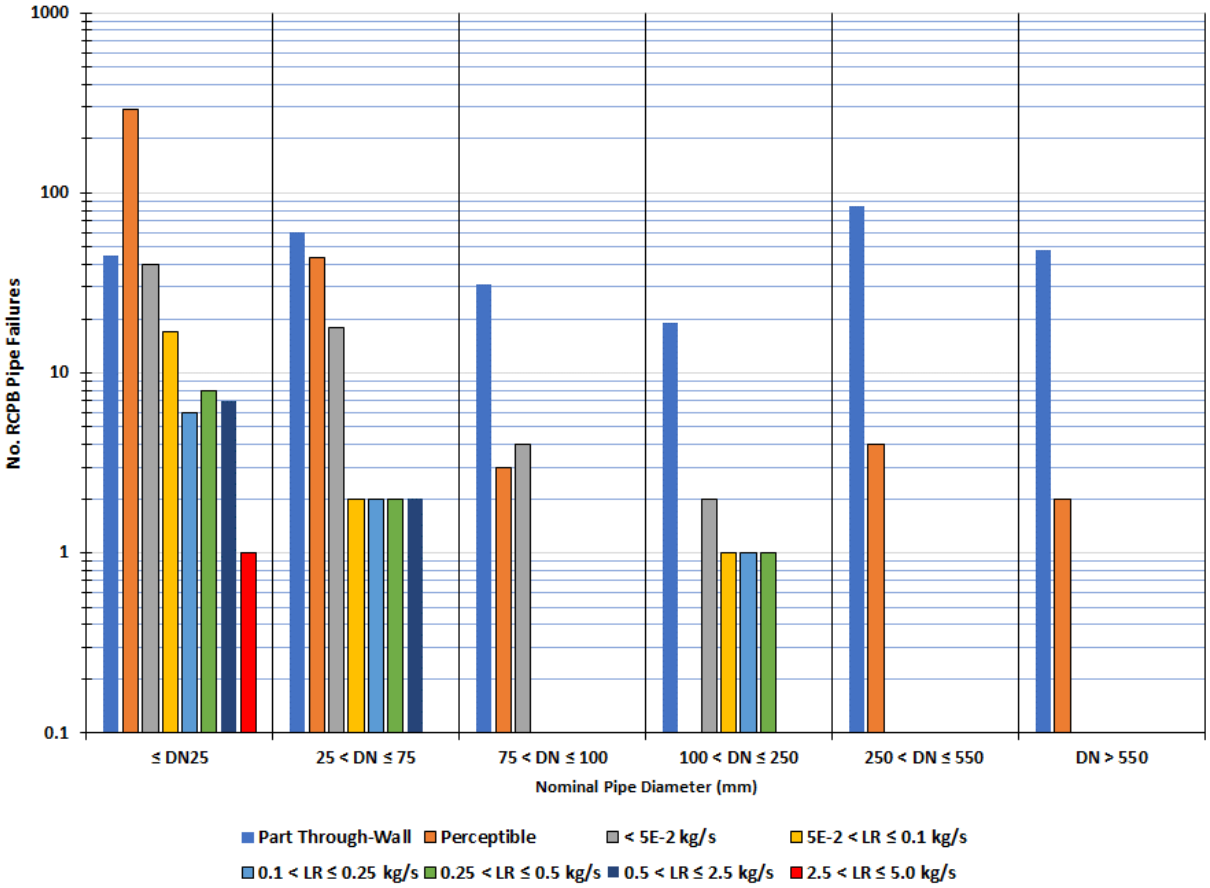


Figure 4. The Pressurized Water Reactor (PWR) Primary Piping Operating Experience.

PIPE FAILURES DURING EARLY LIFE & LONG-TERM OPERATION

The early life pipe failure experience is extensive. Much of this experience is attributed to different metal fatigue mechanisms, compounded by use of un-validated system operating procedures, and less-than-adequate piping fabrication and installation practices. The pipe failure experience during periods of extended operation, beyond 40 years, is extensive and well documented in OECD/NEA (2024). This OE has been subjected to extensive analyses by multiple organizations to establish a technical basis for the estimation of time- and age-dependent pipe failure rates.

Age-dependent pipe failure rate estimation can be performed according to different analysis strategies to obtain piping reliability parameters as a function of the age of an affected pipe section at the time of its observed failure, age of the plant, or as a function of the temporal changes in the piping operating experience. Aging refers to an overall impact of time-dependent factors that can, in principle, affect the pipe failure rate. These factors include physical degradation of pipes due to corrosion and erosion mechanisms, and the applicable inspection and maintenance programs. Trends in pipe failure rates are influenced by physical changes to the structural integrity (e.g., pipe wall loss) due to aging, changes in reporting routines, design changes (e.g., replacing original piping with piping made of material more resistant to time-dependent degradation). Equally important, are changes in reliability and integrity management (i.e., in-service inspection). A variety of data pooling strategies, data window truncation studies and different curve-fit models have been investigated.

Chosen somewhat arbitrarily, “early-life” in Figure 5 covers the period from the initial reactor criticality through the second full year of commercial operation. That is, two years of commercial operation, plus the final commissioning phase that can take anywhere from a few months to more than a year. Also included in Figure 5 is the pipe failure experience during periods of extended operation, beyond 40 years of commercial operation. Much of this experience is attributed to corrosion and flow-assisted degradation.

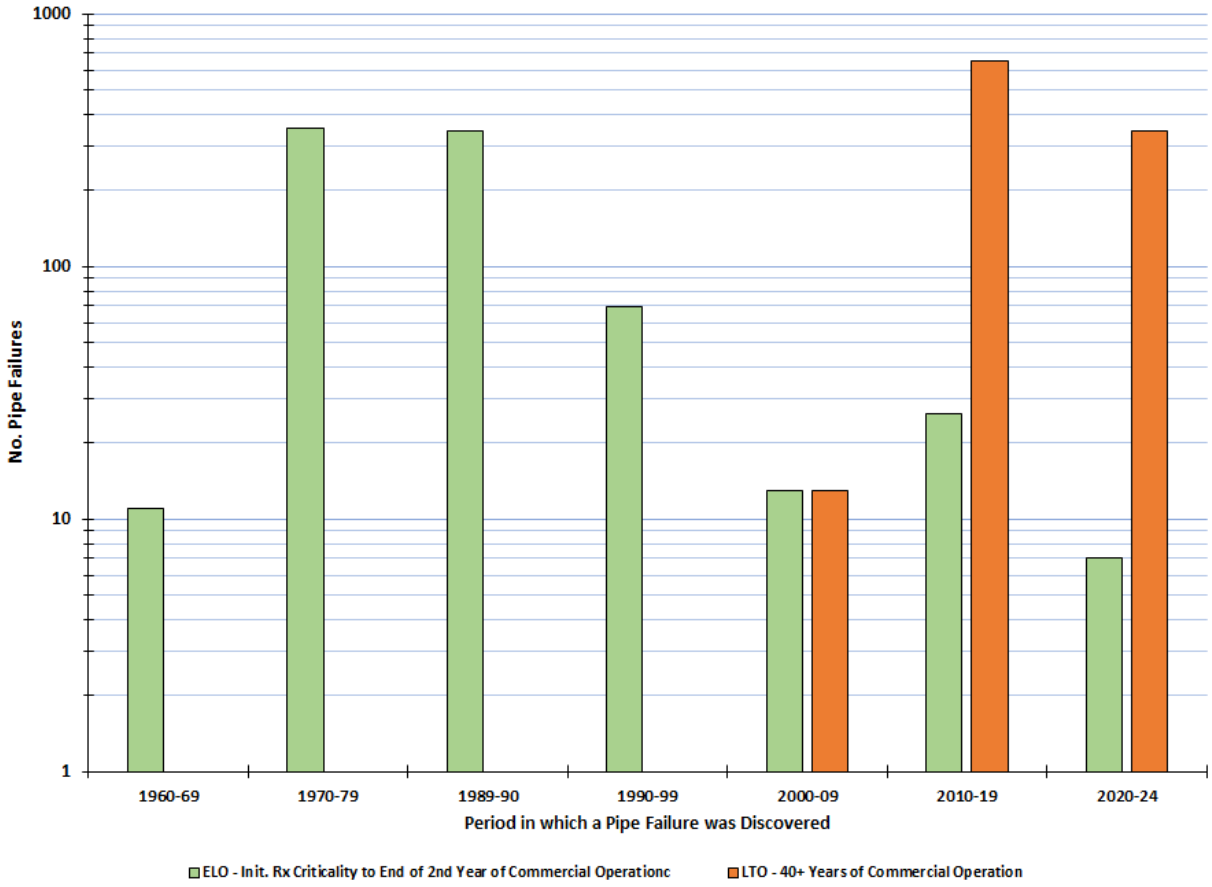
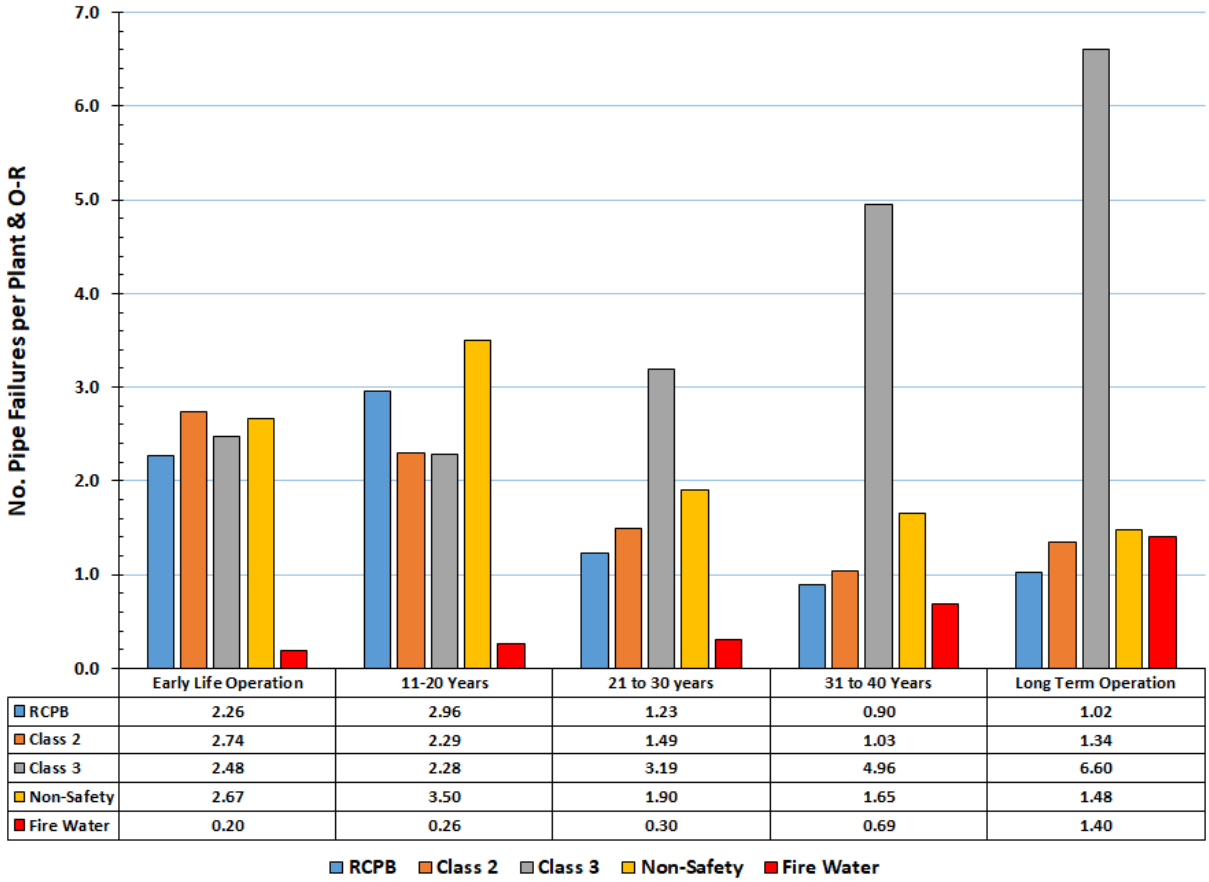


Figure 5. Pipe Failure Experience During Early Life & Long-Term Operation.

Additional high-level insights into the age-dependency of pipe failures are obtained in the following way. The entire failure population is subdivided into five “operating regimes” (O-R) based on the age of the plant when a failure was discovered and as indicated in Figure 6. Next, the failure population in each respective period was normalized against the plant population that generated the failures in the respective operating regime. Obviously, this is an approximation and should be seen as an initial screening for possible trends in the failure data.

The notable uptick in the Safety Class 3 pipe failures is driven by essential service water (or essential raw water cooling) pipe degradation and failure due to a multitude of corrosion mechanisms and flow-assisted degradation mechanisms. The typical piping material is carbon steel, with or without internal lining, the process medium is treated or untreated raw water from the ultimate heat sink (i.e., lake, river, or sea water). Some plants are replacing the original carbon steel material with corrosion-resistant material such as super-austenitic stainless steel or HDPE material. For the Safety Class 1 and 2 piping, underlying the decreasing trend in failure rates compared to early-life and the 11-20 years period are improvements in reliability and integrity management (RIM) processes, i.e., in-service inspection, stress improvement, water chemistry control, use of piping materials that are resistant to stress corrosion cracking. As an example, in

BWRs, the stress corrosion cracking incidence rate post-1990 is substantially lower than what was observed in the 1970s and 1980s. The reason behind the factor-of-improvement is well understood OECD/NEA (2010) and Lydell, Chitose, Focht (2022).



	Early Life Operation	11-20 Years	21 to 30 years	31 to 40 Years	Long Term Operation
RCPB	2.26	2.96	1.23	0.90	1.02
Class 2	2.74	2.29	1.49	1.03	1.34
Class 3	2.48	2.28	3.19	4.96	6.60
Non-Safety	2.67	3.50	1.90	1.65	1.48
Fire Water	0.20	0.26	0.30	0.69	1.40

Figure 6. Piping Operating Experience by Operating Regime and Safety Classification.

CRACK OPENING AREA AND LEAK RATE CORRELATIONS

The piping OE data can be used to correlate the measured pipe through wall leak rates and flow rates with the geometry (e.g., length and width) of the flaw in a pipe wall. Another way of processing the data is to convert a leak rate to an "equivalent break size" EBS, which is defined as an equivalent circular opening in the piping system with a specified diameter. The OE data is organized by piping system safety classification and the leak/flow rates in kg/s for each failure event. The results for Safety Class 1 piping are shown in Figure 7.

Semi-quantitative insights into the structural reliability of piping can be obtained using a simplified trend analysis with the results as indicated in Figure 8. These results build on ca. 8,500 pressure boundary leaks and ruptures. Many different qualitative insights can be derived from this analysis, including the fundamentally different slopes in the respective trend lines, and the very broad range in the observed flow rate versus safety classification. Indirectly, these trend lines indicate that a conditional probability of failure of a certain magnitude and given a pre-existing pipe flaw has different characteristics for piping of Safety Class 1 compared to non-safety-related piping.

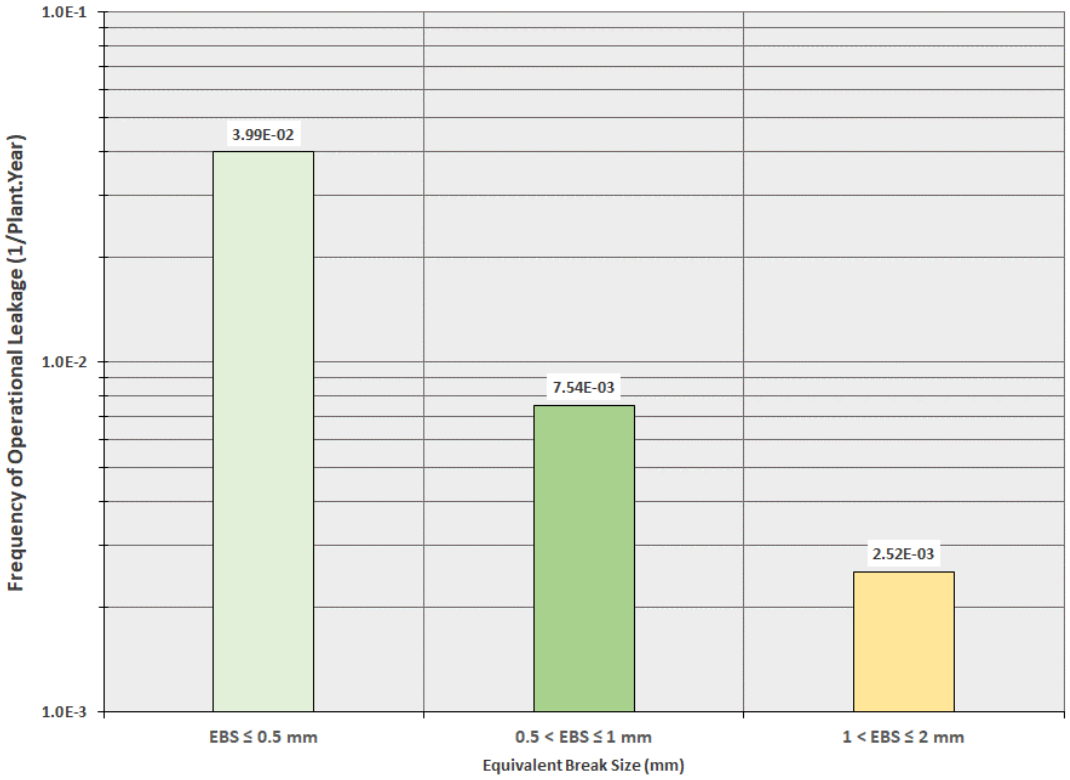


Figure 7. Frequency of Operational Leakage in Primary System Piping.

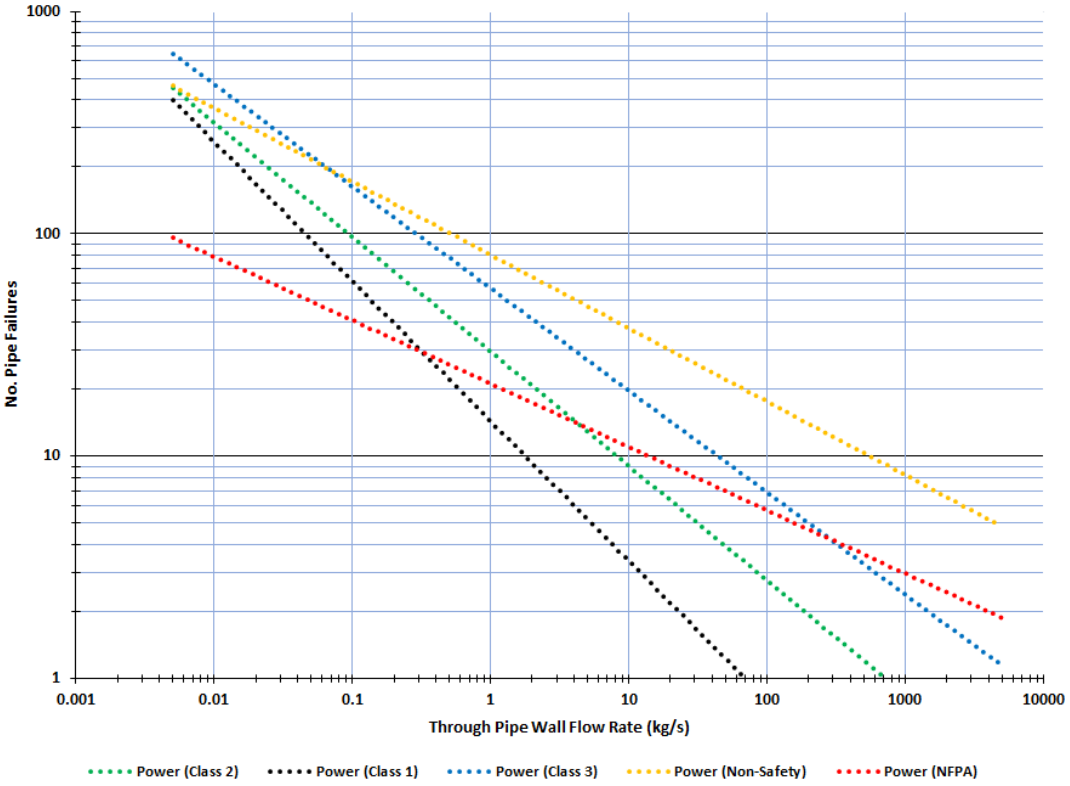


Figure 8. Pipe Failure OE by Safety Classification & Observed Through-Wall Flow Rate.

CONCLUSION

There exists an abundance of operating experience data involving piping pressure boundary degradation and failure. Embedded in this operating experience is detailed information of technical and programmatic processes that have been implemented to prevent or mitigate recurrence of material degradation and failures. The CODAP project has produced an extensive, quality-assured, database on piping operating experience spanning seven decades of commercial nuclear power plant operations. The database supports multiple applications including validation of assumptions and input parameters used in structural reliability models. It also supports the derivation of pipe failure rates in probabilistic safety assessments (PSAs). Additional details on the CODAP project, its organization and progress are available at https://www.oecd-nea.org/jcms/pl_72332/nuclear-safety-research-joint-projects

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