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Summary of Phase III of the Component Operational Experience, Degradation and Ageing Programme (CODAP)

Organisation for Economic Co-operation and Development

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The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia (suspended), the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

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List of abbreviations and acronyms

AEC	Atomic Energy Council (Chinese Taipei)
ANVS	Authority for Nuclear Safety and Radiation Protection (Autoriteit Nucleaire Veiligheid en Stralingsbescherming, Netherlands)
BMI	Bottom mounted instrument
BWR	Boiling water reactor
CANDU	Canada Deuterium Uranium
CASS	Cast austenitic stainless steel
CNSC	Canadian Nuclear Safety Commission
CODAP	Component Operational Experience, Degradation and Ageing Programme
CSN	Nuclear Safety Council of Spain (Consejo de Seguridad Nuclear)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
CSV	Comma-separated-values
E-C	Erosion-cavitation
ENSI	Swiss Federal Nuclear Safety Inspectorate
EPRI	Electric Power Research Institute
ESFAS	Engineered safety features actuation system
FAC	Flow-accelerated corrosion
FAD	Flow-assisted degradation
FIV	Flow-induced vibration
GRS	Global Research for Safety (Gesellschaft für Anlagen- und Reaktorsicherheit, Germany)
HDPE	High-density polyethylene
HELB	High-Energy Line Break
IGSCC	Intergranular Stress Corrosion Cracking
IRS	Incident Reporting System
IRSN	Institute for Radiological Protection and Nuclear Safety (Institut de radioprotection et de sûreté nucléaire) (France)
ISI	In-service inspection
KINS	Korea Institute of Nuclear Safety
LOCA	Loss-of-coolant accident
LTO	Long-term operation
MIC	Microbiologically influenced corrosion
MRP	Materials Reliability Program (of EPRI)
NDA	Non-disclosure agreement
NDE	Non-destructive examination
NDT	Non-destructive testing
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute (United States)
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
OPDE	OECD Pipe Failure Data Exchange Project
OPEX	Operating experience
PEO	Period of extended operation
PFM	Probabilistic fracture mechanics
PHWR	Pressurised heavy water reactor

PSA	Probabilistic safety assessment
PWR	Pressurised water reactor
PWSCC	Primary water stress corrosion cracking
RCPB	Reactor coolant pressure boundary
RCP	Rapid crack growth
RIM	Reliability and integrity management
RPV	Reactor pressure vessel
SCAP	Stress Corrosion Cracking and Cable Ageing Project (NEA)
SCC	Stress corrosion cracking
SCG	Slow crack growth
SEAS	Slovenské Elektrárne A.S.
SKI	Swedish Nuclear Power Inspectorate (now SSM, the Swedish Radiation Safety Authority)
SRE	Selected representative event
SRV	Safety relief valve
STUK	Radiation and Nuclear Safety Authority (Finland)
TAE	Thermal ageing embrittlement
TGSCC	Transgranular stress corrosion cracking
TVO	Teollisuuden Voima Oy (Finland)
TWFR	Through-wall flow rate
VHP	Vessel head penetration
VVER	Water-cooled water-moderated energy reactor
WANO	World Association of Nuclear Operators
WGIAGE	Working Group on Integrity and Ageing of Component and Structures (NEA)
WGRISK	Working Group on Risk Assessment (NEA)

Executive summary

Several member countries of the Nuclear Energy Agency (NEA) agreed to establish the Component Operational Experience, Degradation and Ageing Programme (CODAP) to encourage co-operation in the collection and analysis of data relating to the degradation and failure of metallic piping and non-piping metallic passive components (e.g. reactor internals) in commercial nuclear power plants. The project is organised under the NEA Committee on the Safety of Nuclear Installations (CSNI).

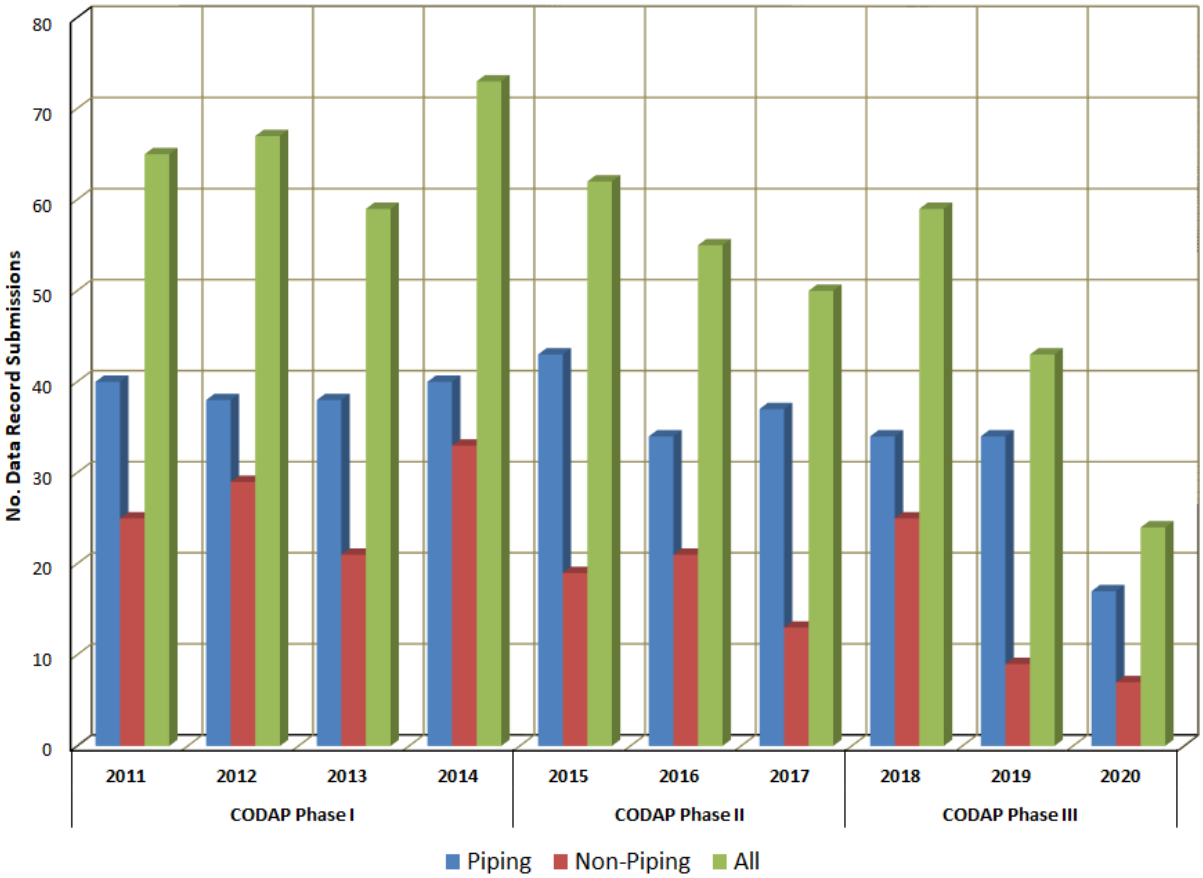
This report, which was approved by the CSNI on 8 December 2021 (NEA, 2021) and prepared for publication by the NEA Secretariat, describes the status of CODAP at the conclusion of Phase III (2018-2020). The key accomplishments of Phase III were as follows:

- Thirteen NEA member countries supported the project. STUK of Finland re-joined the project after a three-year absence. The ANVS of the Netherlands joined the project as a newcomer.
- Two topical reports were completed; 1) review of the thermal fatigue operating experience; and 2) review of material degradation in periods of extended operation and long-term operation.
- The CODAP event database event population was expanded from 4 920 records at the end of Phase II to 5 097 records at the end of Phase III. The total event population has resulted from 11 705 reactor-years of operation, 85% pipe failure events and 15% non-piping passive component failure events. About 65% of this event population comes from the United States.
- In conjunction with the 15th Working Group meeting in April 2018 a one-day workshop was organised to exchange information on how the CODAP event database is used within the respective project member organisations.
- CODAP actively supported the “International Workshop on the Use of NEA Database Project Products for Probabilistic Safety Assessment” (26-27 April 2018), which was organised by the CSNI Working Group on Risk (WGRISK) (NEA, 2023).
- During Phase III the scope of CODAP was expanded to include potential degradation and failure of high-density polyethylene (HDPE) piping, Alloy 690/800 steam generator tubes, and thermal sleeves in the PWR control rod drive mechanism (CRDM) vessel head penetration tubes.
- The Terms and Conditions for Phase IV were finalised at the end of 2020. The project will continue to emphasise the following aspects of operating data exchange and analysis; 1) active data submissions by the project membership, and 2) continued database applications to be pursued through the development of topical reports.

Phase III conclusions

- The national contributions to the systematic evaluation of operating experience (OPEX) are essential to the information exchange to identify possible trends and patterns in material degradation. As noted in previous status reports, encouraging participating organisations to provide OPEX data in an equitable manner continues to be a challenge for the successful operation of CODAP, Figure ES-1.

Figure ES.1. CODAP database submission by calendar year in which an event occurred



- Progress was made in terms of improving the web-based database user interface, and a process for continuous improvement was implemented.
- The scope of CODAP was expanded in 2011 to include material degradation affecting reactor internals. Additional scope expansions were implemented during Phase III to address HDPE piping integrity, Alloy 690/800 steam generator tubing integrity, and CRDM thermal sleeve wear/material loss.

Recommendations for Phase IV

The Management Board recognises that there are many potential challenges related to the environmental degradation of passive components in heavy water and light water reactor operating environments. It is important to ensure that the almost five decades of insights from operating experience be preserved and made readily available to future generations of material scientists, structural engineers and probabilistic safety assessment (PSA) engineers. It is equally important to add new events to the database to ensure that it is up to date. Since CODAP was established in 2002, the issue of an equitable data exchange among participating organisations has been at the forefront of the annual work planning activity. The project still faces challenges in ensuring submittals of data representative of the multi-faceted material degradation issues that arise in any given calendar year. The CODAP-MB's plans for Phase IV are as follows:

- Each participating project member will identify the current national routines for recording and submitting information on material degradation issues, including access to OPEX data.
- Each participating project member will report on the current national regulatory and industry routines/practices and requirements for performing operability determinations or fitness for service assessments. In particular, the question of how such evaluations could provide relevant OPEX data for submission to CODAP should be elaborated.
- The CODAP-MB has devised the term "selected representative event" (SRE) as a means for simplifying data entry. However, it has promoted an ad hoc approach as opposed to a systematic approach to the exchange of reactor internals OPEX. Therefore, the MB members will recommend a list of BWR, PWR, PHWR and WWER reactor internal piece parts and develop a plan for how to conduct the future reactor internals OPEX exchange.

In planning for activities beyond 2020, questions concerning the effectiveness of degradation mitigation processes and non-destructive examination (NDE) continue to be recognised as important. The CODAP event database will remain an important resource in monitoring trends in material degradation. In 2014, the CSNI Project Review Group recommended that CODAP implement operating procedures and processes whereby future national data submissions are commensurate with the number of operating reactors. It remains a challenge to achieve a more equitable data exchange, however.

The CODAP-MB will contemplate procedural changes to ensure that CODAP can sustain its ability to actively track long-term material performance. Thus, the CODAP-MB will consider the following activities in Phase IV:

- In recognition of the importance of long-term environmental effects on reactor pressure vessels and reactor internals' material integrity, the project is actively collecting relevant operating experience data. However, there are challenges in obtaining and evaluating relevant OPEX. Mainly this is due to two factors: a) reactor internals' material flaws discovered during in-service inspections are typically not documented per abnormal occurrence or licensee event reporting routines; and b) associated flaw evaluation reports and NDE results tend to be classified as restricted or proprietary information. Gaining access to information not readily available to the CODAP national co-ordinators would help improve the volume and quality of data on reactor internals OPEX. For CODAP to gain access to material degradation data on reactor internals would require a planning effort with the possible assistance from WGIAGE, regulatory agencies, technical support organisations and industry.

- Collecting and analysing material degradation data is technically challenging and resource-intensive, though rewarding. Continuing with the improvement process for the CODAP event database infrastructure could be key to instilling a deeper interest in and committing adequate resources to the continued data exchange. Plans are in place to develop software upgrades and implement them in the near term. The CODAP-MB will prioritise software development to improve the functionality of the CODAP database website.
- The role of an OPEX database such as CODAP is to support applications. The project will continue to promote practical applications, in particular as:
    1. An information tool for regulatory site inspectors to help identify relevant material degradation scenarios at plants of similar or like designs;
    2. An information tool for evaluating the effectiveness of in-service inspection programmes and technologies;
    3. An information tool for evaluating the effectiveness of ageing management programmes; and
    4. An operating experience data source for structural reliability analysis (e.g. probabilistic fracture mechanics) and PSA.

1. Introduction

Since 2002, the NEA has operated an event database project that collects information on passive component material degradation and failure. The emphasis of the project is on piping and selected non-piping passive components, such as reactor internals. This report summarises the status at the end of Phase III (2018-2020) of the Component Operational Experience, Degradation and Ageing Programme (CODAP).

1.1. The origin of CODAP

The CODAP international collaboration has its origins in the piping reliability R&D sponsored by the Swedish Nuclear Power Inspectorate (SKI) in the early 1990s and in response to what became known as the "Barsebäck-2 strainer event." On 28 July 1992, a steam line pressure boundary breach occurred when a safety relief valve (SRV) inadvertently opened in the Barsebäck-2 nuclear power plant, a third generation Swedish boiling water reactor (BWR) design. At the time of the event, the plant was returning to service after an annual refuelling and maintenance outage. With the reactor at about 2% power and 3.2 MPa pressure, a leaking pilot valve caused a depressurisation of the main safety relief valve, which then opened. When the main valve opened, a rupture disc with design pressure of 3 MPa broke, causing an opening into the containment drywell. The resulting steam jet stripped fibrous insulation from adjacent pipework. Part of that insulation debris was transported to the suppression pool and subsequently clogged the intake strainers for the Containment Vessel Spray System about one hour into the event sequence.

The 1992 "strainer event" confirmed safety concerns that had been raised about two decades earlier, specifically a generic safety issue that was concerned with the impact of a primary pressure boundary breach, such as a pipe break on the operability of emergency core cooling systems. While there had been a number of strainer "precursor" events in the 1970s, 1980s and 1990s, it was the 1992 strainer event that prompted an extensive and still ongoing response by the international nuclear safety community.

The Swedish regulatory and industry response to the strainer event involved the establishment of R&D efforts that focused on physical phenomena associated with containment sump clogging issues, pipe break debris generation, debris transport and the technical basis for more realistic loss-of-coolant accident (LOCA) frequency assessment. In part, the latter aspect of this broad R&D effort consisted of a five-year R&D effort to explore the viability of establishing an international database on the operating experience with piping in commercial nuclear power plants. An underlying objective behind this five-year programme was to investigate the different options and possibilities for deriving pipe failure rates and rupture frequencies directly from service experience data as an alternative to, for example, probabilistic fracture mechanics (PFM).

One outcome of the aforementioned R&D programme was the decision by SKI to transfer the pipe failure database (Swedish Nuclear Power Inspectorate, 1995 and 1997), to an international co-operative effort under the auspices of the NEA. After a series of information exchange and planning meetings organised by the NEA in September 2000 and April 2001, the OECD Pipe Failure Data Exchange Project (OPDE) was officially launched in May 2002 (NEA, 2012).

1.2. CODAP history

During the three OPDE Project Terms (2002-2011), the event database was maintained and distributed as a Microsoft® Access database. This database was distributed on a CD-ROM to the national co-ordinators twice per calendar year. Towards the end of the first Project Term, a web-based database format was developed to facilitate the exchange of operating experience data. With the 2011 transition from OPDE to CODAP, a new and enhanced web-based database format was implemented. It was further enhanced in 2017. The CODAP event database resides on a secure server at the NEA. Provisions exist for online data exchange and database interrogation.

With an initial focus on piping systems components, the scope of the project was expanded in 2011 to address reactor internals as well as certain other metallic passive components that are susceptible to environmental degradation, e.g. cast austenitic stainless steel valve bodies and piping elbows. The scope expansion was enabled through the SCAP project (2006-2010), which was financed through a Japanese voluntary contribution to the NEA. Building on the OPDE database, one of the results of the SCAP project was an expanded database on the international stress corrosion cracking (SCC) experience.

Following the completion of the SCAP project (NEA, 2010), the SCC Working Group participants were interested in some form of continuation and discussions were initiated to explore possible alternatives. It was recognised that there were many aspects very similar to those existing in OPDE and the concept of a new project was envisaged to combine the two projects into the Component Operational Experience, Degradation and Ageing Programme (CODAP). In recognition of the expanded scope, the Management Board approved the transition of OPDE to a new, expanded CODAP.

1.3. Report structure

The CODAP data collection principles are described in Chapter 2. A summary of the database content is found in Chapter 3. Insights from the data collection process are summarised in Chapter 4. The results of the Phase III topical reports are found in Chapter 5. Conclusions and plans for future activities are documented in Chapter 6. A list of references is found at the end of the document. Appendix A includes CODAP activity report. Appendix B is a project bibliography.

2. Data collection principles and guidelines

CODAP collects and analyses information on passive metallic and high-density polyethylene (HDPE) component degradation and failures to promote a better understanding of underlying causes, impact on operations and safety, and prevention. Detailed objectives and schedules for data submissions are defined for each calendar year of project operation. Furthermore, the project analyses the information collected in the event database to develop topical reports on material degradation mechanisms. Objectives and schedules for the topical reports are developed for each calendar year of project operation.

2.1. Quality assurance

As stated in the project's Quality Assurance Plan, the process for data collection and analysis shall result in quality assured data recorded in the database with consistency verification performed within the project. The Coding Guideline defines the format for collecting passive component failure events in a quality assured and consistent database.

Each national co-ordinator is responsible for collecting data according to the relevant internal processes of their respective participating organisation and checked according to the internal quality assurance programmes. The event information provided by the participating organisations is intended to be analysed within the scope of the project; it is not intended to modify the event data unless the events undergo a review by the responsible national co-ordinator.

The role of the CODAP Operating Agent is to ensure that the data submissions are consistent with the Coding Guideline. To ensure the integrity of the database, event information that falls outside of the technical scope of the project is screened out.

2.2. Data collection process

To achieve the objectives of CODAP, a coding format has been developed and this format is documented in the Coding Guideline. This guideline builds on established passive component failure data analysis practices and routines that acknowledge the unique aspect of passive component reliability (e.g. influences by material chemical and mechanical properties, stresses and operating environment). All database development and data coding activities are based on the Coding Guideline.

The exchange of operating experience data is done through an online work area. The online event database facilitates data submissions, various search and sort functions, and database interrogation functions. The latter are performed in the "Statistics" area of the database. This section of the report addresses the four applications: 1) records management; 2) search; 3) database query; and 4) export. The export function of the online version of CODAP produces an XML file that can be converted to Access or

Excel format for further data processing and analysis. In summary, the online database includes the following facilities:

- Records management. The records tab includes a list of all database records. In its current format, the database content can be sorted by status (i.e. "Draft," "Ready for Review by NC," "Ready for QA," or "Approved"), country, plant name, year of the event, plant system, component type, and degradation mechanism.
- Search function. The search tab includes data filters that make it possible to identify specific event populations. The data filters correspond to drop-down menus corresponding to about 700 different data filters.
- Query function. The “statistics” tab includes a database query function that is equivalent to the Microsoft® Access query function. Further data processing may be performed by exporting the query results as a CSV-file. A “comma-separated-values” (CSV) file stores tabular data (numbers and text) in plain text. Files in the CSV-format can be imported to Microsoft® Excel.
- Export function. Downloading records from the online version is straightforward. Pressing the "export" button returns a listing of all records. Selected records or the entire database can be exported to a local computer. The online version creates a zip file ("export" file) that can be opened or saved to a local disc. The data records are converted to an XML file format.

A self-guiding data input form is used to record the event information. A partially filled form can be saved and retrieved and the information modified as needed. The user may append drawings (e.g. piping and instrumentation diagrams, isometric drawings, photographs, PDF files) to a data record. Checking the box “Ready for Review by National Co-ordinator” and submitting the information is an indication that a database record is ready for independent review.

2.3. Coding Guideline

The Coding Guideline is structured as follows. Chapter 1 of the document outlines the scope and content of the event database. Chapter 2 contains instructions on how to work with the online version. Chapters 3, 4 and 5 define database structure, database field categories and data entry requirements, respectively. Chapter 6 contains step-by-step instructions for downloading selected records or the entire database to a local computer.

Detailed information on database field definitions and other supporting information are included in appendices. Additional database user guidelines, frequently asked questions, and tutorials are also found in the secure CODAP work area for which a username and password are required. User help is found within the online database as well.

2.4. Database accessibility

The CODAP terms and conditions contain statements on the use of data within or outside of CODAP and on the handling of proprietary information. Access to the restricted database is limited to participating organisations that provide input data. The restricted database is accessible online via a secure server located at the NEA premises.

The Management Board has recognised that many participating organisations will want to make the CODAP database accessible to their contractors and licensees for use in specific projects. For this purpose, the Management Board established a non-disclosure agreement (NDA) procedure and process. NDAs were made with Fortum (owner/operator of the LO1 and LO2 nuclear power plant units) in 2019 and with Teollisuuden Voima Oy (TVO; owner/operator of the OL1, OL2 and OL3 nuclear power plants) in 2020.

3. Event database status

The CODAP event database is a web-based, SQL database consisting of about 60 data fields. It is a mixture of free-format fields for detailed narrative information, fields defined by drop-down menus with key words (or data filters) or related tables, and hyperlinks to additional background information (e.g. photographs, isometric drawings, root cause evaluation reports). The "related tables" include information on material, location of damage or degradation, type of damage or degradation, system name, dimensional data, safety class, etc.

3.1. Scope of the event database

The event database scope is given in Table 3.1. During Phase III of the project, the scope of the event database was expanded to consider degraded conditions or failures involving high-density polyethylene (HDPE) piping. At some nuclear power plants, continued issues with pinhole leaks, pitting and other localised forms of pipe wall degradation due to microbiologically influenced corrosion (MIC) have resulted in the replacement of portions of the original Fire Water and Service Water carbon steel piping with HDPE piping. This material has demonstrated a high resistance to abrasion and biofouling and it is immune to general corrosion. HDPE material has been used in the commercial nuclear power industry since the mid-1990s. HDPE piping is also used in new reactors. Currently there is a single HDPE pipe failure event in the CODAP event database.

Another database scope expansion was to include steam generator tube degradation involving Alloy 690 and Alloy 800 materials. The former type of material was developed and patented in the late 1960s. A few years later, steam generator manufacturers began considering Alloy 690 as a candidate tubing material. Thermally treated Alloy 690 tubes have been in use in a large number of plants since the mid-1980s. To date, no stress corrosion cracking problems have been reported. At the 18th Working Group Meeting of CODAP (September 2019), the IRSN reported on recent preliminary results from experimental studies indicating possibilities for outside diameter SCC in a low pH operating environment. This research continues at the IRSN.

Alloy 800 material has been used for steam generator tubing since 1972. The operational performance of this alloy has been good, although some degradation modes have recently been observed in German plants (2017 to 2020 time frame). The material has been used in KWU/Siemens designed PWRs, CANDU plants and some Westinghouse-designed plants. The various plants with Alloy 800 tubing have significant differences in design and operating conditions and have shown differing levels of susceptibility to various modes of degradation.

Finally, the thermal sleeve in the control rod drive mechanism (CRDM) vessel head penetration tubes was added to the scope. Some PWR plants in France, Korea, South Africa, Chinese Taipei and the United States have experienced thermal sleeve wear caused by flow-induced vibration (FIV). This wear has the potential to cause a control rod to stick. The database includes four events involving thermal sleeve wear.

Table 3.1. Scope of the CODAP event database

PIPING COMPONENTS	NON-PIPING PASSIVE COMPONENTS AND SG TUBING
Piping - Below Ground / Concealed	Reactor Pressure Vessel (RPV)
Pipe - Concrete Encased Pipe	Vessel Head Penetration - PWR
"Bonna" Pipe	Bottom Mounted Instrument (BMI) Nozzle - PWR
Pipe - External Coating	RPV Head Thermocoupling (T/C) Housing - PWR
Ex-RPV - In-Plant Piping (Accessible)	RPV Head T/C Nozzle - PWR
Pipe - Base Metal	CRDM Thermal Sleeve
Pipe - Cement Lined	Pressuriser
Pipe - Epoxy Lined	Pressuriser Heater
Pipe - Rubber Lined	Pressuriser Manway Diaphragm Plate
Pipe - HDPE	Pressuriser Nozzle
Bend	Pressuriser Relief/Safety Valve Nozzle
Blind Flange	Pressuriser Vessel
Branch-Connection - Socket Welded	RPV Internals
Branch-Connection - Stub-in Weld	Baffle-Former Assembly Bolt - PWR
Cap / End-Cap	Core Shroud Access Hole Cover Weld
Elbow	Core Shroud Head Bolt - BWR
Elbow - Long-Radius	Core Shroud Weld - BWR
Elbow - 45-Degree	Core Shroud Tie Rod - BWR
Elbow - 90-Degree	Core Shroud Support - BWR
Expander	Core Spray Sparger - BWR
Expansion Joint	In-Core Instrument Tube
Fitting	Jet Pump Hold-Down Beam
Mixing Tee	Jet Pump Riser
Reducer	Jet Pump Support Brace
Socket Weld	Steam Dryer - BWR
Tee	Pump
Weld - Butt Weld	Pump Casing
Weld - Dissimilar Metal Weld	RCP Turning Vane Bolt
Weld - Girth Weld (Full Penetration Weld)	Valve
Weld	Valve Body
	Steam Generator
	ALLOY 690 or ALLOY 800 Tube Material

3.2. Database content and data submissions

The database content at the end of Phase III is summarised in Tables 3.2 and 3.3. A data submission summary is documented in Tables 3.4 and 3.5. In Tables 3.6 through 3.9 selected database contents are summarised in terms of observed material degradation mechanisms and component-specific operating experience.

Rather than collecting data on "all events of interest", CODAP primarily collects data that involves "selected representative events" (SREs), Figure 3.1. That is, for a given time period, plant type and material degradation mechanism, a national co-ordinator may select a single event to be representative of potentially multiple similar failures within the same period. Rather than capturing all failure events in a given population of plants and systems, CODAP has good coverage of the different types of degradation mechanisms that act on a particular structure, system or component in a given time period.

Table 3.2. Database content by country, plant type and passive component category

Member country	Plant type	Reactor-years of operation as of 12/31/2020	Pipe failure population	Non-pipe failure population
CA	CANDU	681.4	197	30
CH	BWR	86.7	58	4
	PWR	142.8	49	6
CZ	VVER	175.8	25	7
DE	BWR	214.4	159	11
	PWR	447.4	195	24
ES	BWR	79.1	22	5
	PWR	253.7	31	15
FI	BWR	83.8	34	4
	VVER	84.3	20	6
FR	PWR	2 089.5	93	81
JP	BWR	1 020.7	173	54
	PWR	853.2	54	23
KR	CANDU	106.6	8	--
	PWR	490	69	10
NL	PWR	47.6	5	--
SK	VVER	152.3	12	--
TW	BWR	160.5	9	7
	PWR	72.8	3	10
US	BWR	1 512.8	1 280	107
	PWR	2 949.5	1 529	301
	Totals:	11 704.9	4 025	705

Table 3.3. Database content by country, plant type and component safety class

Member country	Plant type	NO. DATABASE RECORDS BY SAFETY CLASS			
		1 – RCPB	**2**	**3**	**Non-safety**
CA	CANDU	47	13	51	114
CH	BWR	36	7	116	3
	PWR	5	24	20	5
CZ	VVER	4	6	4	18
DE	BWR	30	39	70	30
	PWR	34	59	89	37
ES	BWR	2	11	7	6
	PWR	12	9	12	13
FI	BWR	14	16	1	7
	VVER	5	--	4	17
FR	PWR	80	45	35	14
JP	BWR	130	--	7	21
	PWR	39	19	5	11
KR	CANDU	6	1	--	--
	PWR	13	28	26	10
NL	PWR	2	2	1	--
SK	VVER	2	--	--	10
TW	BWR	1	1	5	13
	PWR	4	--	--	5
US	BWR	620	238	277	252
	PWR	495	395	619	313
	Totals:	1 581	913	1 249	899

Table 3.4. Database submission summary

Project members		Number of data records through end of CY 2014	Data submissions 2015-2017	Data submissions 2018-2020
Country	Status			
BE - Belgium	Member of OPDE (2002-2008)	8	N/A	1
CA - Canada	Member since 2002	187	37	7
CH - Switzerland	Member since 2002	95	4	18
CZ – Czechia	Member since 2002	25	6	1
DE - Germany	Member since 2002	350	8	31
ES - Spain	Member since 2002	50	6	17
FI - Finland	Member since 2002	56	N/A	12
FR - France	Member since 2002	148	21	5
IN - India	Not a member – an event of general interest; extracted from the NEA/IAEA IRS database (refer to Table 3.5)	N/A	N/A	1
JP - Japan	Member since 2002	287	--	5
KR – Korea	Member since 2002	69	12	5
NL – The Netherlands	Member since 2018	N/A	N/A	5
SE - Sweden	Member through end of 2014	365	N/A	1
SK – Slovak Republic	Member since 2011	5	5	N/A
TW – Chinese Taipei	Member since 2011	15	11	3
UK – United Kingdom	Not a member – an event of general interest; extracted from the NEA/IAEA IRS database (refer to Table 3.5)	N/A	N/A	1
US – United States	Member since 2002	3 035	113	68
	Total no. of Records:	4 695	223 (4 921)	189 (5 109)

Table 3.5. Data submissions by member country and event date[1]

Member State	OPDE Phase I				OPDE Phase II			OPDE Phase III			CODAP Phase I			CODAP Phase II			CODAP Phase III			Total
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	
BE	1	--	--	--	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1	N/A	N/A	2
CA	--	11	3	3	15	22	11	3	10	10	4	3	5	5	5	5	4	3	--	122
CH	1	4		6	3	5	1	7	3	2	5	2	5	2	2	1	4	4	--	57
CZ	1	1	2	--	1	--	1	--	1	1	2	1	2	3	--	1	--	--	1	18
DE	17	9	21	21	19	21	7	17	5	6	6	6	6	4	3	3	7	4	2	184
ES	1	4	3	8	1	--	--	1	1	2	--	2	3	5	3	1	7	3	--	45
FI	--	1	--	--	1	--	4	--	1	1	3	--	2	--	--	--	3	3	--	19
FR	7	4	6	2	6	5	3	1	2	4	3	1	2	4	1	4	1	1	--	57
(IN)							IAEA/NEA Incident Reporting System:							1					--	1
JP	111	39	14	6	14	10	13	1	4	1	1	--	--	--	--	1	2	--	--	217
KR	7	2	--	1	--	3	2	2	2	4	3	5	7	1	1	1	1	--	1	43
NL	--	--	--	1	--	--	--	--	--	2	--	--	--	--	--	--	--	--	--	3
SE	1	7	4	1	1	1	--	--	--	1	--	--	--	N/A	N/A	N/A	N/A	1	N/A	17
SK	1	1	1	--	--	--	--	--	2	--	--	2	--	--	--	--	--	--	--	7
TW	--	2	2	--	1	--	1	2	--	2	3	0	2	5	--	3	2	1	--	26
(UK)								IAEA/NEA Incident Reporting System:								1			--	1
US	58	75	66	69	29	22	26	33	28	29	37	37	38	32	37	28	26	23	19	708
(ZA)									IAEA/NEA Incident Reporting System:								1	--	--	1
Totals:	205	160	122	118	91	89	69	67	59	65	67	59	72	62	52	49	59	43	23	1 526

[1] Since the project began in 2002 a standing action item has been to include selected NEA/IAEA IRS event reports of interest as well as other selected event reports of interest (e.g. from Belgium and Sweden).

Table 3.6. Flow-assisted degradation (FAD) events in CODAP

Country	FAD mechanism	Time period in which a FAD failure occurred [No. Events]				
		1970-79	1980-89	1990-99	2000-09	2010-19
CA	E-C	--	--	--	1	--
	E/C	--	--	--	4	--
	FAC / JIE	--	26	6	19	6
CH	E-C	--	--	--	--	--
	E/C	--	--	3	2	--
	FAC / JIE	--	2	2	--	--
CZ	E-C	N/A*	--	--	--	--
	E/C	N/A	--	--	--	--
	FAC / JIE	N/A	1	9	1	2
DE	E-C	--	--	1	--	
	E/C	--	--	--	3	
	FAC / JIE	--	2	6	11	
ES	E-C	--	--	--	--	--
	E/C	--	--	1	2	--
	FAC / JIE	--	2	4	1	--
FI	E-C	--	--	--	--	--
	E/C	--	--	--	--	--
	FAC / JIE	--	2	11	--	--
FR	E-C	--	2	--	2	--
	E/C	--	--	--	--	1
	FAC / JIE	--	1	1	--	--
JP	E-C	--	--	--	--	--
	E/C	--	--	1	--	--
	FAC / JIE	--	2	8	10	--
KR	E-C	--	--	4	1	--
	E/C	--	--	--	--	--
	FAC / JIE	--	--	12	6	3
NL	E-C	--	--	--	--	1
	E/C	--	--	--	--	--
	FAC / JIE	--	--	--	--	--
SK	E-C	--	--	--	--	--
	E/C	--	--	--	3	--
	FAC / JIE	--	--	--	--	1
TW	E-C	--	--	--	--	1
	E/C	--	--	--	--	1
	FAC / JIE	--	--	--	2	4
US	E-C	10	14	7	12	13
	E/C	17	21	39	50	5
	FAC / JIE	38	103	73	47	4

*) N/A = There were no commercial nuclear power plants in operation in CZ during the period 1970-79
E-C = Erosion-Cavitation
E/C = Erosion / Corrosion
FAC/JIE = Flow-Accelerated Corrosion / Jet Impingement Erosion

Table 3.7. Stress corrosion cracking (SCC) failures in CODAP

Country	SCC mechanism	Time period in which a SCC failure occurred [No. Events]				
		1970-79	**1980-89**	**1990-99**	**2000-09**	**2010-19**
CA	IGSCC	--	--	--	11	--
	PWSCC	PWSCC is not a credible degradation mechanism in CANDUs				
	TGSCC	--	--	--	1	--
CH	IGSCC	--	33	1	2	4
	PWSCC	--	--	--	1	1
	TGSCC	--	1	--	--	--
CZ	IGSCC	--	--	--	2	--
	PWSCC	PWSCC is not a credible degradation mechanism in VVERs				
	TGSCC	--	--	--	1	
DE	IGSCC	--	2	15	5	4
	PWSCC	PWSCC is not a credible degradation mechanism in KWU/Siemens PWRs				
	TGSCC	1	4	5	3	3
ES	IGSCC	--	2	1	2	1
	PWSCC	--	--	2	--	1
	TGSCC	--	--	--	7	--
FI	IGSCC	--	12	5	3	2
	PWSCC	PWSCC is not a credible degradation mechanism in VVERs				
	TGSCC	--	3	--	1	--
FR	IGSCC	--	--	2	--	--
	PWSCC	--	2	67	2	1
	TGSCC	--	1	1	--	--
JP	IGSCC	2	8	12	145	1
	PWSCC	--	--	--	23	--
	TGSCC	--	--	1	1	--
KR	IGSCC	--	--	--	--	--
	PWSCC	--	--	--	2	4
	TGSCC	--	--	--	--	--
NL	IGSCC	--	--	--	--	--
	PWSCC	See PWSCC line item for Germany				
	TGSCC	--	1	--	--	--
SK	IGSCC	--	--	--	1	--
	PWSCC	PWSCC is not a credible degradation mechanism in VVERs				
	TGSCC	--	--	--	1	--
TW	IGSCC	--	--	--	1	1
	PWSCC	--	--	--	--	--
	TGSCC	--	--	--	--	--
US	IGSCC	91	465	95	42	22
	PWSCC	--	32	47	133	49
	TGSCC	5	30	17	6	9

IGSCC = Intergranular SCC
PWSCC = Primary Water SCC
TGSCC = Transgranular SCC

Table 3.8. Fatigue failures in CODAP

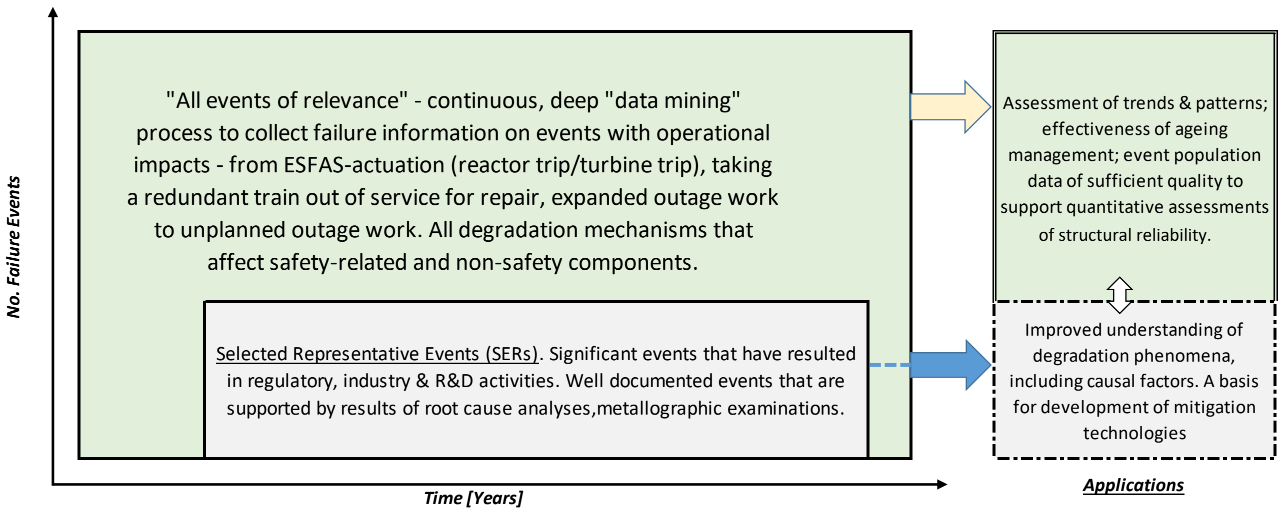
Country	Fatigue mechanism	Time period in which a fatigue failure occurred [No. Events]				
		1970-79	1980-89	1990-99	2000-09	2010-19
CA	Corrosion-Fatigue (CF)	--	2	--	--	--
	High-Cycle Fatigue	29	6	6	8	7
	Low-Cycle Fatigue	--	--	--	2	2
CH	High-Cycle Fatigue	--	1	2	7	5
	Low-Cycle Fatigue	--	--	--	1	1
	Thermal Fatigue	--	1	1	2	--
CZ	Corrosion-Fatigue (CF)	N/A	--	--	--	2
	High-Cycle Fatigue	N/A	--	2	2	2
	Thermal Fatigue	N/A	--	--	--	1
DE	High-Cycle Fatigue	7	5	15	16	5
	Low-Cycle Fatigue	--	1	--	1	--
	Thermal Fatigue	--	1	7	3	3
ES	Corrosion-Fatigue (CF)	--	--	--	--	1
	High-Cycle Fatigue	--	2	3	5	6
	Low-Cycle Fatigue	--	--	--	--	1
	Thermal Fatigue	--	--	--	1	--
FI	High-Cycle Fatigue	--	--	--	--	4
	Thermal Fatigue	1	1	2	1	1
FR	High-Cycle Fatigue	--	10	13	25	6
	Low-Cycle Fatigue	--	--	--	2	1
	Thermal Fatigue	--	--	4	--	--
JP	High-Cycle Fatigue	--	6	5	7	2
	Thermal Fatigue	--	2	3	2	1
KR	Corrosion-Fatigue (CF)	--	--	--	--	2
	High-Cycle Fatigue	--	3	--	2	4
	Thermal Fatigue	--	--	--	3	--
NL	High-Cycle Fatigue	--	--	--	1	--
TW	High-Cycle Fatigue	--	--	--	1	1
	Low-Cycle Fatigue	--	--	--	--	1
US	Corrosion-Fatigue (CF)	6	4	--	--	2
	High-Cycle Fatigue	187	279	162	101	54
	Low-Cycle Fatigue		17	8	9	29
	Thermal Fatigue	14	29	17	6	9
	Total No. Fatigue Failures:	244	370	250	208	153

Table 3.9. Socket weld failure data in CODAP

COUNTRY	Time period in which a socket weld failure was reported [No. Events}				
	1970-79	1980-89	1990-99	2000-09	2010-19
CA	--	--	--	1	
CH	--	--	--	6	3
CZ	N/A	--	1	--	--
DE	--	--	2	1	1
ES	--	--	--	1	5
FI	--	--	--	--	1
FR [1] (SREs)	--	2	5	10	5
JP	--	2	--	2	--
KR	--	--	5	10	1
TW	--	--	--	1	--
US [1] (SREs)	90	117	92	69	54

[1] The technical paper by Economou, J. and Y. Thebault and P.-E. Costes (2012), “Small-Bore Pipe Branch Connections Fatigue”, ASME PVP2011-57983, makes reference to 397 socket weld failures in branch connections in EDF plants during the period 1985 to 2009.[2] In the same period, US PWR plants reported 377 socket weld failures.

Figure 3.1. Data collection process vs. applications



[2] https://asmedigitalcollection.asme.org/PVP/proceedings-abstract/PVP2011/44533/659/361501

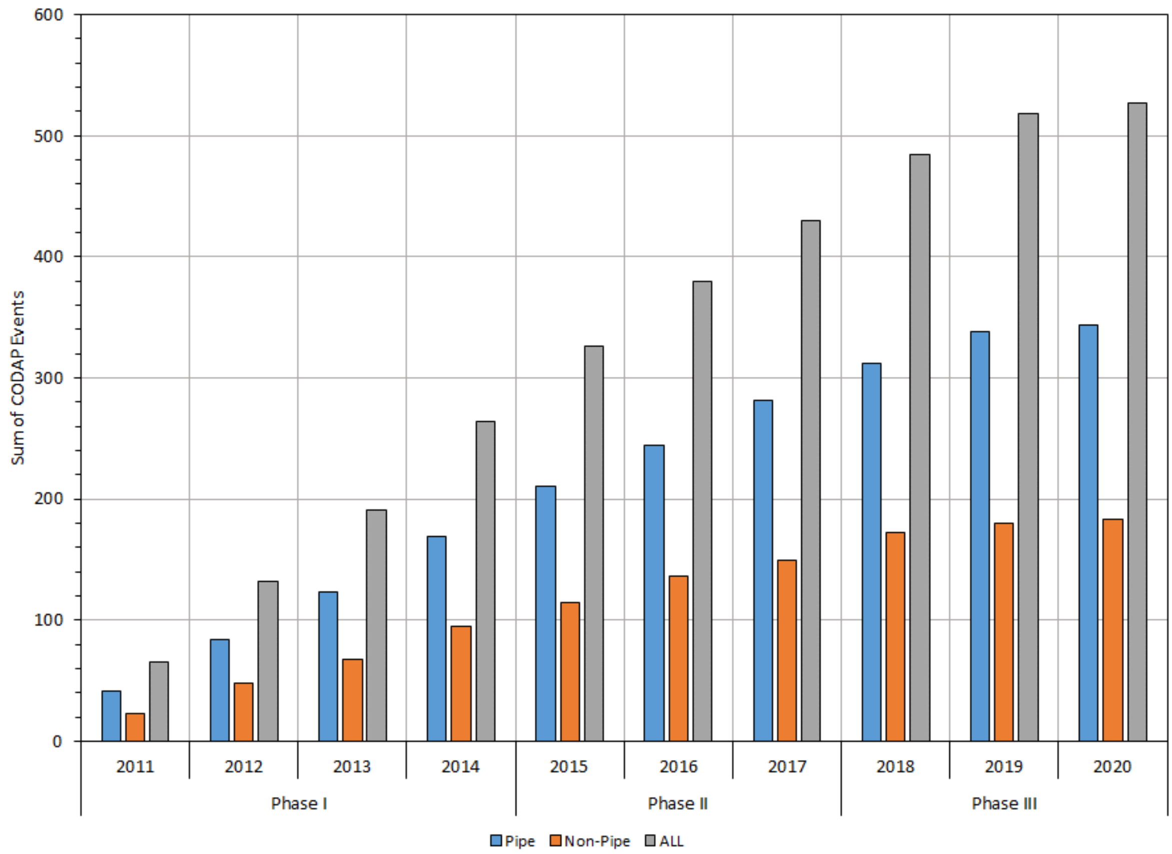
4. Insights from data collection and event analysis

Operating experience data collection is a continuous effort. The quality of the insights that can be obtained from systematic data analysis is proportional to: a) the completeness of the failure event population, and b) the extent to which an event database is updated and validated. This chapter presents the status of the progress in the data collection effort and some insights from event analyses.

4.1. Progress with data collection

The chronological sequence of data collection is shown in Figure 4.1. The graph shows the progress in the continuous data submissions of "selected events of interest" in the three project phases.

Figure 4.1. Data collection progress



4.2. Possible database applications

The objectives of data collection determine the structure of the database as well the expectations for data submission. If the objectives are to exchange information of potential interest to the participants of a data collection exercise, then a selective effort to gather needed information would suffice. On the other hand, if a data collection exercise is initiated in support of specific applications such as PSA or PFM model calibration/reconciliation against operating experience data, the completeness of an event population becomes an issue of concern to the user. While the focus of CODAP remains on "selected representative events", a consideration of different types of possible database applications remains as a standing action item for the project membership. Examples of possible database applications are found in Table 4.1.

Table 4.1. Examples of potential database applications

Objective(s)	Task	Description
PSA and Design Certification PSA	Loss-of-coolant accident (LOCA) initiating event frequencies	Quantification of location-specific LOCA frequencies as a function of equivalent break size or through-wall flow rate. The analysis accounts for multiple sensitivity cases to account for different leak detection and in-service inspection (ISI) activities.
	High-energy line break (HELB) initiating event frequencies	Quantification of location-specific HELB frequencies inside and outside the containment. The analysis addresses safety-related and non-safety-related HELB scenarios. The analysis generates pipe failure frequencies as a function of through-wall flow rate.
	Internal flooding initiating event frequencies (IF-PSA)	Quantification internal flooding scenarios attributed to pipe failure. Pipe failure frequencies account for all potential flood sources; safety-and non-safety-related piping, including fire water piping system.
	Support system failure initiating event frequencies	Examples include loss of cooling (open and closed-loop cooling systems), loss of instrument air, and failure of electro-hydraulic control system. The analysis task is to quantify pipe failure frequencies for the different loss-of-support-system scenarios.
	Estimation of pipe failure frequency due to hydrogen deflagration	WCR plants use hydrogen to cool turbine generators and also to condition the primary circuit coolant.
RIM per ASME XI Division 2 (2019) or equivalent Code	RIM Programme Development for a New Advanced Reactor	Quantification of reliability targets for the different in-service inspection (ISI) locations.
	RIM Programme Development for an Existing Advanced Reactors	As for a new design except that updates may have to be performed to account for new and relevant plant-specific and industry-wide operating experience.

Table 4.1. Examples of potential database applications (Continued)

Objective(s)	Task	Description
Operability determination	Risk-informed "significance determination"	Application of plant-specific PSA to determine the risk significance of a degraded or failed piping component. The analysis involves quantifying piping reliability prior to the discovery of a degraded/failed component as well as quantifying piping reliability in light of the new operating experience.
	Structural evaluation of flawed piping component	Depending on the national codes and standards, a formalised analysis based on structural reliability models is performed to determine whether a flawed component is suitable for continued operation; e.g. until next planned outage of sufficient length to accommodate a code repair or replacement. Probabilistic fracture mechanics (PFM) analysis may be performed in support of an analysis.

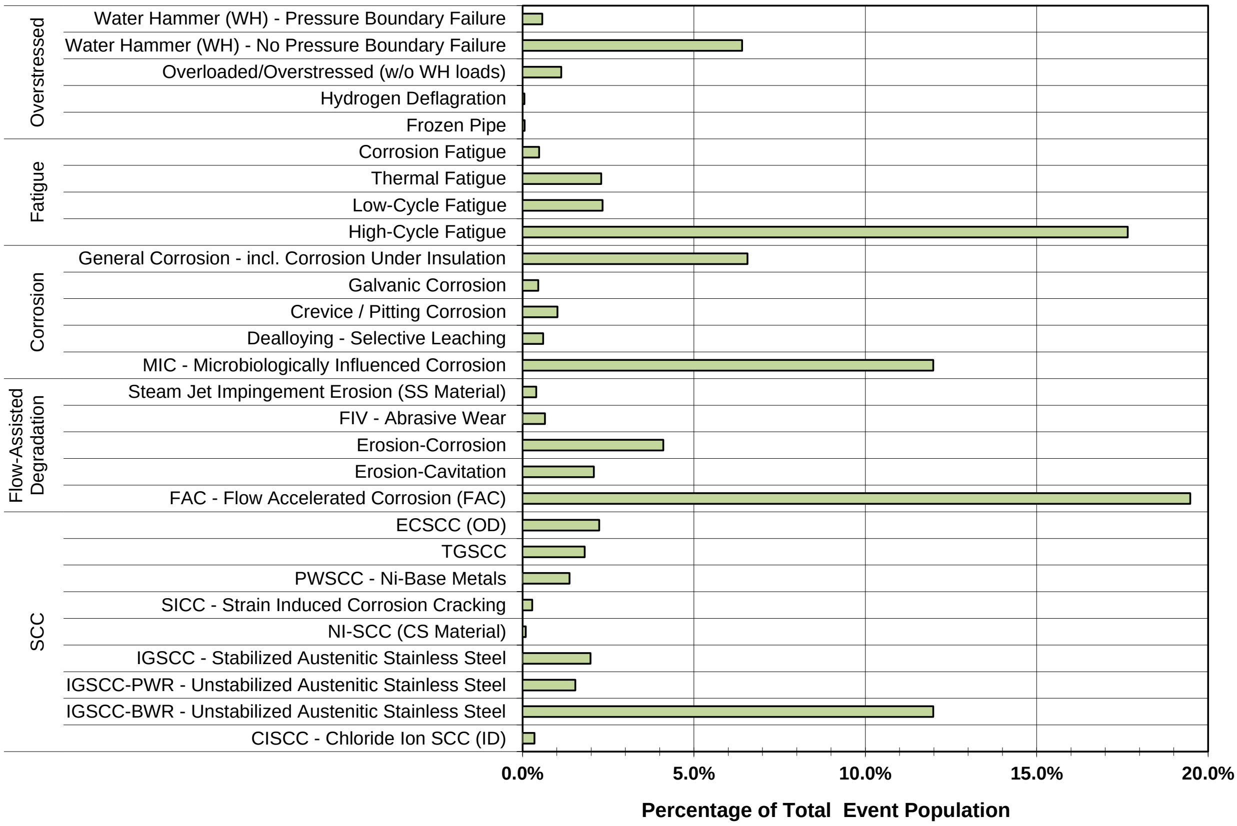
4.3. Passive component environmental degradation mechanisms

Figure 4-2 summarises the observed passive component degradation mechanisms. As indicated in this figure, there are five classes of degradation mechanisms:

1. stress corrosion cracking (SCC);
2. flow-assisted degradation (FAD);
3. corrosion (various mechanisms acting on raw water piping systems);
4. fatigue (corrosion-fatigue, high-cycle fatigue, low-cycle fatigue and thermal fatigue);
5. extreme loading conditions acting on degraded or non-degraded piping.

Major structural failures that have produced significant spatial effects like spraying or flooding have been caused by corrosion damage, fatigue damage and flow-assisted degradation (mainly flow-accelerated corrosion), and water hammer. The majority of SCC failures have produced non-through-wall defects, with a relatively small population of through-wall defects producing less than or much less than a 6×10^{-2} kg/s through-wall mass flow rate.

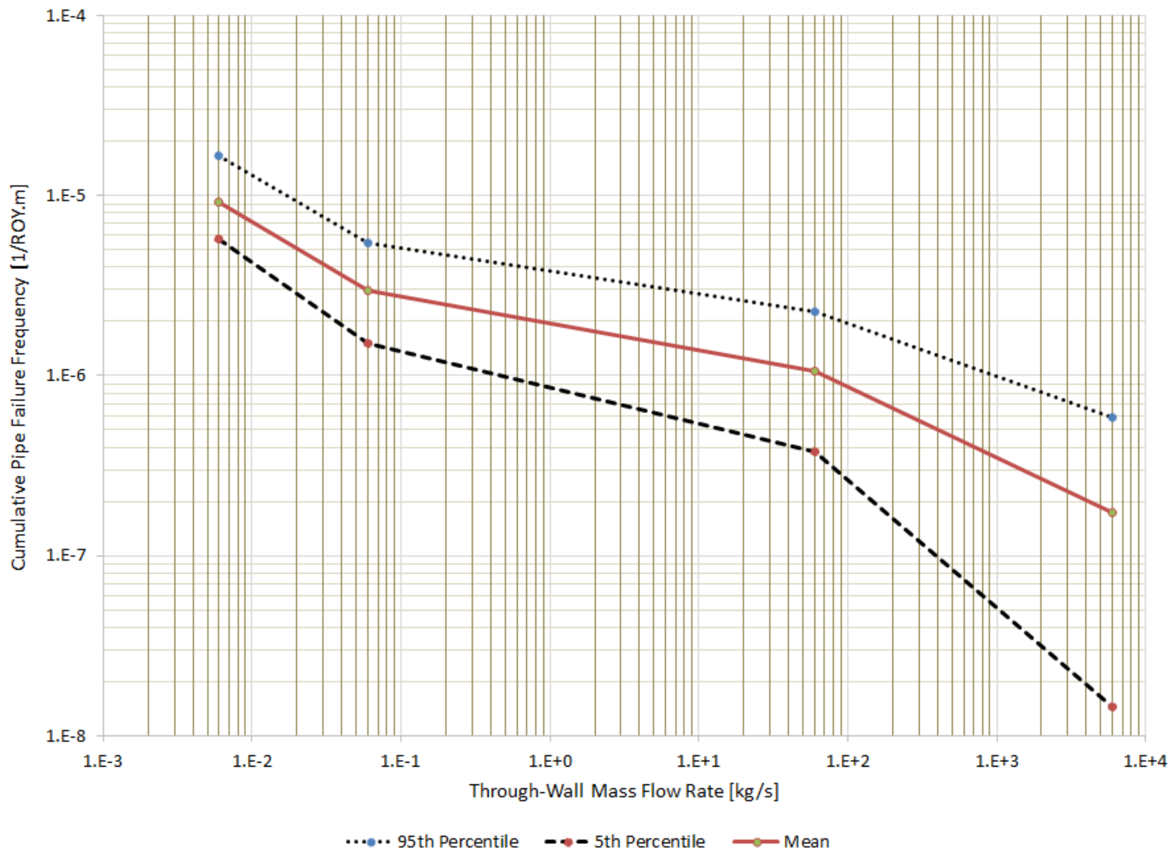
Figure 4.2. Environmental degradation mechanisms in CODAP



4.4. An application of CODAP

In preparing the topical report on below ground/buried pipe operating experience (NEA, 2018a) a data analysis was performed in order to estimate the frequency of buried pipe failure as a function of the through-wall mass flow rate resulting from corrosion or external impact. Sufficient operating experience exists to apply a statistical model to the pipe failure rate estimation task. The results of the analysis are reproduced in Figure 4.3. Two sources of uncertainty were accounted for in the analysis: 1) uncertainty in the state of knowledge about piping system failure rates before and independent of the application of the below ground operating experience data, and 2) uncertainty in the below ground piping population data (i.e. length of piping, which varies across the plant population).

Figure 4.3. Belowground service water pipe failure rates



5. Topical reports

Two topical reports were prepared during the third phase of CODAP. The topical reports summarise the results of data analyses performed by the project participants. The reports are intended as technical bases for future database application projects and in-depth studies of selected degradation mechanisms.

5.1. Review of the post-1998 thermal fatigue experience

On 8-11 June 1998, the Institute of Radiation Protection and Nuclear Safety (IRSN) hosted the "Specialist Meeting on Experience with Thermal Fatigue in LWR Piping by Mixing and Stratification" (NEA, 1998). This meeting was prompted by numerous significant operational events during the 1980s and 1990s, the lessons learnt from the root cause evaluations and the related R&D to improve our understanding of the underlying thermal-hydraulic phenomena. The meeting was co-sponsored by the World Association of Nuclear Operators (WANO) and the NEA Working Group on Integrity and Ageing of Components and Structures (WGIAGE) of the CSNI.

In recognition of the scope of the 1998 workshop the CODAP-MB identified a need to update the thermal fatigue operating experience lessons learnt for the period 1998 to 2018 (NEA, 2022). The topical report summarises the many post-1998 regulatory and industry initiatives to address thermal fatigue management and mitigation.

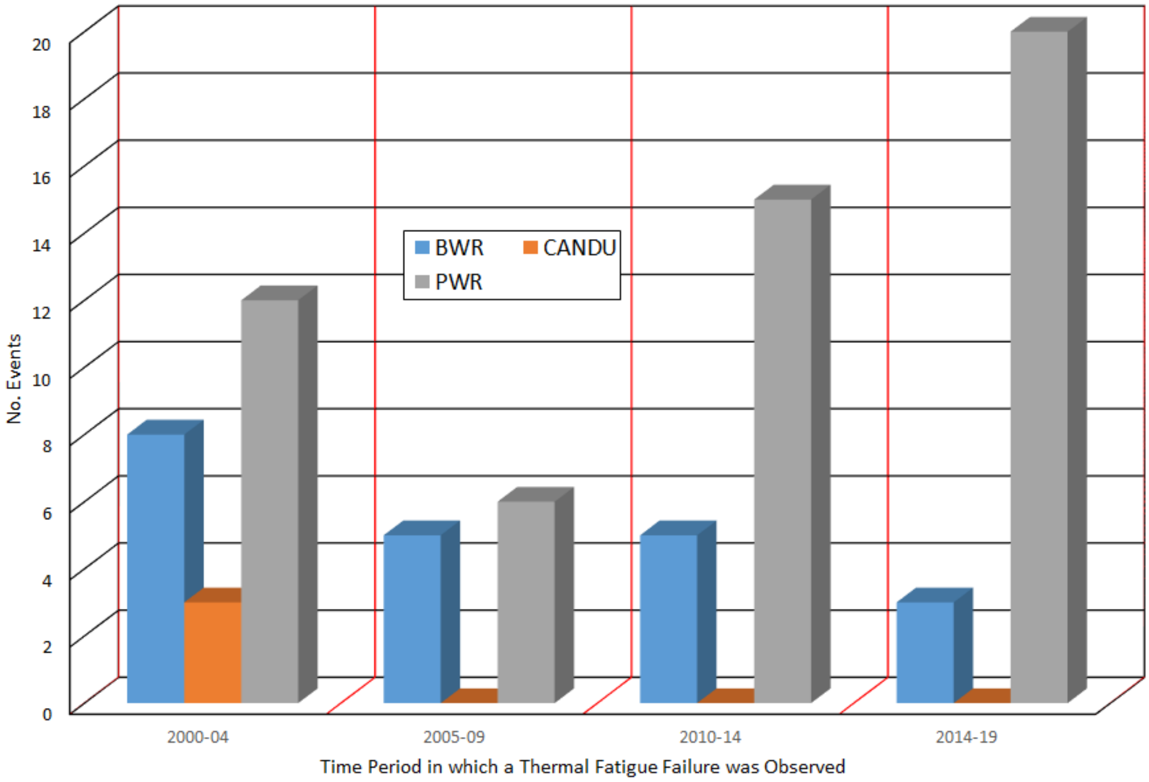
As an example of industry initiatives, the Electric Power Research Institute (EPRI), via its Materials Reliability Program (MRP), has developed thermal fatigue management guidelines, Table 5.1. After the publication of MRP-24 in 2001, additional testing and evaluations were done to better characterise thermal fatigue. In 2003, the Nuclear Energy Institute (NEI) issued NEI 03-08 to provide guidance on thermal fatigue management as implemented, MRP-146 for reactor coolant system branch lines and MRP-192 for residual heat removal system mixing tees. These NEI and MRP documents give recommendations for evaluating and inspecting regions where there may be potential for thermal fatigue cracking. MRP-146 provides a model for predicting and evaluating thermal cycling for PWR stagnant lines, which has been shown through benchmarking results to be effective in predicting the location of thermal cycling in lines attached to the RCS. In 2009, EPRI issued supplemental guidance to MRP-146 to provide a revised evaluation guidance for screened in branch piping.

Table 5.1. Selected EPRI MRP thermal fatigue R&D and guidelines

Document	Title	Year issued
MRP-23	NDE Technology for Detection of Thermal Fatigue Damage in Piping	2017 R2
MRP-24	Interim Thermal Fatigue Guideline	2001
MRP-25	Operating Experience Regarding Thermal Fatigue of Unisolable Piping Connected to PWR Reactor Coolant Systems	2000
MRP-81	Interim Report on Thermal Cycling Model Development for Representative Unisolable Piping Configurations	2002
MRP-83	Lessons Learned from PWR Thermal Fatigue Management Training	2002
MRP-85	Operating Experience Regarding Thermal Fatigue of Piping Connected to PWR Reactor Coolant Systems." The report includes results of a survey conducted of BWR plants to test the prior assumption that thermal fatigue cracking is less of a concern than in PWRs. Thermal fatigue operating experience in CANDU plants has been included as well.	2018 R2
MRP-132	Thermal Cycling Screening and Evaluation Model for Normally Stagnant Non-Isolable Reactor Coolant Branch Line Piping With a Generic Application Assessment	2004
MRP-146	Cyclic Stratification in Non-isolable Reactor Coolant System Branch Lines	2016 R2
MRP-146S	Management of Thermal Fatigue in Normally Stagnant Non-Isolable Reactor Coolant System Branch Lines -Supplemental Guidance	2008
MRP-192	Assessment of Residual Heat Removal Thermal Mixing Tee Thermal Fatigue in PWR Plants	2018 R3
MRP-275	MRP-146/146S Implementation Survey Summary	2010
MRP-409	EdF Assessment of US Thermal Fatigue Management and Operating Experience and Development of Recommendations for Guideline Improvement	2016

A summary of the thermal fatigue OPEX is provided in Figure 5-1. There is an uptick in the PWR-specific thermal fatigue incident rate. However, many of the more recent events do not involve through-wall leakage. This means that non-destructive examination has been effective in detecting flaws before leakage occurs.

Figure 5.1. The post-1998 thermal fatigue operating experience



5.2. Material degradation in periods of extended and long-term operation

During its April 2019 Working Group Meeting, the CODAP Management Board decided to pursue an evaluation of material degradation OPEX during periods of extended operation (PEO) and long-term operation (LTO) (NEA, forthcoming). A five-step approach was used to reach insights on material degradation during PEO/LTO:

- STEP 1. In 2015 the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) of the Committee on the Safety of Nuclear Installations (CSNI) published the results of a "Questionnaire on Long-Term Operation of Commercial Nuclear Power Plants" (NEA, 2015). In preparing this report a comparison was made between the content of the CODAP event database and the results of the WGIAGE questionnaire. This step was taken to identify possible gaps in the scope and content of CODAP.
- STEP 2. A review of the results of two expert panels on potential material degradation issues during PEO/LTO. The subject expert panels were convened by the Office of Nuclear Regulatory Research of the US Nuclear Regulatory Commission. The Proactive Material Degradation Assessment Expert Panel (PMDA; 2004 to 2006) identified the material degradation scenarios that could affect plant systems for up to 40 years of operation, and the Expanded Material Degradation Assessment Expert Panel (EMDA; 2012 to 2014) extended the analysis time frame from 40 years to 80 years. In preparing the topical report a comparison was made between the CODAP event database and the results of the two expert panels.
- STEP 3. In 2019, the US Nuclear Regulatory Commission (NRC) organised an international workshop on age-related degradation of reactor vessels and internals. During this workshop,

the participating organisations were invited to summarise the country-specific state of knowledge, ongoing research and associated operating experience. The workshop information (NRC, 2020) was used to complement the overviews of PEO/LTO material degradation issues in the topical report.

- STEP 4. Review of the material degradation issues as recorded in the CODAP event database. This review included selected reactor vessel internals and safety-related and non-safety-related piping system components.
- STEP 5. Formulation of a synthesis of the PEO/LTO material degradation insights based on the results of Steps 1 through 4. Because of the different plant licensing regimes among CODAP's 13 participating countries, this report considers OPEX from plants that have been in operation for more than 25 years.

The PEO/LTO piping material degradation and failure OPEX is shown in Figures 5.2 and 5.3. The observations of the topical report were as follows:

- The long-term effectiveness of the various degradation mitigation strategies does warrant a continued and systematic OPEX data evaluation effort.
- The impact of environmental effects on fatigue is a research area that continues to receive significant attention. The related OPEX is sparse, however. The continued OPEX data mining efforts would be of significant value in supporting the future research activities.
- Considerable R&D has been directed to furthering the thermal ageing embrittlement (TAE) of cast austenitic stainless steel (CASS) knowledge base, including mechanical testing of CASS components that have been removed from service. As of yet, no TAE failures have been reported.
- The technical and programmatic processes that have been implemented to address stress corrosion cracking (SCC) problems appear to be effective. In comparison with the SCC OPEX during the first 25 years of plant operation, a significantly lower SCC incident rate is noted for plants in PEO/LTO.
- Major piping pressure boundary failures attributed to flow-accelerated corrosion (FAC) are relatively rare events. This is attributed to steps taken to implement effective secondary-side chemistry control (in PWRs), proactive piping replacements using FAC-resistant materials, and implementation of plant-specific FAC monitoring programmes. It is noteworthy that the VVER-specific FAC experience appears to be different from that of PWR plants. There appears to be a "gap" between the CODAP event database content with respect to FAC in VVER plants and the ranking assigned this material degradation mechanism in the WGIAGE questionnaire.
- Corrosion in safety-related raw water-cooling system piping and fire water system piping poses unique ageing management challenges. Applications of non-metallic materials, advanced metallic materials and composite repair technology are receiving increased attention in mitigating corrosion effects on piping pressure boundary integrity.
- The scope of CODAP was expanded in 2011 to include material degradation affecting reactor internals. The OPEX on reactor internals in CODAP is currently limited to selected representative events, however.

Figure 5.2. Piping OPEX as a function of plant age

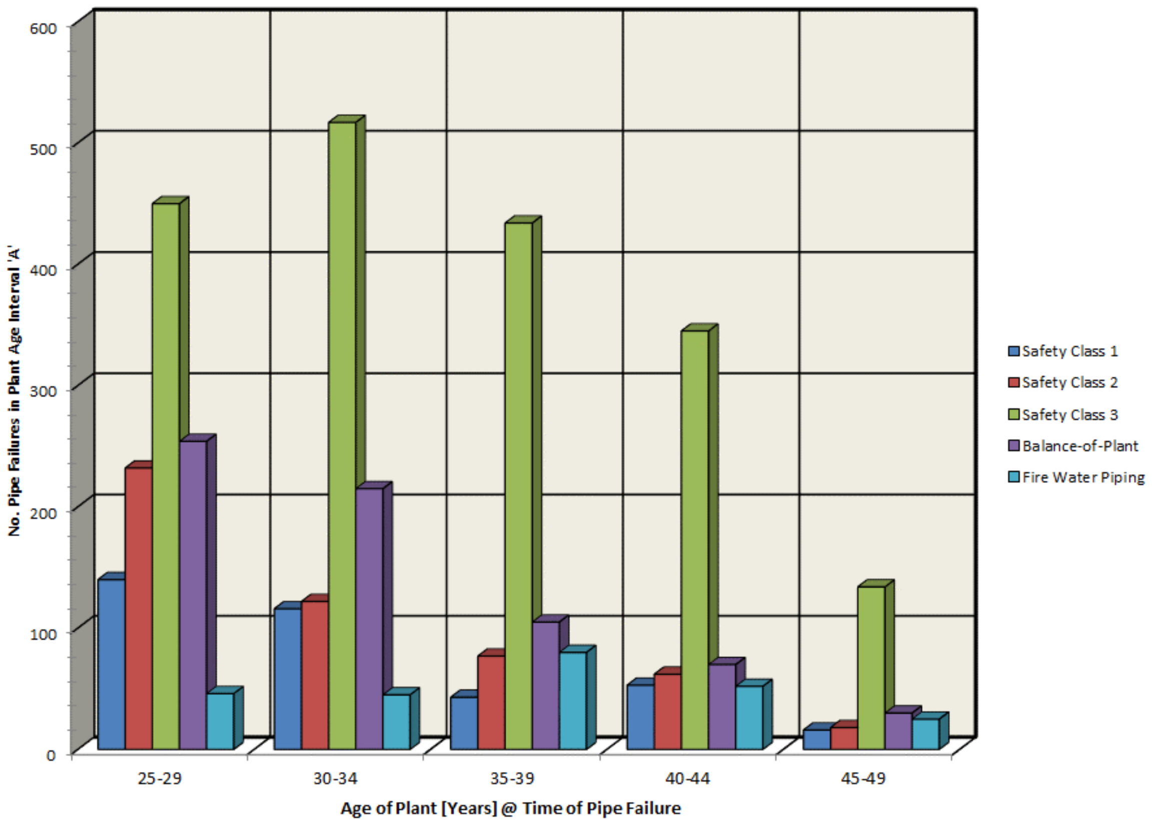
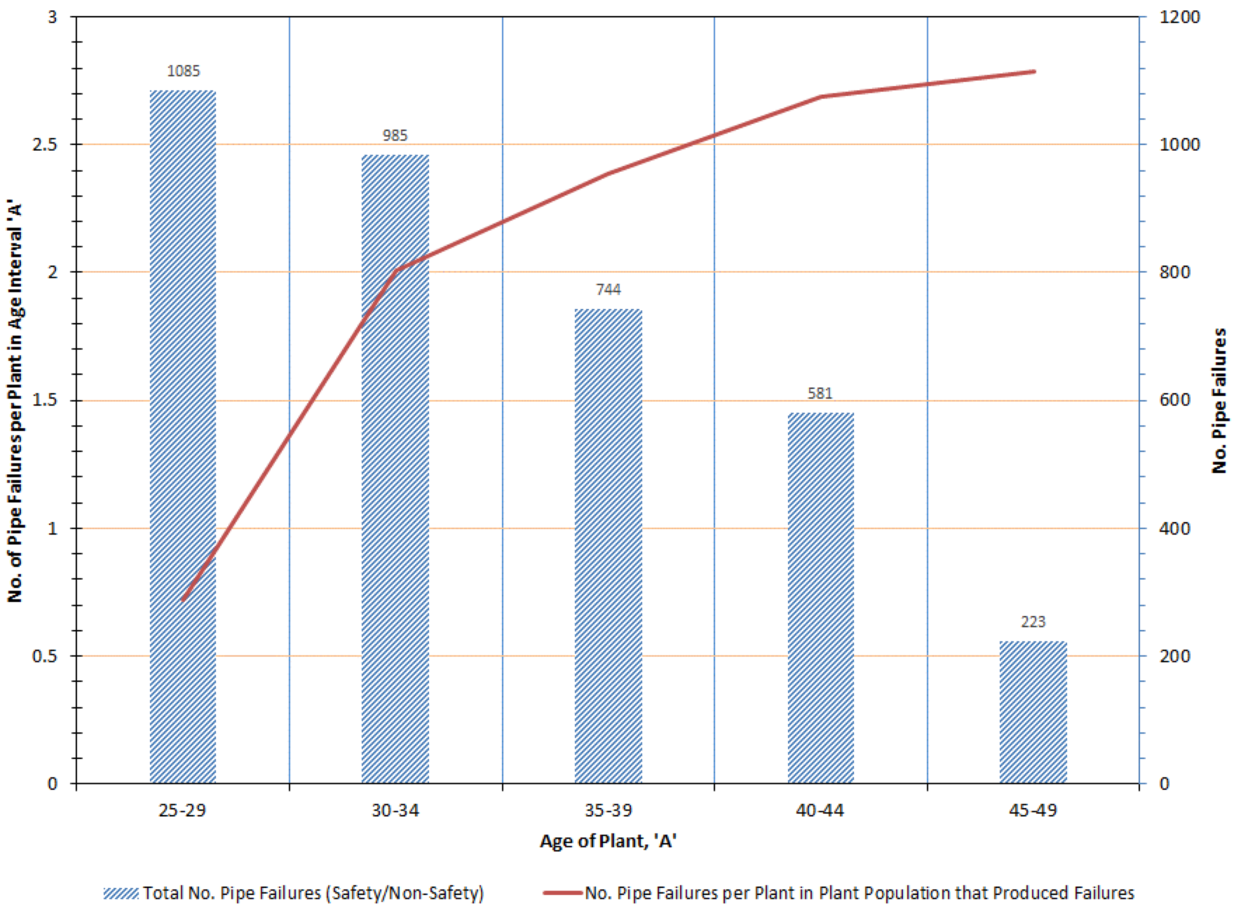


Figure 5.3. Pipe failure rate as a function of plant age



6. Conclusions and recommendations

The third phase of CODAP began on 1 January 2018 with 13 NEA member countries agreeing to exchange metallic passive component failure data. After a three-year absence, Finland re-joined the project. The Netherlands joined the project as a newcomer. Based on the accomplishments of Phase III, summarised below are the conclusions and recommendations of the CODAP Management Board.

6.1. Status of the data exchange effort and Coding Guideline

Data collection and data exchange for metallic passive component types continued as part of the general CODAP operation. The data collection effort for "new" component types (e.g. HDPE/non-metallic piping, Alloy 690/800 steam generator tubes, and reactor internals) was initiated. The Korean experience with fire water system HDPE piping as well as the recent (2017 to 2020) German experience with Alloy 800 steam generator tubes are included in the database. Some PWR plants have experienced wear of the thermal sleeve in the control rod drive mechanism (CRDM) vessel head penetration tubes, which have impaired control rod drive movement. The database includes examples of such operating experience gained in France, Korea, South Africa, Chinese Taipei and the United States.

Data submissions to the project decreased significantly, underlining the need to improve national efforts to collect and code data on passive component material degradation and failures for inclusion in CODAP. Changing this trend will be an opportunity to improve the data collection procedures and process.

The Coding Guideline has been summarised in a Topical Report (NEA, 2018b). The guideline reflects the current state of knowledge with respect to material degradation. New component types are added when there is interest from a participating country. As data collection continues, new needs and interests may arise to further develop the coding guideline.

6.2. Conclusions

The objectives of Phase III of CODAP were to:

- Continue to collect and analyse information on passive metallic component degradation and failures to promote a better understanding of underlying causes, the impact on operations and safety, and prevention.
- Analyse the information collected in the event database to develop topical reports on degradation mechanisms. Objectives and schedules for the topical reports are developed for each calendar year of the project's operation. CODAP will actively seek technical input from the OECD/NEA CSNI Working Group on Integrity and Ageing of Components and Structures (WGIAGE). In addition,

the Project Review Group will communicate and co-ordinate as needed with WGIAGE concerning technical matters of mutual interest.

- Develop and implement an enhanced web-based event database that supports the creation of standard and custom reports on certain aspects of the database content. Building on the experience with the existing web-based event database, the new development will address user-friendliness, improved database structure, analysis tools that enable advanced statistical analyses of the database content, and enhanced data visualisation.
- Provide ageing management programme support that addresses current operability determination practices, performance of new materials in the field, and commendable practices of licence renewal and long-term operation.
- Facilitate the exchange of existing and future information among the participating organisations to improve the quality of decisions made about components material degradation, ageing management and operability determination. The CODAP database, along with other relevant information collected, will be used for applications of service experience data with an emphasis on observed trends and patterns, past and current degradation mechanism mitigation practices, and risk characterisation of passive component failure events.

These objectives were largely met. While an effort was made to reach a consensus on a new software specification, the actual programming effort was deferred to Phase IV of the project. A goal for the fourth term (2021-2023) of the project is to implement operating procedures and processes whereby future national data submissions are commensurate with the number of operating reactors. Furthermore, database applications will be pursued to investigate the correlations between reported degradation and failure events versus piping system design modifications, degradation mitigation practices and NDE qualification.

It is equally important to implement a process to capture legacy information concerning significant events. In the context of CODAP, the term “significant” implies both significant unexpected structural degradation or failure, and events that have prompted significant regulatory action. Database completeness strongly affects the ability to perform database applications.

The CODAP-MB prepared “Terms and Conditions” for the fourth phase (2021-2023) of CODAP. The fourth term of the project places an emphasis on two aspects of operating experience data exchange and analysis. First, to encourage active data submissions by the MB membership, an improved web-based database structure will be implemented. Second, continued database applications will be pursued through a programme to develop topical reports and CODAP software applications. Efforts are in progress to recruit additional participating countries to the project.

6.3. Recommendations for Phase IV

The Management Board recognises that there are a multitude of future potential challenges concerning the response to environmental degradation of passive components in heavy water and light water reactor operating environments. It is important to ensure that the almost five decades of insights from operating experience be preserved and made readily available to future generations of material scientists, structural engineers and PSA engineers. It is equally important to add new events to the database to ensure that the database content is up to date. Since CODAP was established in 2002, the issue of an equitable data exchange among participating organisations has been at the forefront of the annual work planning activity. The project still faces challenges in ensuring submittals of data representative of the multi-faceted material degradation issues that arise in any given calendar year. The CODAP-MB's plans for Phase IV are as follows:

- Each participating project member will identify the current national routines for recording and submitting information on material degradation issues, including access to OPEX data.
- Each participating project member will report on the current national regulatory and industry routines/practices and requirements for performing operability determinations or fitness for service assessments. In particular, the question of how such evaluations could provide relevant OPEX data for submission to CODAP should be elaborated.
- The CODAP-MB has devised the term "selected representative event" (SRE) as a means for simplifying data entry. However, it has promoted an ad hoc approach as opposed to systematic approach to the exchange of reactor internals OPEX. Therefore, the MB members will recommend a list of BWR, PWR, PHWR and WWER reactor internals' parts and develop a plan for how to conduct the future reactor internals' OPEX exchange.

In planning for activities beyond 2020, questions concerning the effectiveness of degradation mitigation processes and NDE continue to be recognised as important. The CODAP event database will remain an important resource in monitoring trends in material degradation. In 2014 the CSNI Project Review Group recommended that CODAP implement operating procedures and processes whereby future national data submissions are commensurate with the number of operating reactors. It remains a challenge to achieve a more equitable data exchange, however.

The CODAP-MB will contemplate procedural changes to ensure that CODAP can sustain its ability to actively track long-term material performance. Thus, the CODAP-MB will consider the following activities in Phase IV:

- In recognition of the importance of long-term environmental effects on reactor pressure vessels and reactor internals material integrity, the project is actively collecting relevant operating experience data. However, there are challenges in obtaining and evaluating relevant OPEX. Mainly this is due to two factors: a) reactor internals' material flaws discovered during in-service inspections are typically not documented per abnormal occurrence or licensee event reporting routines; and b) associated flaw evaluation reports and NDE results tend to be classified as restricted or proprietary information. Gaining access to information not readily available to the CODAP national co-ordinators would help improve the volume and quality of data on reactor internals' OPEX. For CODAP to gain access to material degradation data on reactor internals it would require a planning effort with the possible assistance from WGIAGE, regulatory agencies, technical support organisations and industry.
- Collecting and analysing material degradation data is technically challenging and resource intensive but also rewarding. Continuing with the improvement process for the CODAP event database infrastructure could be key to instilling

a deeper interest in and committing adequate resources to the continued data exchange. Plans are in place for software upgrades to be developed and implemented in the near term. The CODAP-MB will prioritise software development to improve the functionality of the CODAP database website.

- The role of an OPEX database such as CODAP is to support applications. The project will continue to promote practical applications of the database, in particular as:

  1. An information tool for regulatory site inspectors to help identify relevant material degradation scenarios at plants of similar or like designs;
  2. An information tool for evaluating the effectiveness of in-service inspection programmes and technologies;
  3. An information tool for evaluating the effectiveness of ageing management programmes; and
  4. An operating experience data source for structural reliability analysis (e.g. PFM) and PSA.

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Appendix A. Activity report of the CODAP Management Board

A.1 CODAP working group meetings

During Phase III (2018-2020) of CODAP, the Management Board met on six (6) occasions per Table A.1. CODAP16 was hosted by STUK in Helsinki, Finland. At the invitation of TVO, this meeting included a 1-day field trip to the Olkiluoto Unit 3 (OL3) Nuclear Power Plant. CODAP18 was hosted by the CSN in Madrid, Spain. At the invitation of Technatom, this meeting included a 1-day field trip to the Technatom NDT Centre in San Sebastián de los Reyes.

Table A.1. Working Group Meetings 2011-2020

Meeting	Location	Date(s)
	Phase I (2011-2014)	
CODAP01, Phase I Kick-off Meeting	OECD Conference Centre; Paris	18-19 May 2011
CODAP02	NEA Headquarters; Issy-les-Moulineaux	8-9 November 2011
CODAP03	OECD Conference Centre; Paris	29-30 May 2012
CODAP04	OECD Conference Centre; Paris	11-12 December 2012
CODAP05	OECD Conference Centre; Paris	30-31 May 2013
CODAP06	OECD Conference Centre; Paris	6-7 November 2013
CODAP07	OECD Conference Centre; Paris	14-15 May 2014
CODAP08	NEA Headquarters; Issy-les-Moulineaux	9-10 December 2014
	Phase II (2015-2017)	
CODAP09, Phase II Kick-off Meeting	NEA Headquarters; Issy-les-Moulineaux	11 December 2014
CODAP10	NEA Headquarters; Issy-les-Moulineaux	5-6 May 2015
CODAP11	OECD Conference Centre; Paris	23-24 February 2016
CODAP12	Seoul, Korea; Meeting hosted by KINS	10-11 October 2016
CODAP13	Cologne, Germany; Meeting hosted by GRS	3-4 May 2017
CODAP14	NEA Headquarters; Boulogne-Billancourt	3-4 October 2017
	Phase III (2018-2020)	
CODAP15, Phase III Kick-off Meeting	NEA Headquarters; Boulogne-Billancourt	23-25 April 2018
CODAP16	Helsinki, Finland Meeting hosted by STUK	4-6 September 2018
CODAP17	NEA Headquarters; Boulogne-Billancourt	16-17 April 2019
CODAP18	Madrid, Spain Meeting hosted by CSN	24-26 September 2019
CODAP19	WebEx – Virtual Meeting	7 May 2020
CODAP20	WebEx – Virtual Meeting	29-30 September 2020

A.2 CODAP topical reports

Two topical reports were prepared during Phase III of the project. These reports represent CODAP event database insights reports intended to serve as a basis for future database application projects including in-depth studies of selected degradation mechanisms.

- **NEA/CSNI/R(2019)13**. "A Review of the Post-1998 Experience with Thermal Fatigue in Heavy Water and Light Water Reactor Piping Components."
- **NEA No. 7614**. A Review of Operating Experience Involving Passive Component Material Degradation in Periods of Extended/Long Term Operation. This report was finalised in November 2020 and submitted to the CSNI-PRG for final review.

A.3 Mini-workshop on database applications

The format for the mini-workshop on 24 April 2018 was a roundtable discussion, which addressed the following questions:

1. How is information about CODAP (the database, topical reports, PRG meeting agendas and minutes) distributed and/or communicated within your own organisation, your Technical Support Organisation(s) and licensees?
2. How many individuals and/or departments within your organisation have direct access to the CODAP event database? Have you arranged such access to CODAP to any other organisations?
3. Have you offered, or do you intend to offer training in how to utilise CODAP? If training has been offered, what feedback can you give?
4. Provide a summary of recent database applications. If "none", explain why?
5. Periodically the Operating Agent distributes an Excel-file with a listing of "Events of Potential Interest." Are you reviewing and responding to the information contained in this Excel-file? In other words, does the Excel-file compel you to exchange new event information with fellow PRG Members? Do you think that the events of your country could be added to CODAP database during Phase III?
6. Topical Reports. What are the benefits of producing these reports? Have you or your organisation in any way benefitted from these topical reports? If beneficial, what new topics should be considered during Phase III of the project?
7. CODAP has a strong US bias in terms of the number of events in the database and also in terms of number of submittals made on a year-on-year basis. Why is this so? Could you please explain possible limitations on reporting of events to the CODAP database in your country? Do you have a national procedure for how to make submittals to CODAP? If the US "domination" is considered to be an important issue, in what ways would you or your organisation be willing to ensure a more equitable sharing of information?
8. Other databases or operating experience exchange platforms. Please share with CODAP how you are obtaining operating experience data of direct relevance to your national nuclear power programme.
9. What are the compelling reasons (if any) to encourage PSA analysts to gain access to the database? Have you obtained requests from PSA analysts within your organisation?

10. In your opinion, does CODAP provide a reasonably complete set of information regarding material degradation? What measures of "completeness" should guide the continued database development and database maintenance?

Part II – Roundtable discussion

The objective of the roundtable discussion was to summarise the country-specific presentations and with a focus of expectations with respect to database content, completeness and equitable sharing of operating experience going forward. The roundtable discussion addressed software issues and how to ensure the ongoing programming effort addresses user interface issues.

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