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Operating Experience Insights into Below Ground Piping at Nuclear Power Plants

A Topical Report by the NEA Component Operational Experience, Degradation and Ageing Programme

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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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

ACCA	Alternating current coating attenuation survey
ACVG	Alternating current voltage gradient survey
AEC	Atomic Energy Council (of Taiwan)
AFI	Area-for-improvement
AFWS	Auxiliary feedwater system
AMP	Ageing management programme
APEC	Area potential earth current survey
APR	Advanced power reactor
ASME	American Society of Mechanical Engineers
ASN	L'Autorité de Sûreté Nucléaire (Nuclear Safety Authority of France)
AUXC	Auxiliary cooling water
AWWA	American Water Works Association
BP	Buried piping
BPIG	Buried pipe issues group (of EPRI)
BR	Backing ring
BTP	Buried tanks and piping
BWP	Bar wrapped cylinder pipe
BWR	Boiling water reactor
CANDU	CANada Deuterium Uranium
CCS	Component cooling system
CE-OEF	Clearinghouse on operating experience feedback
CEP	Concrete encased piping
CFRP	Carbon fibre reinforced polymer
CIPP	Cured-in-place-pipe
CIPS	Close-interval potential survey
CODAP	Component Operational Experience, Degradation and Ageing Programme
COG	CANDU Owners Group

CP	Cathodic protection
CPS	Cathodic protection system
CRP	Conditional rupture probability
CSN	Consejo de Seguridad Nuclear (Nuclear Safety Council of Spain)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
CUI	Corrosion under insulation
CW	Circulating water
CWS	Circulating water system
DCVG	Direct current voltage gradient survey
DN	Diamètre nominale
DOE	United States Department of Energy
EBS	Equivalent break size
EBSC	Equivalent break size class
ECW	Emergency cooling water
EDF	Électricité de France
EDG	Emergency diesel generator
EMAT	Electromagnetic acoustic transducer
ENSI	Eidgenössische Nuklearsicherheitsinspektorat (Swiss Federal Nuclear Safety Inspectorate)
EPRI	Electric Power Research Institute (United States)
ESW	Essential (or Emergency) service water
FAC	Flow-accelerated corrosion
FPS	Fire protection water system
GALL	Generic ageing lessons learnt
GAO	Government Accountability Office (United States)
GPR	Ground-penetrating radar
GRP	Glass-reinforced plastic
GWT	Guided wave ultrasonic testing
HDPE	High density polyethylene
IA	Instrument air
IAGE	CSNI Working Group on Integrity and Ageing of Components and Structures (NEA)
ICES	INPO Consolidated Events Database
ICW	Intake cooling water

ID	Inside diameter
IGALL	International GALL
INPO	Institute of Nuclear Power Operations (United States)
ISI	In-service inspection
JRC	Joint Research Centre (of the European Commission)
KKG	Kernkraftwerk Gösgen (Gösgen Nuclear Power Plant, Switzerland)
KTA	Kerntechnische Ausschuss (Nuclear Safety Standards Commission)
KWO	Kernkraftwerk Obrigheim (Obrigheim Nuclear Power Plant, Germany)
LCO	Limiting condition for operation (according to Technical Specifications; also referred to as “Operational Limits and Conditions” (OLC))
LPSW	Low pressure service water
MFL	Magnetic flux leakage
MIC	Microbiologically influenced corrosion
NACE	National Association of Corrosion Engineers (United States)
NDE	Non-destructive examination
NDT	Non-destructive testing
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute (United States)
NFPA	National Fire Protection Association (United States)
NGS	Nuclear generating station
NPP	Nuclear power plant
NRA	Nuclear Regulation Authority (of Japan)
NRC	Nuclear Regulatory Commission (United States)
NSIAC	Nuclear Strategic Issues Advisory Committee of NEI
NSSS	Nuclear steam supply system
OAR	Owner activity report (per ASME Section XI)
OD	Outside diameter
OECD	Organisation for Economic Co-operation and Development
OPDE	NEA Pipe Failure Data Exchange
OPG	Ontario Power Generation (Canada)
PCC	Post Construction Committee (of the ASME, United States)
PCCP	Prestressed concrete cylindrical pipe

PCS	Power conversion system
PE	Polyethylene
PEO	Period of extended operation (e.g. in the United States PEO starts after 40 operation years)
PIG	Pipeline inspection gauge
PRG	Project Review Group (of NEA CODAP)
PS	Prestressed
PSA	Probabilistic safety assessment
PSR	Periodic safety review
PVC	Polyvinyl chloride
PWR	Pressurised water reactor
RAS	Reactor auxiliary system
RCA	Root cause analysis
RCP	Rapid crack propagation
RCCP	Reinforced concrete cylinder pipe
RF	Range factor
RHWG	Reactor Harmonisation Working Group (of the WENRA)
RIM	Reliability and integrity management
RI-ISI	Risk-informed ISI
ROY	Reactor operating year
RT	Radiographic testing[1]
S.A.	Service air
SCAP	Stress corrosion & cable ageing project
SEAS	Slovenské Elektrárne AS
SFC	Spent fuel cooling
S/G	Steam generator system (e.g. Blowdown)
SIR	Safety injection & recirculation
SLR	Subsequent licence renewal
SRM	Staff requirements memorandum
SVTI	Schweizerischer Verein für technische Inspektionen (Swiss Association for Technical Inspections, Switzerland)
SW	Service water
TS	Technical specification

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[1] Circulating Water System (intake/discharge) and cooling tower blowdown system.

UHS	Ultimate heat sink
UHSS	Ultimate heat sink system
UNS	Unabhängiges Notstandssystem (independent remote shutdown system)
UT	Ultrasonic testing
VT	Visual inspection technique
VVER	Water-water energetic reactor
WANO	World Association of Nuclear Operators
WENRA	Western European Nuclear Regulators Association
WGIAGE	Working Group on Ageing and Integrity of Components & Structures (NEA)

EXECUTIVE SUMMARY

Structural integrity of piping systems is important for safety and operability of nuclear plants. In recognition of this, information on degradation and failure of piping components and systems is collected and evaluated by regulatory agencies, international organisations and industry organisations worldwide. This information is often used to provide systematic feedback to reactor regulation and research and development programmes associated with non-destructive examination (NDE) technology, in-service inspection (ISI) programmes, leak-before-break evaluations, risk-informed ISI, and probabilistic safety assessment (PSA) applications.

Several NEA member countries have agreed to establish the Component Operational Experience, Degradation and Ageing Programme (CODAP) to encourage multilateral co-operation in the collection and analysis of data relating to degradation and failure of passive metallic components in commercial nuclear power plants. CODAP is the continuation of the 2002-2011 NEA Pipe Failure Data Exchange Project (OPDE) and 2006-2010 NEA Stress Corrosion Cracking and Cable Ageing project (SCAP). In December 2014, 11 countries (Canada, the Czech Republic, France, Germany, Japan, Korea, the Slovak Republic, Spain, Switzerland, the United States and Chinese Taipei) agreed to enter into an agreement for the CODAP 2nd Phase (2015-2017).

Since its inception in 2002, operating experience with below ground piping has been an intrinsic aspect of the technical scope of the CODAP event database project. Specifically, CODAP collects data on below ground piping failures with operational impacts as well as potential safety impacts. The category "below ground piping" includes: 1) buried piping (BP) in contact with soil; 2) buried piping encased in concrete; and 3) underground piping that is below grade but is contained within a tunnel or vault such that it is in contact with air and is located where access for inspection is restricted. The three types of below ground piping are exposed to different environments, they corrode by different mechanisms, and they are protected from corrosion differently. This fourth topical report documents the results of below ground piping operating experience evaluations performed by the CODAP Project Review Group (PRG).

The PRG identified on the order of 300 below ground pipe failures. It is important to recognise that not all below ground piping failures are considered. Typically, only failure events that have an impact on safety are reported to regulators and their technical support organisations. Of the total data subset, ca. 75% represents the United States operating experience. It is recognised that this 3:1 ratio is not a true reflection of the status of the below ground ageing management practices across the CODAP member countries but more a reflection of the generally greater accessibility to information about US events.

Based on the operating experience review, below ground service water system piping has produced the largest event population including several significant events with major operational impact. This system group includes non-safety-related and safety-related Service Water.

The amount and type of below ground piping systems vary significantly among nuclear power plants. As nuclear power plants age, their below ground piping systems tend to corrode, and since these systems are largely inaccessible, it can be challenging to determine their structural integrity. The report includes the results of a survey of below ground piping systems in CODAP member countries and notes some country-specific differences in the use and safety relevance of these types of systems.

With respect to the continued database development and maintenance (i.e. data submissions and validation), it is recommended that the following items be considered in the ongoing active data submission activities by the CODAP-PRG members as well as in the current programme for an enhanced version of the online database:

- Sharing metallic passive component operating experience insights in details during CODAP meetings and discussing effective means to share CODAP data analysis insights with the nuclear safety community.
- Expanding the sharing of operating experience data in CODAP meetings with presentations of national overviews of recent operational events, including the findings of root cause analyses: i.e. the technical as well as organisational factors contributing to material degradation and failures.
- Sharing insights from ageing management programme audits in the CODAP meetings with a focus on below ground piping, including the associated NDE experience.
- On the basis of the CODAP event database, considering the means to perform a risk categorisation of below ground piping systems, conditional on different degradation susceptibilities and different reliability and integrity management (RIM) strategies.

As a specific recommendation, an international benchmark exercise is proposed on the use of service experience data to quantify piping reliability parameters for input to a standard problem application (e.g. risk-informed operability determination). One possible first step could be to actively pursue the development of recommended guidelines for risk characterisation of below ground pipe failures.

1. INTRODUCTION

Since 2002, the NEA has operated an event database project that collects information on passive metallic component degradation and failures. The scope of the database includes primary system piping components, reactor pressure vessel internals ("reactor components"), main process and standby safety systems and support systems (i.e. ASME Code Class 1, 2 and 3, or equivalent) components, as well as non-safety-related (non-Code) components whose degradation or failure can have significant operational impact. With an initial focus on piping systems components (the NEA Piping Failure Data Exchange [OPDE] Project) the scope of the project in 2011 was expanded to also address the reactor pressure vessel and internals as well as certain other metallic passive components that are susceptible to damage or degradation. In recognition of the expanded scope, the Project Review Group (PRG) approved the transition of OPDE to a new, expanded Component Operational Experience, Degradation and Ageing Programme" (CODAP). The CODAP 2011-2014 and 2015-2017 work programmes include the preparation of topical reports to foster technical co-operation and to deepen the understanding of national differences in plant ageing management.

Apart from recognising the intrinsic value of exchanging operating experience data and related root cause analysis results and insights, an important motivation for supporting the international collaboration in 2002 was embedded in the then emerging trend towards risk-informed regulation, including risk-informed in-service inspection (RI-ISI). An area of specific interest at the time was concerned with the technical basis for performing pipe failure probability analysis in support of RI-ISI programme development. The potential synergies between a database such as CODAP and the development of statistical passive component reliability models have been explored in multiple database application projects[2]. The fourth CODAP topical report is concerned with operating experience with below ground piping systems. The report responds to a recommendation by the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) of the Committee on the Safety of Nuclear Installations (CSNI) to produce a "topical report on buried piping (BP) and tank events"; see page 37 of the report NEA/CSNI/R(2016)11 [1].

1.1. Background and related work

Nuclear power plants have extensive piping systems. Some of these piping systems are below ground and contained in pipe tunnels (culverts) or buried in soil or concrete[3]. cooling water (i.e. circulating water[4] and service water) is the most common process

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[2] Appendix A includes an OPDE/CODAP bibliography that identifies selected database applications that have been performed or sponsored by the OPDE/CODAP member organisations.

[3] The Western European Nuclear Regulators Association (WENRA) uses the term "concealed piping" to refer to piping that is buried in soil or concrete, cast in concrete, or is located in covered trenches.

[4] Also referred to as "intake cooling water" (ICW).

medium transported in below ground. Cooling water is generally taken from a lake, sea, or river and, except for a slight increase in temperature, is returned unchanged to the same body of water (also referred to as the ultimate heat sink, UHS). Generally, this water contains only naturally occurring, background levels of radioactive materials. Some below ground piping also transports smaller amounts of water that may contain slightly elevated levels of radioactive isotopes, most commonly tritium. A few below ground piping systems may contain materials other than water. Diesel fuel is the most significant of these materials. Other examples are service water (SW) chlorination and instrument air below ground piping systems.

At nuclear power plants, the below ground systems are comparable to those used in other industries such as public water supply and oil and gas transmission. Preventive measures are taken for piping that may corrode, such as coating piping with corrosion resistant material, use of quality backfill[5], cathodic protection, or replacing original carbon steel piping with corrosion resistant material. While below ground piping is normally reliable, damage to the corrosion resistant coatings can lead to impaired structural integrity and leaks.

As a result of internal and/or external corrosion, several leaks in below ground piping systems have occurred. These leaks in general have not created safety hazards at the plants because, in spite of the leak, the affected piping was still carrying more than enough water to cool the plant. While some of these leaks did introduce slightly elevated levels of radiation into the ground water, they did not result in the exposure of any member of the public or power plant employee to radiation beyond regulatory limits. As an example, in the United States, the Nuclear Regulatory Commission (NRC) and the nuclear power industry as a whole have been re-examining the issue of below ground piping systems to determine whether any changes are required in the current approach to the design, maintenance and inspection of inaccessible piping. Additional perspectives on below ground piping ageing management and operating experience can be obtained from:

- The NEA and its Working Group on Integrity and Ageing of Components and Structures (WGIAGE) of the CSNI: in 2016, the WGIAGE published its “Results of Questionnaire on Buried and Underground Tanks and Piping (BTP)” [1].
- The Reactor Harmonisation Working Group (RHWG) of the Western European Nuclear Regulators Association (WENRA) has issued the “Topical Peer Review 2017 Ageing Management Technical Specification for the National Assessment Reports” [2] [3] . Section 04 of the RHWG Technical Specification addresses “Concealed Pipework” and defines the structure and content for the national assessments of the ageing management of below ground piping.
- The International Atomic Energy Agency (IAEA): the agency has undertaken to develop a technical document on information regarding good practices for assessment and management of ageing related to below ground piping and tanks within a nuclear power plant [4].
- US Nuclear Regulatory Commission (NRC) below ground piping activities are documented at: www.nrc.gov/reactors/operating/ops-experience/buried-piping-activities.html

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5. The term “quality backfill” implies that the processes and materials used for backfill meet certain requirements for compaction and drainage.

- The US Department of Energy (DOE). The DOE “Light Water Reactor Sustainability Programme” addresses R&D to develop the scientific basis for understanding and predicting long-term environmental impacts on materials and to provide data and methods to assess the performance of systems, structures and components essential to sustained nuclear power plant operations. One area of research focuses on underground piping [5].
- The Nuclear Energy Institute (NEI). In April 2013, the NEI issued Revision 3 of its “Guideline for the Management of Underground Piping and Tank Integrity” [6]. This guideline describes the policy and practices that the US nuclear industry commits to follow in managing below ground piping and tanks. When originally approved in November 2009 as the “Buried Piping Integrity Programme” the scope was limited to piping that was in direct contact with the soil due to the inability to directly inspect this piping and due to the potential impact on the environment and public confidence if leakage occurred. However, additional operating experience showed that piping that is below grade and is not in direct contact with the soil and underground tanks can also degrade with potential adverse consequences. As a result, the “Underground Piping and Tanks Integrity Initiative” was developed to incorporate and expand upon the Buried Piping Integrity Initiative: its scope also includes selected below ground piping that is not in direct contact with the soil and specified underground tanks.
- NACE International (formerly the National Association of Corrosion Engineers). NACE is an international professional organisation devoted to corrosion prevention and control. Through its technical committees, NACE has developed state-of-the-art reports that address below ground piping systems in nuclear power plants (e.g. NACE SP0169-2007 [7] and NACE-41013 [8]). This organisation is in the process of developing a standard practice document on “External Cathodic Protection for Nuclear Power Plant Piping Systems”.
- In October 2014 the IAEA in co-operation with the Electric Power Research Institute (EPRI) organised the “Technical Meeting on Ageing Management of Buried and Underground Piping and Tanks for NPPs.” The technical presentations made at the meeting are available from the indicated web-site and include country-specific overviews of below ground piping ageing management and operating experience.
  www.iaea.org/NuclearPower/Meetings/2014/2014-10-13-10-15-TM-NPE.html

1.2 Objectives and scope

Since its inception in 2002, the OPDE/CODAP database project [9] [10] has collected operating experience data on below ground piping. As for OPDE, the scope of the CODAP event database is to collect, evaluate and exchange operating experience data on metallic passive components with potential plant safety impact as well as operational impact. In the database, the earliest recorded buried pipe failure event dates from April 1976 when a significant (ca. 3 kg/s) through-wall buried pipe leak developed in an SW system pipe line at a US boiling water reactor (BWR) plant. More recently, significant below ground pipe failure events have occurred in Spain (2004), the Czech Republic (2014), and the United States (2008, 2015, 2017); for details; see Section 4.3 of this report.

The scope of this report includes an assessment of CODAP database events related to below ground piping systems and their corrosion and ageing effects. Through an examination of the operating experience as recorded in the CODAP event database, the field experience with the different below ground piping systems is evaluated to draw qualitative and quantitative insights about the damage and degradation mechanisms that are unique to these piping systems. The specific objectives of this report are as follows:

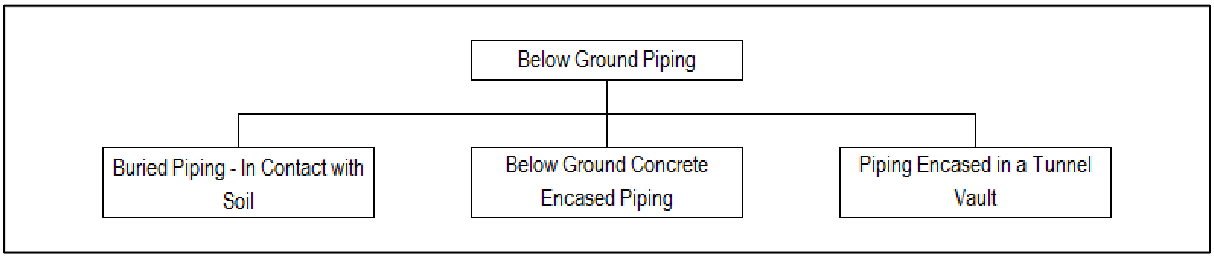
- Document the results of a survey of the different below ground piping systems at commercial nuclear power plants in the CODAP member countries.
- Based on the information stored in the CODAP event database, summarise the damage and degradation mechanisms that are unique to below ground piping systems. A comprehensive safety assessment of hazards of below ground piping involves the consideration of biological fouling (e.g. micro-organisms, seaweed, jellyfish), effects of floating debris on the water and effects of frazil ice and impurities (e.g. sand) in the cooling water.
- Document examples of country-specific operational events attributed to degraded or failed below ground piping systems.
- Determine the potential consequences of below ground piping leaks.
- Perform a below ground piping operating experience data evaluation. This evaluation will differentiate tritium-bearing systems from non-tritium-bearing systems.
- Summarise completed and ongoing activities to introduce corrosion resistant piping materials to resolve below ground carbon steel piping corrosion issues.
- Demonstrate how to use the below ground piping failure data in CODAP to draw qualitative and quantitative insights about structural reliability and integrity management.

As stated, the technical focus is on below ground plant process piping, i.e. piping systems that are required for the safe and reliable operation of a commercial nuclear power plant. Below ground potable water piping and sewage piping systems are excluded from consideration in this report.

1.3 Nomenclature

In this report, the term "below ground piping" is used collectively for three types of "concealed" piping systems that are located underground (Figure 1). Below ground piping includes buried piping (BP) that is in contact with soil or concrete, and piping that is below grade, but is contained within a tunnel vault (or culvert) such that it is in contact with air and is located where access for inspection is restricted. The three types of piping are exposed to different environments, they corrode by different mechanisms, and they are protected from corrosion differently.

Figure 1: The Different Types of Below Ground Piping



The term “access restriction” refers to the level of accessibility for non-destructive examination (NDE). Because of access restrictions, the condition assessment of below ground piping is based on in-line inspection using, for example, PIG (pipeline inspection gauge) inspection techniques or opportunistic inspection of excavated pipe. In-line inspection, robotic “crawlers” are used to assess complex below ground piping systems. These crawlers include electromagnetic acoustic transducer (EMAT) ultrasonic testing sensors to measure pipe wall thickness and locate corrosion damage.

In commercial nuclear power plants, the service water (SW) system provides cooling to various components while using the raw water from a nearby reservoir (e.g. river water, lake water, brackish water or sea water) as the heat transfer medium At many plants portions of the SW piping system is located below ground and in contact with soil or contained within a vault. It is an important support system that cools safety-related (i.e. ASME Code Section III Code Class 2 and 3) equipment and non-safety-related equipment [11] [12]. The detailed piping system design (including routing, material selection, number of main pipe header suction and discharge trains) tends to be highly plant-specific. Typically, the terms “essential service water” (ESW) or “emergency cooling water” (ECW) apply to that part of the system that is dedicated to the cooling of safety-related equipment such as Component Cooling Heat Exchangers, Residual Heat Removal Heat Exchangers, Emergency Core Cooling pump room coolers, etc. At some nuclear power plants the term “intake cooling water” (ICW) encompasses what at most other plants are the circulating water system (CWS) and the SW system[6].

1.4 Disclaimer

The CODAP Project places strong emphasis on data quality, including the completeness and comprehensiveness of recorded events. Data quality is achieved through a formal validation process as articulated in a Coding Guideline. The roles and responsibilities with respect to data submissions and data validation are defined in the CODAP Operating Procedures. This topical report is concerned with the below ground/BP operating experience including the international practice to detect and manage degradation of this category of plant process piping. The CODAP event database relies on information provided by respective PRG members[7].

The results of the data processing and analysis that are presented herein are based as much as possible on the results of root cause analyses. However, the writing team for this topical report has not performed any re-assessments of the findings related to the degraded below ground piping deficiencies as documented in the root cause analysis reports that are embedded in the CODAP event database.

The CODAP-PRG is fully aware of the fact that the full root cause analysis documentation as prepared by an owner/operator or its subject matter experts is not normally disseminated outside the industry and national regulators. The CODAP Coding Guideline includes instructions for what “root cause information” to include in the database. As a guiding principle, the instructions provided state that any relevant information on a cause-consequence relationship is to be included. Each respective

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[6] For example, this applies to some plants constructed in the United States.

[7] Details on the CODAP Project organisation, including data quality assurance and control are included in the project document library as itemised in Appendix A of this report.

National Coordinator assumes responsibility for the accuracy on the technical information that is input to the event database. Furthermore, the web-based database has provisions for uploading (or attaching) any available supporting information (e.g. laboratory reports, root cause analysis reports).

1.5 Report structure and reading guide

This topical report consists of six sections and three appendices. Section 2 includes a survey of below ground piping and the associated ageing management processes in CODAP member countries (Canada, Czech Republic, France, Germany, Japan, Korea, Slovak Republic, Spain, Switzerland, the United States and Chinese Taipei). Section 3 explains the reasons why below ground piping operating experience data is collected and analysed. Section 3 also addresses the potential safety significance of below ground piping failures. Section 4 summarises the country-specific operating experience, and includes a demonstration of an application of the below ground pipe failure data. The summary and conclusions are documented in Section 5. Finally, a list of references is provided in Section 6.

Appendix A is an OPDE/CODAP bibliography including references to database applications performed or sponsored by OPDE/CODAP member organisations since 2002. Appendix B is a nuclear plant system cross-reference table, which identifies selected national plant system designators. Appendix C is a glossary of terms.

2. BELOW GROUND PIPING AT NUCLEAR POWER PLANTS

Most, if not all, commercial nuclear power plants have extensive below ground piping systems that transport cooling water to and from the plant, fire protection system water, emergency diesel generator fuel oil, instrument air and water containing radioactive isotopes (e.g. tritium). The amount and type of below ground piping systems vary significantly among nuclear power plants. As nuclear power plants age, their below ground piping systems tend to corrode, and since these systems are largely inaccessible it can be challenging to determine their structural integrity. Section 2 documents the results of the survey of below ground piping systems in CODAP-PRG member countries. Also summarised are the relevant ageing management practices.

2.1 Survey of below ground piping systems

The different types of below ground piping systems, including material and design parameters are summarised in Reference [4]. In a survey performed by the CODAP-PRG (Table 1), some country-specific differences were noted in the use and safety relevance of these types of systems. The 11 respondents make reference to presence of below ground service water (SW) (or raw water cooling) piping. EPRI Report 1006994 [13] includes results from reviews of below ground service water (SW) piping at five US plants. The total length of buried piping (BP) referenced in the EPRI report ranged from 2 768 to 25 163 m. Another survey performed by EPRI [14] showed that buried SW piping ranges in diameter from 400 to 1 070 mm, and has uninterrupted total lengths of 30 to 1 524 m, with as few as 2 elbows to a maximum of 50 elbows. An example of plant-specific below ground SW piping weld populations is summarised in Table 2[8]. Internal linings of piping include coal-tar enamel, plastic and cement lining. Access to the piping typically is by inspection ports, valves, blind or open flanges, or a spool piece.

2.2 Below ground piping system design considerations

The most commonly used materials for below ground safety-related and non-safety-related piping in nuclear power plants are carbon steel and cast iron. In most nuclear power plants the carbon steel piping is normally coated (e.g. primer, coal-tar epoxy, cement) but may not be cathodically protected. Other material types in use include 300-Series stainless steels, titanium, copper alloys, aluminium and high-strength (6% Molybdenum) stainless steels [15] [16].The application of a primer to the exterior piping surface is intended to inhibit corrosion due to diffusion of water and/or salts.

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[8] A comprehensive survey (by system, pipe size, material and length) of plant-specific below ground piping systems is documented in the report, “Description of Embedded Piping, Penetrations, and Buried Pipe to Remain in Zion End State.” (https://adams.nrc.gov/wba/; Accession No. ML17208A116)

The typical in-service life of some coating materials is on the order of 30 to 40 years. Many older coatings are susceptible to biodegradation in service. Microbial attack can be seen, for example, in some polyvinyl chloride (PVC) coatings. While the polymer itself remains relatively inert due to its large molecular size, biological degradation of plasticisers used to make the material flexible can occur. Loss of plasticiser in older PVC tape coatings on pipelines has led to embrittlement and coating failure in service. In a related example, the adhesive used to affix polyethylene tape coatings to line pipe has been found to be a source of nutrients for microbial sulphate reduction in external corrosion sites. Biodegradation of adhesive may contribute to the loss of adhesion seen when these coatings are exposed to biologically active soils. Coating failures of this type block cathodic protection (CP) and have led to corrosion problems on piping.

Table 1: Below Ground Piping Systems in CODAP Member Countries

SYSTEM	CODAP Member Country																	
	CA	CH		CZ	DE		ES		FR	JP		KR		SK	TW		US	
	PHWR	BWR	PWR	VVER	BWR	PWR	BWR	PWR	PWR	BWR	PWR	PHWR	PWR	VVER	BWR	PWR	BWR	PWR
Auxiliary Feedwater	[1]					X		X	X									X
Auxiliary Steam					X	X	X		X				X				X	X
Boron Recycle													X					
Circulating Water (CW)	X			X	X	X	X	X	X	X	X	X	X	X	X		X	X
Component Cooling Water													X					
Condensate Storage & Transfer							X	X		X			X			X	X	
Containment Spray																	X	
Cooling Tower Blowdown				X	X	X	X							X			X	X
Demineralised Water	X					X	X	X	X	X		X	X			X		
EDG Cooling Water	X									X		X						
EDG Fuel Transfer	X					X	X	X	X	X		X	X		X	X	X	X
Emergency Core Cooling	X											X	X					
Emergency Service Water (2)	X	X			X	X						X						
Fire Protection	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
HPCS – High Pressure Core Spray							X										X	
HPSI – High Pressure Safety Injection																		X
Hydrogen Supply					X	X	X			X			X			X	X	X
Independent Remote Shutdown System (UNS) (4)					X	X												
Instrument Air	X						X	X	X			X	X			X	X	X
Liquid Waste	X							X	X			X	X				X	X
Lube Oil	X																X	X
Radwaste					X	X	X	X					X		X	X		
Offgas Holdup										X							X	
RCIC – Reactor Core Isolation Cooling							X										X	
Reactor Make-up Water																		
RWST – Refuelling Water								X					X					X
Reactor Water Cleanup Sludge Transfer																	X	

SYSTEM	CODAP Member Country																	
	CA	CH		CZ	DE		ES		FR	JP		KR		SK	TW		US	
	PHWR	BWR	PWR	VVER	BWR	PWR	BWR	PWR	PWR	BWR	PWR	PHWR	PWR	VVER	BWR	PWR	BWR	PWR
Reactor Water Cleanup (RWCU)																	X	
Service Air	X						X	X	X	X		X	X			X	X	
Service Gas (H2, N2, CO2)										X			X					
Service Water Chlorination										X							X	X
Service Water – Non-Safety-Related	X		X	X	X	X	X	X	X	X	X	X	X	X		X	X	X
Service Water – Safety Related	X		X	X (3)	X	X	X	X	X	X	X		X	X	X	X	X	X
Spent Fuel Cooling	X											X						
Steam Generator Blowdown	X											X	X					X
SUSAN (Mühleberg NPP) (5)		X																

Notes:

1. A blank cell = 'NO'
2. Also referred to as essential service water (ESW) or safety-related service water (ASME Code Class 3 or equivalent)
3. Buried ESW piping at the Dukovany site. No buried ESW piping at the Czech VVER1000 plants (i.e. Temelin Units 1 and 2)
4. The UNS building is connected to the Reactor Building via a below ground pipe tunnel, which contains service water system piping and low pressure injection system piping.
5. SUSAN = Selbstständiges, unabhängiges System zur Abfuhr der Nachzerfallswärme; a bunkered emergency building containing systems to ensure safe reactor shutdown and heat removal in case of extreme external events, including extreme weather related events. The Cooling Water System of SUSAN includes portions of piping located below ground.

Table 2: An Example of Aluminium-Bronze SW Piping Weld Populations at a Dual Unit PWR Site[9]

Pipe Diameter [DN]	Above Ground Service Water Piping	Below Ground Service Water Piping		
	No. Butt Welds with & w/o backing ring (BR)	No. Butt Welds w/BR	No. Butt Welds w/o BR	Total No. Below Ground Butt Welds
75	306	--	--	--
100	260	--	--	--
150	342	6	12	18
200	98	--	--	--
250	236	76	350	426
350	24	--	--	--
600	42	--	--	--
750	156	275	1 224	1 499
Total:	1 464	357	1 586	1 943
Notes:	• The use of a backing ring when welding aluminium-bronze piping results in the formation of a crevice that can give rise to a greater potential for weld cracks and selective leaching. • Without backing rings – there is less dilution and a longer cooling period in weld root pass which creates a more susceptible microstructure for selective leaching.			

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[9] Extracted from ADAMS Public Documents at https://adams.nrc.gov/wba/; accession no. ML17006A008.

2.3 Below ground piping degradation mechanisms

As stated in References [4] [17] [18] [19] [20], and as corroborated by the CODAP event database, degradation of below ground piping may occur from the inside and/or from the outside. Its origin may be linked to poor design, construction, maintenance or the internal or external environment of the buried pipe. The surveyed below ground piping systems transport diesel fuel oil, instrument air and water. For these systems, a predominant piping material degradation mechanism is corrosion (e.g. crevice corrosion, microbiologically influenced corrosion (MIC), coating degradation followed by external corrosion, pitting corrosion and galvanic corrosion). Other forms of potential degradation mechanisms include:

- Liquid droplet impingement
- Fatigue
- Settlement and soil displacement
- External erosion/wear

2.4 Method of detecting degradation

IAEA-NP-T-3.20 [4], the GALL Report [21] and NEI 09-14 [6] address inspection of below ground piping. The number of recommended inspections is a function of the importance of the pipe, the environment in which the pipe is located, the effectiveness of preventive actions (i.e. coatings, backfill, CP), and the corrosion resistance of the material from which the pipe is constructed. The need for inspections is significantly reduced when the piping is constructed from corrosion resistant material (e.g. non-metallic material such as high density polyethylene (HDPE) or high-strength stainless steel material). Maintenance and inspection periods of below ground/buried piping are dependent on the following:

- types of degradation mechanisms expected;
- operating experiences of below ground piping in similar locations;
- results on previous inspections of the piping.

Inspection options include indirect and direct examinations. Direct inspections include excavations, with subsequent non-destructive examination (NDE). Direct examinations yield quantitative wall thickness values that can be used to establish fitness-for-service. Indirect inspections include electrochemical and electromagnetic tests conducted on the surface of the ground above the pipe and guided wave inspections in which inspections of buried portions of a pipe are made using a transducer attached to an exposed section of pipe. Indirect inspections provide qualitative and semi-quantitative data that are not sufficient to support fitness-for-service evaluations but are useful in establishing appropriate locations for direct examinations.

In-line inspection, also referred to as pigging in the transmission (oil and gas) pipeline industry, is a means of placing an inspection tool inside a pipe so that an inspection can be made. This is done without stopping the flow. Inspection pigs are used to gather information about the pipe such as corrosion/metal loss, temperature and pressure. Two methods of inspection to detect corrosion/metal loss are used: 1) magnetic flux leakage (MFL) sends magnetic flux into the pipe walls for leak, corrosion and flaw detection, and 2) ultrasonic testing (UT) system sends ultrasonic sound wave echoes to determine pipe wall thickness

Some of the common methods for indirect inspections of pipelines in the oil and gas industry have been attempted in nuclear power plants. Indirect inspections are typically coupled with direct examinations to obtain conclusive information concerning the integrity of below ground piping. According to NACE-41013 [7] [22], examples of indirect inspection techniques include:

- Close-Interval Potential Survey (CIPS): CIPS is conducted using a voltmeter with one lead connected to the pipe to be inspected and the other to a reference electrode in contact with the soil directly above the pipe of interest. The principle of CIPS is to record the pipe-to-soil potential profile of a pipe over its entire length by measuring potentials at intervals that do not significantly exceed the depth of the pipe. Localised dips in the potential profiles (to less negative values) may indicate the presence of a poor quality coating.
- Direct Current Voltage Gradient Survey (DCVG): a DCVG is based on the concept that when DC voltage is applied to a pipe, a voltage gradient can be observed if the soil is adjacent to discontinuities in the coating. This voltage gradient is measured by two probes that are moved over the surface of the ground and over the pipe being examined.
- Alternating Current Voltage Gradient Survey (ACVG): an ACVG is similar in concept to a DCVG survey except that alternating current (AC) is used.
- Alternating Current Coating Attenuation Survey (ACCA): an ACCA survey is based on the concept that the application of AC to the pipe creates an electromagnetic field around the pipe. The field can be measured using a magnetometer: a change in the current flowing through the pipe affects the field strength and changes the reading of the magnetometer.
- Area Potential Earth Current Survey (APEC): this technique uses three reference electrodes to measure two individual pipe-to-soil potentials and two simultaneous earth current voltage gradients. The three electrodes are arranged in a 90° X-Y grid pattern of equal spacing to collect rectangular coordinate earth current voltage gradients that are then converted to polar coordinates representing each current vector directions and relative earth current magnitudes. Based on the vectors and magnitudes obtained from the converted and calculated earth current voltage gradients, active corrosion cells and pipe coating issues are identified.
- Guided Wave Ultrasonic Testing (GWT): the GWT technique uses ultrasound energy to locate changes in the pipe cross section area along a substantial length of piping from a single small excavation area.

Three forms of direct examinations are currently used: 1) excavation in conjunction with conventional NDE, 2) hydrostatic testing, and 3) internal (inside surface) inspections. IAEA-NP-T-3.20 [4] includes a detailed documentation of direct examination techniques.

ASME Section XI, Article IWA-5244 includes the requirements for visual inspection of buried components. Additionally, in the United States most plant owners have implemented NDE as part of their raw water piping integrity programmes (e.g. circulating water and SW piping). Moreover, periodic inspections are performed when components are excavated for maintenance or any other reason. In the United States, for plants receiving a renewal licence it is expected that an opportunistic inspection of BP will occur commencing 10 years prior to the period of extended operation (PEO). In other CODAP countries, the need for inspection results of below ground/buried piping should be assessed during the periodic safety review (PSR).

2.5 Repair/Replacement techniques

This section addresses repair and replacement techniques for below ground piping systems. Repair can be by a welding or non-welding technique that is applied to the external or internal pipe surface. For detailed technical information on below ground metallic piping repairs the reader is referred to ASME PCC-2-2015 “Repair of Pressure Equipment and Piping” [23] and the Pipeline Research Council’s “Pipeline Repair Manual” [24]. For detailed information on the repair of concrete reinforced below ground piping the reader is referred to Reference [25].

2.5.1 *Repair of below ground metallic piping*

Replacement of degraded sections of piping is the most expensive option to restore degraded below ground piping. With the same material, the original performance can be restored and improved performance can be achieved with the choice of a corrosion resistant material. The typical approach to pipe replacement is to cut out the corroded segment of the pipe and put in a new piece. The key precaution to be exercised in this case is to isolate the water inside the pipe before draining and cutting the pipe. In order to maintain the flow of the pipe, a bypass pipe can selectively be installed before replacement without shutting down the system operation. When using this type of repair, the relevant code used during the design and construction of the plant, must be satisfied. Generally, ASME Section III is applied for the safety class piping and ASME B31.1 (Power Piping) [26] is applied for non-safety class piping, while Standard AWWA C604-06 [27] is applied for the general industrial piping. There are two approaches to repairing a buried metal pipe; welded and non-welded metallic buried pipe repair techniques are listed in Table 3.

Table 3: Metallic Buried Pipe Repair Techniques

Welded Repair	Non-Welded Repair
- Pipe Replacement - Fillet Welded Patch - External Weld Overlay - Structural Inlays - Corrosion Resistant Cladding - Butt-Welded Insert Plates - Welded Sleeve - Leak Box - Peening and Welding - Pipe Cap	- Inverted Liner / Cured-In-Place Pipe (CIPP) Liner - Slip Lining - Mechanical Clamp - Threaded Repair - Leak Strap - Wrap Repair - Sprayed or Brushed Linings

2.5.1.1 *Welded repair of metallic buried piping*

(1) Welded Patch

The repair of a pin-hole leak can be made by applying a fillet-type welded patch or pipe cap to the thinned wall or otherwise degraded area. The patch material must be equivalent or superior to the material of the affected pipe section, and fabricated to match the configuration of the pipe where the repair is to be applied. The welded patch shall be able to maintain the design pressure and its design life has to be selected in consideration of the environment where the stagnant water between the patch and pipe may accelerate the crevice corrosion.

(2) External Weld Overlay

The overlay technique is used to deposit weld reinforcement on the outer wall of a locally corroded or eroded section of the pipe and has proven to be effective in repairing cracks as well. The overlay technique can be focused on the specific area degraded due to pitting or microbiologically influenced corrosion and a localised surface of the pipe to repair single or multiple defects.

(3) Structural Inlay

A structural inlay is used to address the loss of pipe wall thickness caused by diverse degradation mechanisms including general corrosion. The oxide layer or other surface contamination of the pipe must be removed before the application of the inlay. In most cases, the same type of metal as the base metal is used for the structural inlay, but improved metal can also be applied to enhance the corrosion or degradation resistance of the pipe. The location of its application must be carefully selected to prevent the creation of a corrosion cell, which can accelerate the damage in the surrounding areas.

(4) Corrosion Resistant Cladding

Corrosion resistant cladding is effective in preventing corrosion in the sensitive sections of the piping system. Clad pipe can be the initial choice of installation and it is also possible to apply cladding to a specific section of the pipe after installation. The corrosion resistant layer can be added to the surface of the pipe after installation through welding, or corrosion resistant piping can be manufactured using roll bonding or explosive bonding technologies.

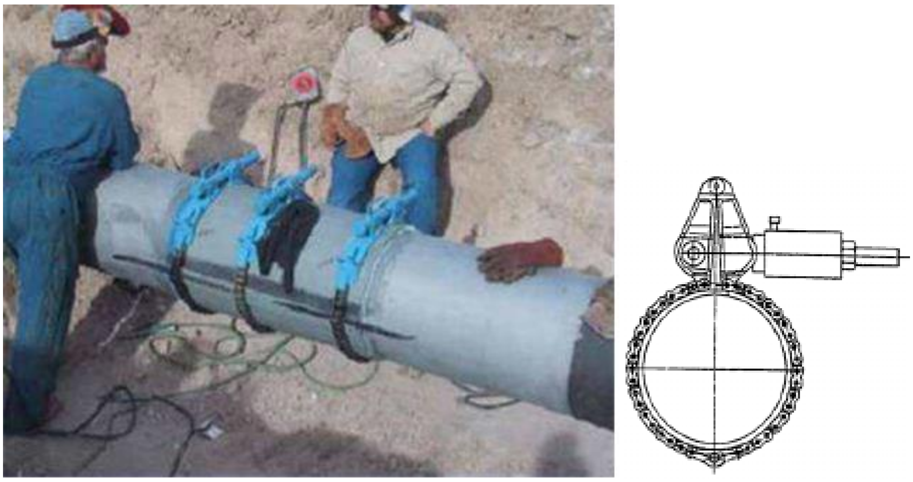
(5) Butt-Welded Insert Plate

The repair of a degraded pipe by butt-welded insert plates involves the replacement of pressure boundary material with an insert plate attached by full penetration butt welds[10]. This technique is mostly applicable to the large bore pipes because it is difficult to bend or align the small insert plate for flush butt welding. An application to small bore pipes is possible but with some limitations. Per ASME PCC-2-2015 [23], when applying this repair method, consideration shall be given to compatibility of materials, operating conditions for the intended life of the component, fitting and welding to minimise the residual stresses and distortions, and any limitations on non-destructive examination (NDE) and pressure testing.

(6) Weld Sleeve

The wrap-around weld reinforcement sleeve is manufactured as a cylindrical shell that fits the section of the pipe to be repaired and a pair of those sleeves is welded along the longitudinal joint. Figure 2 shows an example of a welded sleeve [24]. A sleeve of material ‘Type A’ is welded in the longitudinal direction and not along the circumference of the host pipe. This type of sleeve acts as reinforcement to the pressure boundary of the thinned wall location rather than as a leak barrier. On the other hand, a sleeve of material ‘Type B’ is welded along the circumference of the pipe to provide leak prevention against the entire pipe system pressure. This repair technique is considered appropriate for the repair of leaking or potentially leaking locations.

Figure 2: “Type A” Welded Sleeve Repair Techniques



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[10] For details, see Article 2.1 of ASME PCC-2-2015.

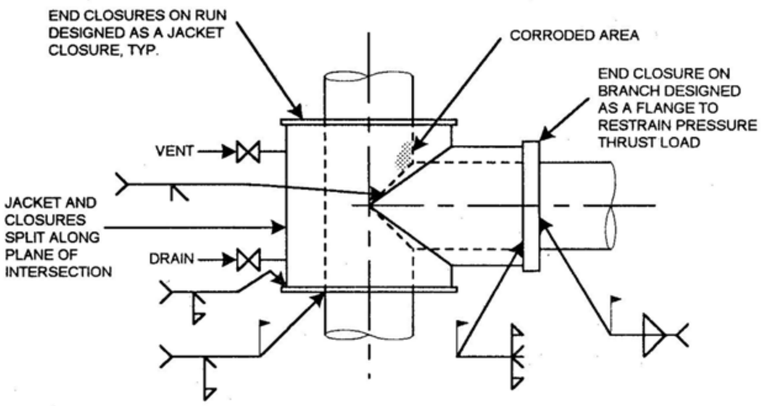
(7) Welded-on Leak Box

As illustrated in Figure 3, a section of pipe larger than the degraded or leaking pipe is split in half and placed onto the leaking pipe and then welded. The annular space between the leak repair box and the repaired pipe section can be left empty, or filled or lined with epoxy, sealant, or other compounds. When repairing a leaking pipe the leak box (or leak containment device) should be designed with vents and drains to permit venting the leak while assembling the box, then draining the annulus as necessary.

(8) Welded-on Leak Box[11]

As illustrated in Figure 3, a section of pipe larger than the degraded or leaking pipe is split in half and placed onto the leaking pipe and then welded. The annular space between the leak repair box and the repaired pipe section can be left empty, or filled or lined with epoxy, sealant, or other compounds. When repairing a leaking pipe the leak box (or leak containment device) should be designed with vents and drains to permit venting the leak while assembling the box, then draining the annulus as necessary.

Figure 3: An Example of Welded-on Leak Box[12]



(9) Peening and Welding

Peening may be utilised to repair pin-hole leaks after welding to isolate the leak and effectively close the leaking gap. When the leak area is small, additional materials can be welded to provide a permanent seal to the leak area. When there is a large leak, welding is applied to isolate the leak and peening is performed afterwards to give more solid leak isolation (e.g. induce compressive stresses, relieve tensile residual stresses).

If a pin-hole type leak develops within a wall thinned area it can be completely isolated by combining the welding and peening techniques. The heat input during welding needs to be minimised to avoid the burn-through, and a permanent solution can be provided by applying the overlay after the sealing.

(10) Pipe Cap

A pipe cap is useful in repairing the localised defect or leak. The pipe cap is widely used to more precisely protect the degraded area or the repaired location. The pipe cap is also applicable to the

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[11] For a detailed description, see http://www.carmagen.com/news/engineering_articles/news39.htm

[12] Reproduced from http://www.carmagen.com/news/engineering_articles/news39.htm

condition where the leak is limited to a small pitted area. In this case, the use of a Weldolet to the location where the branch line is added before installing a cap is recommended to provide a more effective pressure boundary.

2.5.1.2 Non-welded repair of metallic below ground pipe

(1) Inverted Liner

The insertion of a non-metallic inverted liner is a common non-welded repair technique applied not only to metal pipe but also concrete pipe. Two access points are established at the locations where the identification of the corroded area is possible by excavation or through a nearby manhole. Pipe repair flow path is secured from these points and a repair liner is inserted through one end and hydraulic pressure is applied from the other end to substitute the corroded area of the host pipe with the corrosion resistant liner. This technique is called cured-in-place pipe (CIPP).

For non-safety-related below ground piping, CIPP has been used as a temporary repair technique by some plant owners to allow for continued operation until the next scheduled outage of sufficient length to allow for a permanent repair or replacement. Reference [28] includes a discussion of the ageing management of internal corrosion of below ground SW system piping. At one BWR plant [29] the SW discharge piping consists of one 240-foot loop (Loop A) and a second 225-foot loop (Loop B) of 9.5 mm thick, 550 mm diameter pipe. The carbon steel base metal of the pipe is supplemented internally by (1) a rubber internal liner that was installed when the pipe was manufactured, and (2) an additional CIPP liner that was installed throughout the entire length of Loops A and B in 2003 and 2001, respectively. Additionally, prior to the CIPP installation, 40-foot sections of Loop A and Loop B were replaced in 1999 with new carbon steel pipe sections, which were coated both internally and externally with an aliphatic amine epoxy. As originally installed, the internal liner for the SW discharge pipe was a rubber sleeve that was put in place as part of pipe fabrication. This liner had an expected life of approximately 20 years. The plant owner monitored the integrity of the original rubber liner under the Service Water Integrity Programme, which was established as part of the in-service inspection (ISI) requirements for the SW developed in response to Nuclear Regulatory Commission (NRC) Generic Letter 89-13, "Service Water System Problems Affecting Safety-Related Components[13]."

As the original rubber liner approached the end of its expected life, the subject plant undertook increasingly intensive inspections under the SW Integrity Programme, prompted initially by a series of refuelling outage inspections of the rubber liner, which, beginning in 1995, revealed some degradation of the liner. In 1995, the rubber liner was visually inspected, using a robot crawler fitted with a camera, and minor age-related degradation was found. The rubber liner was re-inspected using this same method in 1997, and additional degradation was identified. In 1999 the plant undertook more intensive inspections by sending an inspector into the pipe to do both visual and ultrasonic examinations, with the intent to make any necessary replacements or repairs. In this inspection, it was discovered that a piece of the rubber liner in one of the loops had torn away from the carbon steel, leading to through-wall holes in the pipe. Some thinning near the end of the other pipe was also discovered, which was slightly below the [minimum wall thickness]. Following this discovery of degradation and small area of through-wall holes in 1999, the owner replaced 40-foot pipe sections in each loop and made other repairs.

Prior to installation of the CIPP liner inside the rubber-lined SW Loop B discharge piping in 2001 and Loop A discharge piping in 2003, all of the rubber linings were again visually inspected, to ensure they were still in good enough shape for the installation of the CIPP. The rubber was also

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[13] https://www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1989/gl89013s1.html

scraped to remove any marine matter and roughen the surface so that the rubber would bond properly with the CIPP liner.

The CIPP liner is a product designed to be used in old piping as an alternative to replacing or repairing such piping. Nominally 1/2-inch thick, the CIPP liner forms a rigid barrier to protect the carbon steel discharge pipe against internal corrosion. The liner material consists of a nonwoven polyester felt tube, which is saturated with a resin and catalyst system in loop A and an epoxy resin and hardener system in loop B, and which has a polyurethane or polyethylene inner membrane. Based on the service conditions and the design of the CIPP liner, its expected life is approximately 35 years.

(2) Slip Lining

A composite or high density polyethylene (HDPE) slip liner is used to repair the pipe degraded by such mechanisms as the wall thinning, erosion and pitting. Generally, the slip lining repair is considered to be a simple technique that involves inserting a new pipe into an aged large bore pipe. In addition, glass-reinforced plastic (GRP) and PVC materials are also used for slip lining. To install the slip liner, the fitting or the cross section at one end of the pipe is removed and then the liner is pushed into the host pipe.

The HDPE liner is inserted by pulling the collapsed U-shape through the host pipe and then the U-shaped liner is inflated into position. Although the inner diameter of the host pipe is slightly reduced because of the liner thickness, the internal friction coefficient is reduced at the same time so that in general there is no adverse impact on the design or operational flow of the pipe. An effective lining technique for the large bore pipe is to insert the collapsed steel liners inside the host pipe followed by the expansion from the inside and perform welding in both the longitudinal and circumferential directions. In this way the loss of the pipe diameter can be minimised.

(3) Weko-Seal® Repair

Weko-Seal® repair is applied to large man-entry pipes and entails inserting a cylindrical rubber liner into a localised area in order to inhibit the corrosion in the leak risk area. As shown in Figure 4, a metal band is normally used to firmly secure the rubber liner into the desired position.

Figure 4: Weko-Seal® Repair

(4) Mechanical Clamp

Mechanical clamp is a semi-cylinder shape bolted pipe attachment which clamps around the pipe. The leak barrier is provided by either one of the following two methods.

Spraying sealant through the nozzle positioned around the clamp

Applying O-ring gasket along the circumference of the clamp

The clamps are directly applied to the leak area of the pipe, and the design and other requirements of the mechanical clamp are referenced in the ASME Section XI, Appendix IX.

(5) Threaded or Welded Plug Repairs

This method involves removing a flaw or defect through the drilling or machining of a hole without replacing the component material. Leak and pressure tightness is achieved by inserting a solid or threaded plug and applying a seal weld.

(6) Leak Strap

This is a type of clamp repair methods that involves tightly wrapping the damaged location of the pipe using a water-activated resin and coated fibreglass tape. The type of device shown in Figure 5 is needed.

Figure 5: Leak Strap

(7) Wrap Repair

This repair technique using a non-metal composite material is effective in repairing degraded pipe as it uses a high-strength adhesive and a composite fabric material made of a large amount of fibres. Generally, fibreglass, aramid or carbon fibre is used. To repair, first coat the degraded area with multi-layers of composite fibres and perform wrapping followed by curing to ensure permanent surface adhesion as illustrated in Figure 6. Multiple fibre layers are applied to compensate for the loss of pipe thickness and attain the strength sufficient to meet the pressure boundary requirements.

Figure 6: Carbon Fibre Wrap Repair

(8) Sprayed or Brushed Lining

This technique involves the application of a high-strength adhesive or thermo-hardening resin to the inner surface of the degraded pipe. The resin is often used along with fibreglass or carbon fibres. The fibre material can be used in a cloth or chopped form and in some cases, polymer material mixed with another ingredient such as ceramic particles is used to enhance erosion resistance. Surface cleaning is required to obtain adequate adhesion, and the epoxy and resin must be appropriate for the operating temperature range.

2.5.2 Repair of concrete buried pipe

Repair techniques of concrete buried pipe are listed in Table 4. The application of either an external or internal repair technique depends on accessibility, water pressure and repair cost, and all repairs must be justified in terms of strength, stability and durability. The reader is referred to References [27] and [30] for additional technical details on repair of concrete piping.

Table 4: Concrete Buried Pipe Repair Techniques

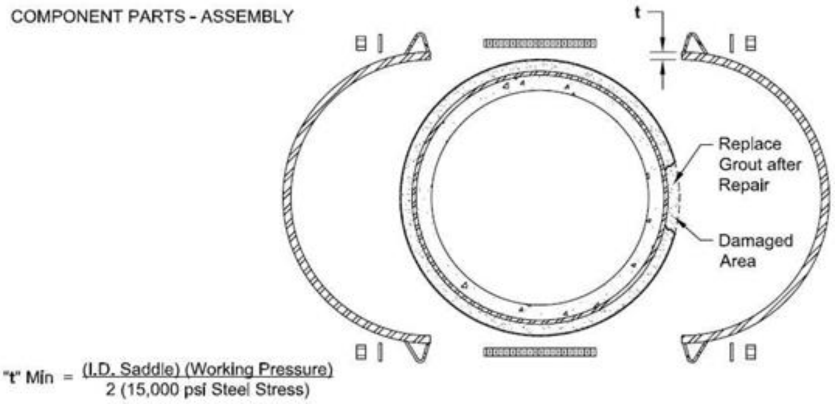
External Repair	Internal Repair
- Reinforcing Clamps - PCCP Post-Tensioning - Pipe Replacement - Pipe Encasement - Concrete Pipe Joint Repair with External Clamp	- CFRP Liner - Slip Lining

A. Concrete piping external repair

(1) Reinforcing Clamp

For the prestressed (PS) concrete cylindrical pipe (PCCP), locally damaged prestressing wire shall be repaired so that the original tensile strength is maintained and reinforcing clamps as shown in Figure 7 are used for repair. The reinforcing clamp shall be expanded by not less than 12 inches across each defect area of the mortar coating, and normally the number of the reinforcing clamps should be the same as the number of the failed PS steel wires. The minimum thickness of the reinforcing clamp is calculated using the hoop stress equation provided in Figure 7 and the clamp must be designed with an appropriated ID to ensure a uniform contact with the external pipe surface. Post-installation, mortar coating or concrete wrapping must be performed to the clamps to prevent external corrosion of the clamps.

Figure 7: Reinforcing Clamps



(2) PCCP Post-Tensioning

The PS concrete cylindrical pipe (PCCP) is designed to maintain strength by applying compressive stress to the core by the PS steel wires. The post-tensioning repair is a technique to provide post-tensioning using high-strength strands of steel followed by wrapping in order to restore the lost compressive stress caused by failed steel wires. Figure 8 shows the post-tensioning repair. The design of the post-tensioning repair must consider the following loads.

- Loads including the pipe and fluid weights, seismic loads, live loads, operational and transitional pressures
- Compressive stress that exists in the pipe area where the steel wires are not removed (undamaged)
- Additional loads including the loads concentrated from the anchor block and compressive loads shall be distributed and provided by the post-tensioning strands and couplers.

Figure 8: Post-Tensioning Repair

The post-tensioning design shall satisfy all the restrictions and limitations listed in the AWWA C304[14] and any potential new cracks on the core must be examined. When necessary to ensure the

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[14] American Water Works Association (AWWA) Standard for Design of Prestressed Concrete Cylinder Pipe

durability of the repair, the provision of anti-corrosion measures and CP equipment must also be considered for the post-tensioning system. The post-tensioning strands must be protected by anti-corrosion grease, a polypropylene sheet or a fibre reinforcing agent and electrically connected to the steel cylinder.

The post-tensioning repair does not require access to the inside of the pipe. The scope of application is determined depending on the presence of water inside the pipe and existence of pressure and the level of degradation. A post-excavation safety analysis is required to evaluate the condition of the degraded pipe and the excavation shall be performed in a way that allows the examination of the entire circumference of the pipe. The key steps of the post-tensioning repair are as follows:

- Locate and excavate degraded pipe
- Clean external surfaces
- Inspect for pipe degradation
- Remove loose mortar coating and prestressing wires
- Install and Tension Strands
- Bond Strand Anchor Blocks
- Place Shotcrete Bedding and Cover

(3) Pipe Replacement

When a concrete pipe section cannot be repaired, it must be replaced with a closure piece, which is normally composed of three sub pieces that are welded together – two short pipe sections having plug joint adapters and a butt-strap. The closure piece is usually designed by the pipe manufacturer and concrete pipe replacement can be an economical option when a long length of the pipe needs to be reused or when replacement is required by regulation.

(4) Pipe Encasement

Pipe encasement with reinforced concrete is an option to repair the PCCP, Reinforced Concrete Cylinder Pipe (RCCP) and Bar Wrapped Cylinder Pipe (BWP) type buried pipe systems but is not frequently used. Pipe encasement using reinforced concrete to cover the defective area is designed to withstand all internal and external loads including the operational overpressure, seismic load, live load as well as the weight of the pipe and fluid.

(5) Repair of Concrete Pipe Joint Area using External Clamp

Repairing leaking joints of a concrete pipe by using metal clamps can be performed without isolation of the pipe section. The external repair clamp is composed of elastic gasket and steel band which is used to secure the gasket that works as a compressive seal between the pipe surfaces. The pipe surface must be relatively uniform to ensure the adequate seal performance of the gasket. In order to install these clamps the entire circumference of the pipe must be excavated and the appropriate support procedures must be provided during the excavation and clamp repair installation.

B. Concrete piping internal repair

All of the inner repair options of the concrete pipe require access to the inside of the pipe and space for application. For the inner surface repairs, steel, fibreglass, HDPE liner or carbon fibre reinforced polymer (CFRP) liner is used as a repair material. One thing to note is that all of the above mentioned materials except the CFRP liner may have an impact on the hydraulic capacity and performance of the pipe.

(1) CFRP Liner

CFRP liner repair involves manual lay-up of the high-strength CFRP liners to the inner wall of the concrete pipe using an epoxy adhesive. This does not require excavation since all the materials can be inserted and transported to the repair location of the pipe through a manhole.

CFRP liner repair can be applied only to the affected pipe and does not affect nearby intact pipes. In addition, it does not affect the hydraulic performance of the pipe and is quite resistant to the corrosive elements. The design bases for the CFRP liner repair technique have not been developed yet, but AWWA is in the process of developing a repair standard. In the meantime, the following considerations, dependent on the condition of the host pipe, must be reviewed prior to applying CFRP liners:

- The CFRP repair design depends on the states of the host pipe.
- Non-degraded host pipe: repair is in the form of strengthening of the pipe.
- Degraded host pipe: at the time of repair, the host pipe has some broken wires, may or may not have cracked core and is circular. In the future, the host pipe will experience additional corrosion and breakage of wires, core cracking, deformation and corrosion of steel cylinder.
- Severely Degraded host pipe: at the time of repair, the host pipe has severe corrosion with most wires broken, multiple and wide core cracks, uneven internal surface and significant pipe deformation.

The following is the sequence for installation of the CFRP liners.

- Locate the degraded pipe
- Prepare the pipe inner surfaces for CFRP lay-up by power washing or sand blasting
- Inspect for pipe degradation
- Prepare pipe joints
- Install longitudinal and circumferential layers of CFRP per design
- Install coating layer

(2) Slip Lining

The degraded internal surface of the concrete pipe can be repaired using metal, fibreglass-reinforced plastic (FRP) or HDPE liners. Slip liners can be installed by ‘slipping’ the liners into the degraded pipe from one end of the pipe or at the location where one of the pipe fittings has been removed. The metal liners are split into smaller pieces in the longitudinal direction and can be folded to easily transfer inside the pipe. The FRP liners are inserted and connected like a pipe, and the space between the liners and the host pipe can be grouted depending on the design requirements.

HDPE liners are installed by pulling the collapsed U-shaped liner through the host pipe and allowing it to inflate to develop the lining inside the pipe. This type of lining installation reduces the inner diameter of the host pipe but the inner wall friction coefficient is also reduced, and therefore there is no adverse impact to the flow inside the pipe.

3. SAFETY SIGNIFICANCE OF BELOW GROUND PIPING FAILURES

The consequences of a below ground and buried pipe failure on plant operation can be direct impacts (e.g. flow diversion and loss of the affected train or system or an initiating event; immediate operator action is needed) or indirect impacts (e.g. a degraded pipe condition that is subjected to an operability determination and without need for immediate operator intervention). The operating experience as recorded in the Component Operational Experience, Degradation and Ageing Programme (CODAP) event database includes examples of buried pipe failures that have had multi-unit impacts as well as flooding of equipment areas and utility tunnels. An example of an initiating event (as modelled in probabilistic safety assessments (PSA) could be loss of service water (SW) or dual-unit loss of SW. These types of events are modelled in probabilistic safety assessments. Based on the CODAP operating experience insights, this section summarises observed consequences of buried pipe failures.

3.1 Consequences of below ground pipe failures

Organised by operational impact and consequence of a below ground pipe failure, Figure 9 is a very high-level summary of the total failure population of 287 events. In this figure the operating experience data is grouped into eight consequence categories[15]. While it is possible for some events to result in more than one consequence, the dominant consequence is assigned within the database.

- Fire Protection Pipe Break with Coincident Fire Suppression Demand: this category includes events that involve an active in-plant fire and fire water system actuation, which cause that a break develops in a below ground pipe header. The CODAP event database includes two events of this type, details of which are discussed in Section 4.3.10.
- Dual Unit Shutdown: applies to multi-unit reactor sites with shared buried piping (BP) systems. An example of a recent below ground pipe failure causing the manual shutdown of two reactor units is discussed in Section 4.3.3.
- Flooding of Equipment Area / Utility Tunnel / Valve Pit.
- Unplanned Outage Work: applies to situations involving scheduled below ground piping system inspections performed during a maintenance or refuelling outage and the discovery of a severely degraded pipe condition that requires prompt remediation.
- Manual Shutdown: typically this means that a manual reactor shutdown is performed when a limiting condition for operation (LCO) cannot be met; see below.
- Expanded Outage Work: applies to situations involving scheduled below ground piping system inspections performed during a maintenance or refuelling outage and the discovery

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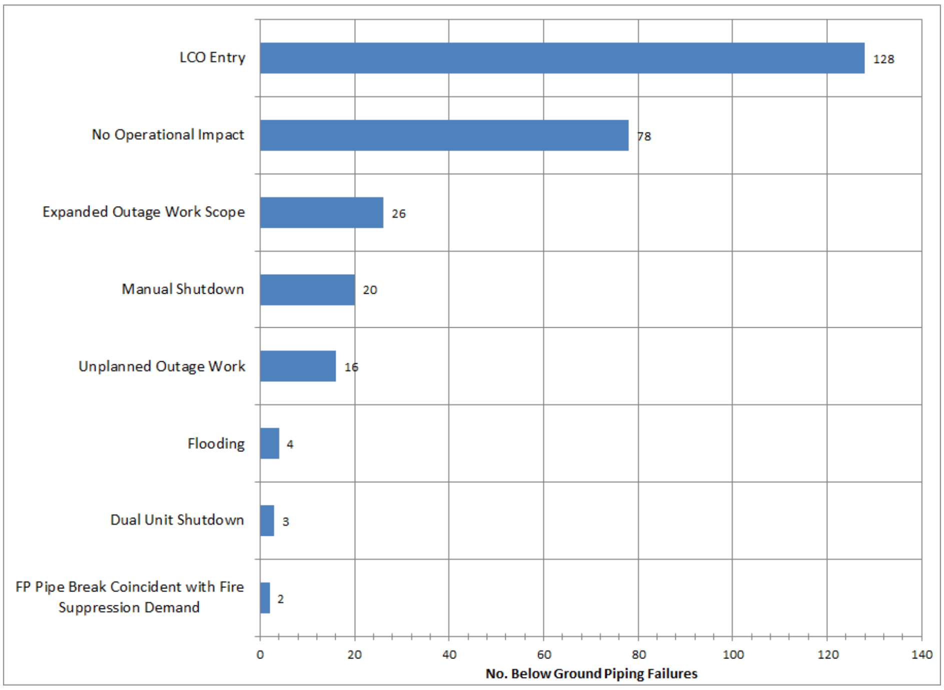
[15] In CODAP the event classification is done in multiple ways. It is done by “event type” (e.g. small leak, large leak, rupture), “event category” (e.g. primary pressure boundary leakage, tritium release to environment), “isolable/non-isolable pressure boundary breach” (YES/NO), “collateral damage” (e.g. flooding of equipment area, spray impact on adjacent equipment) and “direct impact on plant operation” (e.g. automatic turbine trip/reactor trip, manual shutdown, power reduction).

of a degraded pipe condition that prompts further non-destructive examinations (NDEs) but without impacting the overall outage schedule.

- No Operational Impact: a below ground pipe failure that can be corrected without impacting any other routine plant operation activities. This category mainly applies to non-safety-related buried pipe failures that have no impact on normal plant operations. While an event may not have any immediate impact on safe plant operation it could nevertheless involve the release of tritiated water to the environment necessitating remediation.
- LCO Entry[16]: for safety-related BP, a discovery of a degraded condition results in an LCO action statement. When an LCO cannot be met, the reactor must be shut down or the licensee must follow any remedial action permitted by the licensing basis (e.g. Technical Specifications) until the condition can be met. In CODAP this consequence category is applied to pipe failure events for which corrective action is completed within a time frame as specified in the Technical Specifications.

Figure 9: Operational Impact of Below Ground Pipe Failure



The potential safety and operability impacts of below ground pipe degradation or failure are outlined in further detail in Table 5. This table builds on insights from plant-specific probabilistic safety assessment (PSA) studies. Included in this table are selected and relevant reliability and integrity management considerations. Many plant operators have implemented augmented or "owner controlled" NDE programmes to manage below ground pipe ageing.

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[16] For a definition, refer to the "Glossary of Technical Terms".

Table 5: Potential Safety/Operability Impact of Below Ground Pipe Failure

System	**Through-Wall Leak Impact**		
	Potential Safety Impact	**Potential Plant Operability Impact**	**RIM Considerations**
Circulating Water	Loss of ultimate heat sink is modelled as an initiating event in Level 1 PSA. Addressed in post-Fukushima Daiichi accident management initiatives. Potential for flooding of Turbine Building basement (see Section 4.3).	Could result in a controlled reactor shutdown and forced outage.	In some plants the CW system is classified as a safety-related system for which an owner controlled inspection programme has been implemented. Also, at some plants the CW and SW systems share portions of the cooling water intake piping.
EDG Fuel Transfer	EDG reliability is addressed in Level 1 PSA and seismic PSA[17]. Addressed in post-Fukushima Daiichi accident management initiatives.	Entry into an LCO Action Statement.	See “ESW” below.
Fire Protection Water	Addressed in seismic PSA and Fire PSA[18]. As described in Section 4.3.11, failure of buried FP piping coincident with fire suppression could have plant risk impact. Also addressed in post-Fukushima Daiichi accident management initiatives.	Entry into an LCO Action Statement and activation of a fire watch.	See “ESW” below.
Essential Service Water (ESW)	Loss of SW is modelled as an initiating event in Level 1 PSA studies[19]. In some plants, the SW system is a shared system that could potentially have a multiple-unit safety impact. Addressed in post-Fukushima Daiichi accident management initiatives.	Entry into an LCO Action Statement and potentially a controlled manual reactor shutdown.	Development of augmented or enhanced non-destructive examination programme. Some plants have or are in the process of replacing the original piping with corrosion resistant materials.
Seismic PSA studies include consideration of the fragility (i.e. conditional probability of failure at a given seismic hazard level) of certain below ground/buried piping systems (e.g. Fire Water and Service Water systems).			

3.2 Reporting of below ground pipe failures

Depending on plant operability impact and/or potential safety impact, the reporting of below ground pipe failures is done at different levels. As one of several examples, in the U.S. whenever a degraded condition is discovered in safety-related below ground components (e.g. CW and SW piping) Section XI of the ASME Boiler and Pressure Vessel Code requires that safety-related BP repair/replacements be documented in a 90-day ASME XI Owner Activity Report (OAR). Additional details on national differences in reporting requirements are documented in a survey by the WGIAGE [1], which concluded:

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17. See for example Part 5, Requirements for Seismic Events At-Power PRA of ASME/ANS RA-Sb-2013.

18. An integral part of Fire PSA is the systematic evaluation of the possible degradation of fire suppression systems; see for example NUREG/CR-6850, “EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities” (2005).

19. See for example, Table 2-2.1-2, Item IE-A10 of ASME/ANS RA-Sb-2013, “Standard for Level 1/Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications.”

- “No country has direct means to receive information related to BTP leaks unless a radioactive release has occurred as a result of the BTP leak. Canada and Switzerland have reporting requirements if the leak has occurred in a safety-related pressure boundary component (Canada) or safety-classified component (Switzerland). Both Germany and the Netherlands indicated that they require reporting only if the leak results in radioactive discharge, not including tritium.”
- “Such events are also not reported to the US NRC, but the NRC has access to the INPO ICES database[20], which contains records of leaks from buried and underground piping. The information in this database is particularly comprehensive for leaks occurring since 2009. As a result of the general lack of reporting of these events to the regulatory organisation, it will be difficult to obtain and share information among countries.”

In the United States, the plant operators also follow the guidelines of the voluntary initiative described in the Nuclear Energy Institute’s NEI 07-07 [31] for reporting and evaluating spills, leaks and groundwater concerns. Section 2.2, “Voluntary Communication,” of NEI 07-07 states:

- “Make informal communication as soon as practicable to appropriate state/local officials, with follow-up notification to the NRC, as appropriate, regarding significant on-site leaks/spills into ground water and on-site or off-site water sample results exceeding the criteria in the radiological environmental monitoring programme described in the off-site dose calculation manual.”

The guidance in NEI 07-07 provides a threshold for this informal communication to state/local officials of spills or leaks exceeding 100 gallons from a source containing licensed material (e.g. tritiated water). The guidance also recognises that some states may require different communication thresholds, but specifies that the licensee shall document any agreements with state/local officials that differ from the industry guidance.

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20. Each utility in the United States is inputting equipment failure data to the proprietary Institute for Nuclear Power Operations (INPO) Consolidated Events Database (ICES).

4. OPERATING EXPERIENCE DATA REVIEW

Summarised in this section is the below ground piping operating experience as recorded in the Component Operational Experience, Degradation and Ageing Programme (CODAP) event database. For each country a discussion is included of selected significant events. The term “significant” refers to operational impact as well as impact of an event on regulation and/or industry initiatives to address below ground piping ageing issues.

4.1 Below ground piping operating experience in CODAP

Since its inception in 2002, operating experience with below ground piping has been an intrinsic aspect of the technical scope of the CODAP database project. Specifically, CODAP collects data on below ground pipe failures with operational impacts as well as potential safety impacts. The scope of the CODAP event database is to collect, evaluate and exchange operating experience data on metallic passive components with potential plant safety impact as well as operational impact. In the database the earliest recorded buried pipe failure dates from April 1976 when a significant (ca. 3 kg/s) through-wall buried BP leak developed in a buried service water (SW) system pipe line at a US boiling water reactor (BWR) plant. More recently, significant buried pipe events have occurred in the Czech Republic (2014), Spain (2004) and the U.S. (2008, 2015 and 2017).

4.2 High-level database summary

The CODAP event database content with respect to below ground piping degradation and failure is summarised in Figures 10 through 15. Of the total data subset, ca. 75% represents the US operating experience. It is recognised that this 3:1 ratio is not a true reflection of the status of the below ground ageing management practices across the CODAP member countries but more a reflection of the generally greater accessibility to information about US events. In the CODAP Project, respective member countries are responsible for making data submissions in an equitable manner. Except for “significant” failure events, information on degraded below ground piping is not generally available to regulators and its technical support organisations.

In the high-level database summary, the below ground piping operating experience data is organised by time period (Figure 10), safety-related non-tritium-bearing versus tritium-bearing pipe failures (Figure 11), number of below ground pipe failures by plant type and calendar year (Figure 12), below ground pipe failures as a function of the age of the failed piping at the time of occurrence (Figure 13), below ground pipe failures by system group (Figure 14) and below ground pipe failures as a function of observed through-wall flow rate (Figure 15).

Various high-level quantitative insights may be derived from these charts. As an example, according to Figures 10 and 13, the need for inspections (visual and non-destructive examination) and fitness-for-service assessment of below ground piping appear to increase after 25-30 years of plant operating time. Furthermore, the operational experience points to instances of major operational impacts from below ground piping failures. Trends in the operating experience data are attributed to:

- Material ageing.
- Changes in reporting practices and requirements.
- Changes in inspection practices and requirements.

More in-depth evaluation of the events is needed to distinguish the significance of each of these three causal factors in the trends exhibited in Figures 10 and 13.

Figure 10: Number of Below Ground Pipe Failures by Time Period[21]

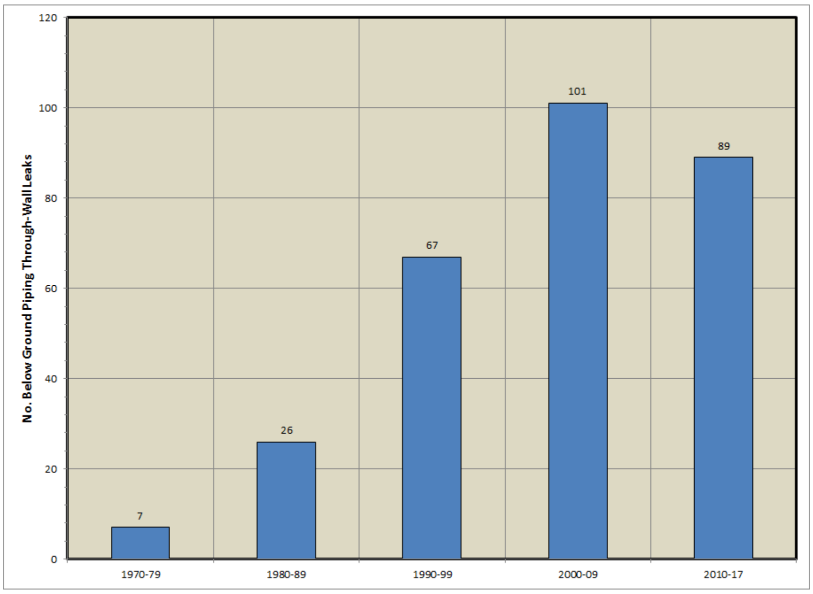
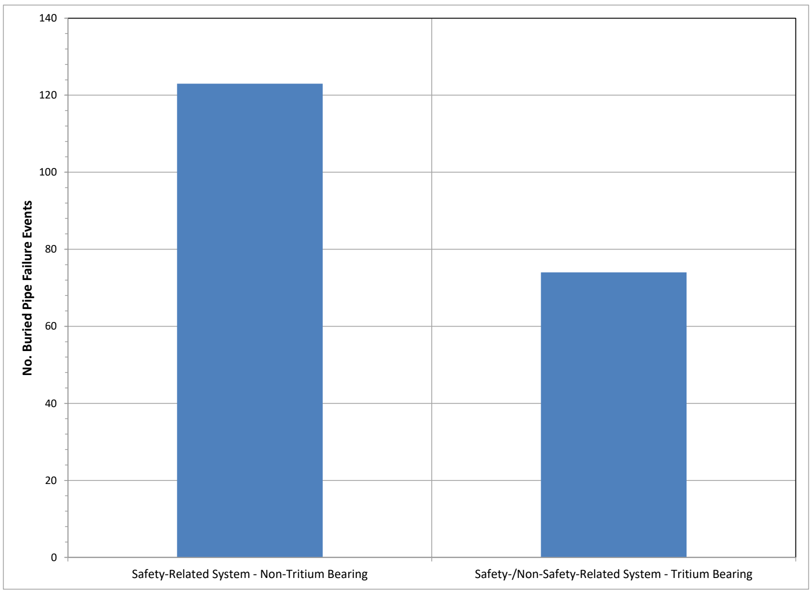


Figure 11: Tritium-Bearing vs. Non-Tritium-Bearing Below Ground Pipe Failures in CODAP



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[21] Information on below ground pipe failures is still being collected for the period 2010-2017.

Figure 12: Number of Below Ground Pipe Failures per Calendar Year & Plant Type

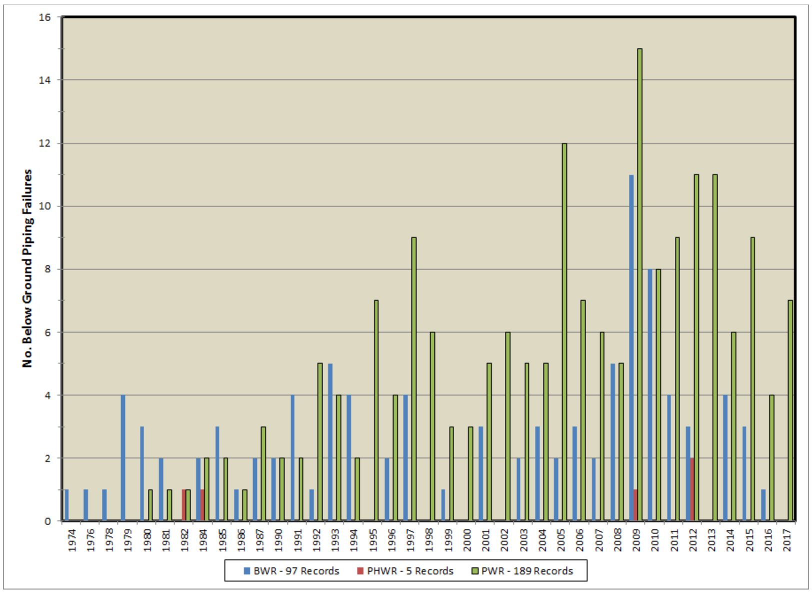


Figure 13: Below Ground Pipe Failures as a Function of Age at the Time of Failure

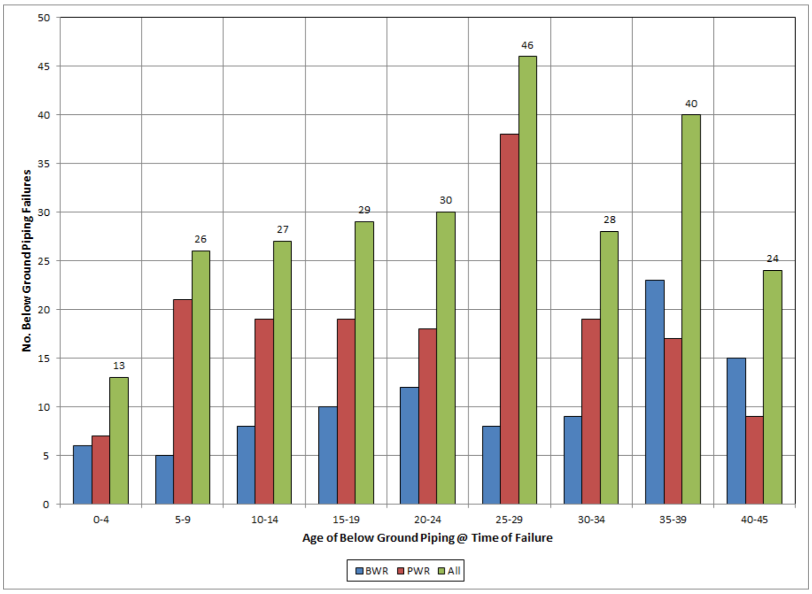


Figure 14: Below Ground Pipe Failures by System Group

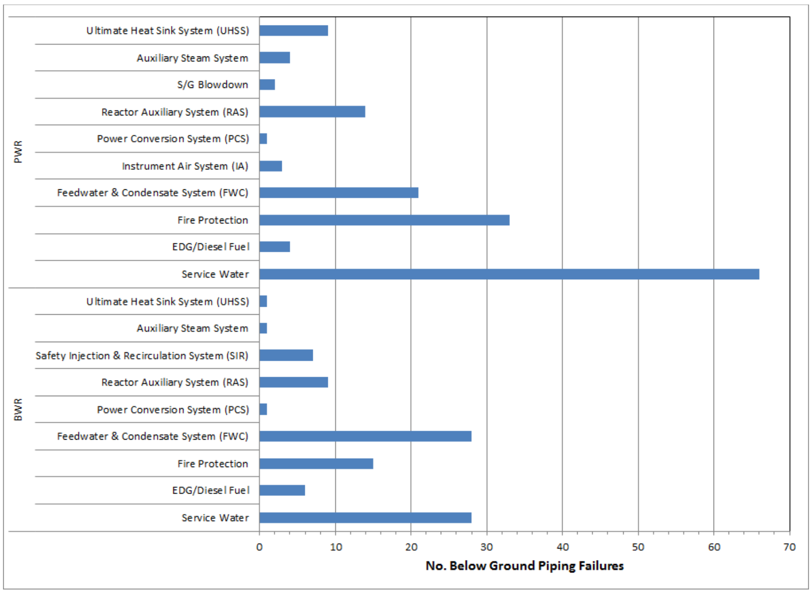
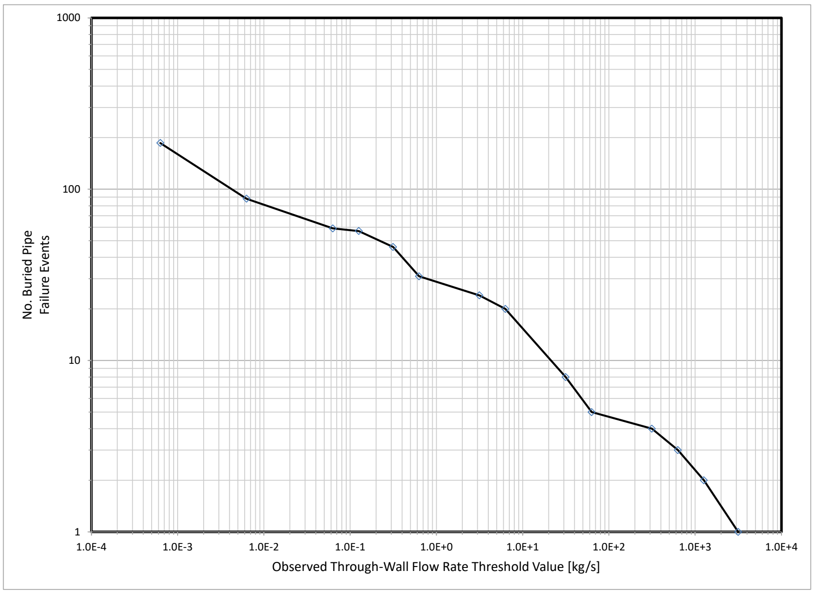


Figure 15: Below Ground Pipe Failures by Through-Wall Leak Threshold Value



Details on the country-specific operating experience with below ground piping are outlined below (Section 4.3) including abbreviated narratives of selected, significant events. An example of a quantitative assessment of the operating experience data is presented in Section 4.4.

4.3 Country-specific operating experience

Organised by Project Review Group (PRG) member countries and economies, this section includes summaries of current below ground piping ageing management approaches and selected key operational events involving significant pipe through-wall flow rates.

4.3.1 Canada (CA)

The CANada Deuterium Uranium (CANDU) nuclear generating stations (NGS) have several kilometres of buried piping (BP). In-service inspection (ISI) and assessment of BP systems are rather complex tasks due to the relatively small physical footprint that results in congested piping runs. Additional complexities are seen as a result of needing to ground all the piping due to the amount of electricity being produced (most of CANDU's are multi-unit stations). CANDU plant operators have adopted the Nuclear Energy Institute's (NEI's) "Guideline for the Management of Underground Piping and Tank Integrity" [6], as the basis for ageing management of BP.

Upon discovery of a leakage in buried hydrogen supply piping at Darlington NGS (a 4-reactor unit site), a BP programme was initiated in 2006 by Ontario Power Generation (OPG). A framework for the BP programme, in alignment with current industry guidance, has evolved through multiple benchmarking activities through the Electric Power Research Institute (EPRI) and CANDU Owners Group (COG). OPG initiated the development of the "Risk Classification and Ranking" and "Buried Piping Strategy Manual" in 2006 and shared and peer reviewed these technical and programme management documents through numerous workshops at EPRI and COG [32] [33] [34]. OPG has supported industry activities to develop software tooling, such as BPWORKS, in order to manage the buried piping programme requirements. Darlington NGS was proactive and initiated comprehensive validation testing of a new "non-intrusive" scanning technology to investigate its capabilities in identifying potential corrosion sites in underground piping, which was finally implemented with the initial non-destructive examination (NDE) technology testing on Darlington essential service water (ESW) in 2007. In addition, OPG followed the Institute of Nuclear Power Operations' (INPO's) guidance to ensure risk assessments were prepared for all BP systems and the assessments were subject to periodical review and updates as conditions change. Darlington, the newest generating station in the OPG fleet, has 14 BP systems and the BP programme is also protected by a sacrificial anode cathodic protection (CP) system. The Darlington CP system includes 91 test stations, 4 rectifiers and 10 polarisation cells. Darlington has inspected all high risk systems such as standby and emergency power generators fuel lines, hydrogen supply lines, ESW and low pressure service water (LPSW) piping (Figure 16) and BP systems are inspected on an annual basis. Recent World Association of Nuclear Operators (WANO) peer reviews and audits of the Darlington programme in 2014 found no areas-for-improvement with regard to the BP programme.

Pickering nuclear generating station (8 reactor units) has 50 BP systems, and its BP programme uses a sacrificial anode CP system. Currently there are no impressed cathodic protection systems used at OPG sites. From the inception of the programme, Pickering has completed several direct inspections of BP systems which began with the ESW system in 2009. In 2013, WANO performed an audit of Pickering NGS performance and found no areas-for-improvement (AFIs) in regards to the BP programme.

Bruce nuclear generating station, with its eight nuclear units, is among the largest power generation sites in the world. The BP programme at Bruce was initiated in 2008. Risk Classification and ranking as well as the first round of inspections involved the Fire Protection Water Supply, Emergency Water, Standby Generator Fuel line, Generator Hydrogen Storage, Carbon Dioxide, Common Service Water, Condensate Make-Up and Rejection, Lubricating Oil and LPSW systems.

Figure 16: NPS 6 Buried Condensate Discharge Line Exhibiting Corrosion Under Insulation (CUI)

From the early days of the Canadian BP programmes it has been apparent that there were a range of issues with the application of many of the techniques and technologies that have been developed to ensure proper inspection and maintenance of BP in the oil and gas industries. In order to provide the necessary scientific support and technological knowledge to improve the BP programmes being implemented in CANDU NGS's, Canadian utilities initiated an extensive applied research and development programme through the COG currently integrated under the "Buried Piping Programme Management". COG's "Buried Piping Programme Management" programme [34] is interfaced with EPRI's Buried Piping Integrity Group (BPIG) through the information and experience exchange. Currently, COG's programme involves metallographic examination of carbon steel and cooper coupons removed from soil, using a series of tests on galvanic corrosion of carbon steel (anode) coupled to copper (cathode), using soil from NGS's sites (Bruce, Darlington, Pickering, Chalk River) to match specific site soil composition and chemistry conditions. COG also continues work on the development and maintenance of the BPWORKS software tool.

4.3.2 Chinese Taipei (TW)

There are three operating nuclear power stations in Taiwan, each with two reactor units. Maanshan has two 3-loop pressurised water reactors (PWRs) with nuclear steam supply systems (NSSS) supplied by Westinghouse, while for the other two plants, Chinshan and Kuosheng, each has two boiling water reactors (BWRs) with NSSS supplied by General Electric (GE). Among these 4 BWRs, the two Chinshan units are BWR-4 with Mark I containments, while the other two Kuosheng units are BWR-6 with Mark III containments. The regulatory approach to plant ageing management and licence renewals follows that of the U.S. Nuclear Regulatory Commission (NRC). Examples of buried pipe failures include:

1. On 5 November 1996, Chinshan Unit 1 was in routine power operation at the time of the event with the emergency diesel generator B (EDG-1B) in standby. The sand buried fuel oil transfer pipe near the 345 kV switch yard was found to be leaking. After excavating, a dent and a pinhole was found at the surface of the pipe due to galvanic corrosion caused by stray current. After draining of the fuel oil in the pipe, a section of new pipe was replaced according to code repair procedure. The surface of the pipe was recoated. A set of sacrificial anodes was installed on the pipe following this event to prevent the galvanic corrosion.
2. On 2 June 2015,with Maanshan Unit 2 at rated power, the operator was alerted that a Nuclear Service Cooling Water piping to Central Chilled Water system heat exchanger was

leaking at pipe number 007-24-HGD which is a buried pipe. After excavating the pipe, a dent and a pinhole size through-wall defect were found on an elbow and confirmed to be the leak source. A temporary repair was performed using a rubber gasket and a clamp. The integrity of the repaired area was subjected to periodic monitoring. According to the analysis of the piping location, the main damage factor of the rubber-lined piping was consistent with previous experience. The cause of the damage was attributed to:

- Corrosion holes caused by ageing of rubber.
- Incomplete rubber adhesion at seams causing the corrosion of pipe wall.
- The thickness of rubber at elbow being less than normal thickness, due to erosion.

On 2 December 2015, the carbon steel piping was replaced with stainless steel piping joined by welding and the rubber liner was repaired. The repair was successfully completed after the pipe leakage test.

4.3.3 *Czech Republic (CZ)*

In November 2014, a major leak developed in the buried portion of the common ESW system of Dukovany Units 3 and 4. Due to the prolonged unavailability of one of three trains of the ESW system, both units were manually shut down in a controlled mode as required by the pertinent limiting condition for operation (LCO). Train 2 was taken out of service for replacement of the affected pipe section. After a successful repair and leak test of the damaged pipeline, the SW Train 2 was returned to service on 16 November 2014. The Dukovany 3 was reconnected to the grid on 19 November.

The event arose due to a minor through-wall leak in a welded joint of the DN800 Train 2 ESW piping. The leaking water then created a cavern under the pipeline, resulting in inadequate support of the affected pipe section. As the leak was located under the road used by heavy trucks going to a Ventilator Cooling Tower construction site (a post-Fukushima Daiichi plant modification project), the pipeline damage increased (Figure 17) causing the ESW Train 2 to trip and the subsequent shutdown of Dukovany Units 3 and 4.

Figure 17: Damage to DN800 ESW Pipe[22]

There was no other equipment damage, injury or a radioactivity release due to this event. As a corrective measure, the plant has inspected other underground ESW pipelines using a geo-radar (ground-penetrating radar, GPR) non-destructive testing (NDT) system. The roads crossing the

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[22] Photograph is courtesy of the Nuclear Research Institute ŬJV Řež a.s.

pipelines have been reinforced by steel plates in the crossing points to distribute impact of the truck traffic over a larger area and protect the pipelines underneath.

4.3.4 France (FR)

Buried pipe events are not at the moment in the scope of Électricité de France (EDF) piping operating experience events to be uploaded into the CODAP database. Nevertheless, in the EDF French nuclear power plant (NPP) fleet, many process systems contain one or more lines that are buried. These systems include safety and non-safety SW, circulation water, fire protection and diesel fuel oil systems. Degradation of such buried pipe systems therefore is a major issue that has to be addressed in France. It is all the more important in that the French fleet has an average age of more than 25 years and that lifetime extension beyond 40 years is one of the major objectives for EDF.

In the context of plant life extension and after several meetings with the French regulatory body L'Autorité de Sûreté Nucléaire (ASN), EDF has decided to launch a specific programme to address the reliability and integrity management of BP. To do so, EDF decided to perform a risk analysis related to buried pipes in collaboration with EPRI. The EPRI methodology allows EDF to prioritise inspections that should be done on buried pipe systems subject to degradation by determining the likelihood of a leak or a break in a given piping segment and the consequences of that leak or break of that segment[23]. Such a method is all the more relevant given that the French fleet is characterised by a high level of standardisation. The first results of the buried pipe risk analysis were obtained by the end of 2015. For the Bugey NPP, EDF prepared a prioritised list of inspections to be performed including the NDE techniques to be used. Final results of EDF BP assessment should be presented and analysed during the 4th periodic safety review of the 900 MWe reactors[24].

France is a participant of the IAEA Underground Piping and Tanks Initiative that started in 2012 [4] in response to industry concerns and activities related to ageing of underground pipes and tanks. As buried and underground pipes and tanks are part of EDF's ageing management programme, EDF is one of the contributors of that project.

The internal flooding event at the Nogent-sur-Seine NPP on 18 February 2006 is selected as the French representative below ground piping operating experience. Nogent Units 1 and 2 were at power when a massive water leak developed in the manhole located at Unit 2 Train 1 Circulating Water System pump discharge (Figure 18) flooded the Unit 2 turbine hall, then the Unit 1 turbine hall and the basement document storage rooms, via the tunnel connecting the two units. Both turbine halls were filled with water to a height of about 1 metre. The water then spread through non-leak tight penetration sleeves from the tunnel between the plant units to the ESW system gallery, before entering the Unit 1, Train A component cooling system (CCS) pump rooms via drains. The Nogent flooding incident resulted in the Unit 1 reactor trip. In compliance with the Technical Specifications, the operator then returned both units to normal shutdown with the residual heat system in operation.

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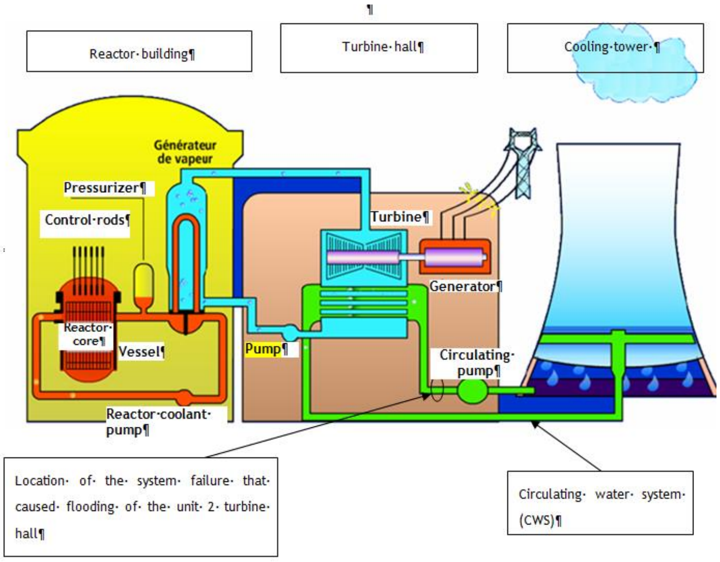
[23] As an example of EPRI buried piping risk analysis, BPWORKS 2.1 is a multi-programme software application. It builds on the basic principles of risk-informed in-service inspection (RI-ISI). The first programme is an extensive data management tool that stores a wide range of information related to buried and underground piping systems. The second programme is a risk ranking module that uses most of this stored information to evaluate the risk of the buried and underground pipe. The end result is a relative risk rating and mapping for each major piping system that accounts for both the consequence of failure and likelihood of degradation.

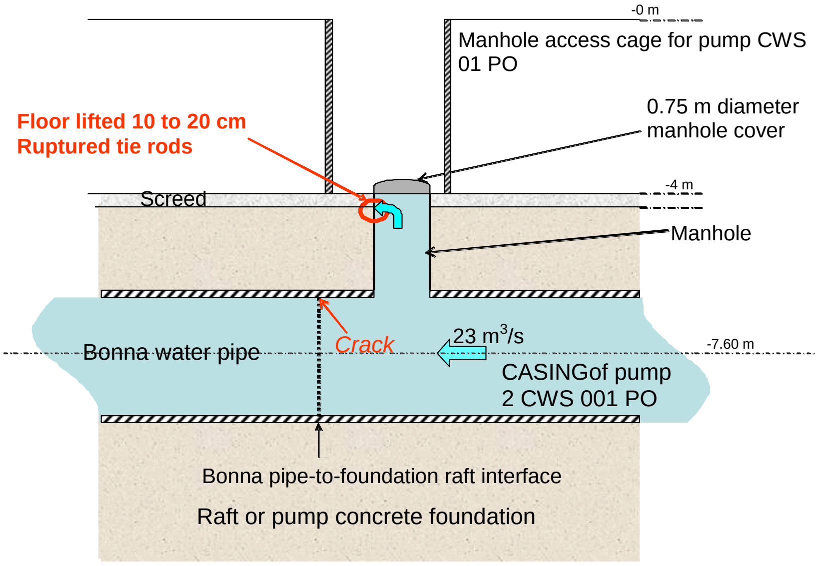
[24] For additional details and effective April 2016, see http://www.french-nuclear-safety.fr/Information/News-releases/ASN-position-statement-concerning-generic-guidelines-for-the-periodic-safety-review

Figure 18: Operating Principle of the Circulating Water System (CWS)



The cause of this event was a leakage at the CWS pump discharge (cracking of Bonna® pipe) to the foundation raft interface that induced a pressure rise (Figure 19). The floor was then partially lifted due to the propagation of floodwater at CWS pump discharge pressure in the concrete surface. This resulted in misalignment of the manhole, creating a leakage path between the water pipe and the turbine hall basement. The floor was lifted 10 to 12 cm higher than to the raft.

Figure 19: Design of CWS Civil Structures



4.3.5 Germany (DE)

In German NPPs, BP is primarily used in the ESW systems of PWRs as well as BWRs. In PWRs, the piping system of the emergency feedwater system runs below ground between the emergency feedwater building and the reactor building. ISIs and operational monitoring of the aforementioned systems are performed in line with KTA 3211, part 4 [35]. Reporting of degradation and failure of below ground/BP is done in accordance with the “Nuclear Safety Officer and Reporting Ordinance” [36].

So far, no degradation or failure compromising the safety function of the affected systems has been reported. However, throughout the lifetime of German NPPs several minor events have occurred. Key lessons learnt specifically for below ground piping included the potential for undetected active degradation, the need for knowledge of the exact pipe routing and the essential importance of the integrity of internal as well as external pipe coatings. Examples of BP operating experience include the following events:

- During a routine walk-down on 23 July 1990, a moisture discharge from the soil was detected in the owner controlled area at the Krümmel nuclear power plant. During subsequent examinations the leak was localised in the buried part of the closed cooling water system of the circulating water pumps. The leakage was associated with an intrusion of a small amount of tritium into the soil, most likely stemming from the generator cooling system. The leak was caused by through-wall corrosion of the pipe following severe degradation of the outside bitumen coating.
- On 18 September 1993, during operation of the ESW system of Isar-2, leakage from the soil was detected on the plant site. An inner inspection of the affected prestressed (PS) concrete pipe (DN700) revealed no indications. Therefore, the decision was made to excavate the pipe. The excavation revealed a leaking pipe connection/sealing. After exchanging the damaged connection (new connection type: AMEX 100[25]) and performing a hydraulic pressure test, two further leaking pipe connections were found and exchanged later.
- During a recurrent inspection on 16 November 1993, water leakage from the soil was detected on the way to the emergency diesel building of the Krümmel nuclear power plant. Digging up the area revealed a leakage at a 90° bend in an auxiliary water supply line (nominal diameter DN 200, material St 37) for an emergency diesel. A defective bitumen coating at the outside, mechanical damage at the pipe wall and a hole of a size of about 2 cm^2 were found causing the leakage. Further extensive material erosion was detected at the exposed pipe wall, whose surface, however, had an intact metallic anticorrosive inner coating. The damage at the bitumen coating and the outer wall surface was presumably caused during the construction of a concrete channel in the years 1981/82. Since minimum distance of the concrete channel to the damaged pipe bend is about 15 cm, electrochemical corrosion must have occurred due to the proximity of major iron-reinforced concrete masses which, apparently, led to a penetration of the wall. The water leakage was only prevented by the inner coating. The pressure fluctuations caused by switching on of the auxiliary water pump finally led to the leakage. The defective pipe bend was replaced.
- During a hydraulic pressure test performed on 12 September 1996, a leak was found on a buried pipe containing radioactive waste water of KWB-A (Biblis-A). The leakage was caused by local damage to the external bitumen coating and subsequent corrosion of the pipe. The affected pipe section was replaced.

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[25] For details, go to www.amex-10.de.

- On 8 August 1997, while digging a pit on the plant site of the Obrigheim Nuclear Power Plant (KWO), a buried pipe of the emergency SW system with nominal diameter DN 250 was damaged by the drill bit (Ø 140 mm). The root cause of the event was the use of an invalid pipe routing plan. Remedial measures included replacement of the affected pipe section and an update of the construction documentation.
- On 4 April 2007, within the framework of scheduled maintenance work in the nuclear SW system of GKN-1 (Neckarwestheim-1), an almost circular hole with a diameter of about 20 mm was detected in a buried flow line. The leakage had no safety relevance. Due to the small size of the hole, the function of the SW system had not been impaired. The line has a nominal diameter of DN700 and is made of steel St 37. The line is buried between the intake structure/pump house and the reactor building. The root cause was attributed to corrosion at the outer surface of the line due to a local damage of the external insulation. As a provisional measure, the operator sealed the leakage with a clamp. The line was repaired within the framework of the following refuelling outage.
- In 2009, replacement of the BP system of the ESW system of KWB-A (Biblis-A) was planned. On 19 January, during the corresponding excavation work a piping system a leak was discovered on the DN 600 main header of Train 20. Later, minor leaks were also detected on the other trains of the ESW system. Before the digging work there were no indications of any leaks. The root cause of the event was attributed to corrosion starting from the outer surface of the lines due to localised damage of the external insulation. There were also indications of corrosion on the inner surface of the carbon steel pipes. The replacement campaign started in 2009 and was completed in the following years. The new piping system has an inner concrete coating. A similar event occurred in the Gösgen Nuclear Power Plant (KKG) on 31 March 2008. In this case, the indication of the leak was found after excavation of the pipe for a planned inspection. Apparently, a local coating defect caused through-wall corrosion starting from the outer surface of the pipe.

4.3.6 Japan (JP)

The Japanese nuclear power plants have experienced failures of BP and concrete encased piping (CEP). As an example of the latter (CODAP Event ID #3661), in October 1991 one of the operating BWR units experienced a significant SW pipe leak. During a routine inspection in the Turbine Building, sea water was detected on the floor adjacent to a motor-driven reactor feedwater pump. The leakage originated from a pipe diverging from main sea water line to the auxiliary cooling system. By excavating the concrete floor where the leak was discovered, a hole was identified in the DN250 pipe diverging from the main raw water line to the auxiliary cooling water system. The through-wall flow rate was estimated to be ca. 6 kg/s. This leakage was massive enough to subsequently immerse two of the Emergency Diesel Generators located in the Turbine Building basement.

The root cause analysis concluded that foreign material (e.g. shellfish) had damaged the internal pipe wall liner, and that the ID corrosion created a hole through which the leak occurred. In addition to replacing the affected pipe section, the new piping was installed above the floor to improve access for inspections. In the replacement, a lining with more adhesion and resistance against breaking away was to be adopted.

4.3.7 Korea (KR)

In 2003, at Hanul Units 5 and 6 shortly after installation a fire protection water system (FPS) header pressure drop was observed. The pressure drop was noted in the fire water supply pipe located at the underground common tunnel and buried outside the building. Because of the header pressure drop, there was an excessive start-up/shutdown cycling of the jockey pump to maintain the header pressure. The leak rate was estimated to be ca. 3.2 kg/s. The fire water supply pipe located at the underground common tunnel is made of carbon steel and the ex-building buried portion of the pipe is made of cast iron.

The root cause analysis concluded that the leak was caused by the displacement of the carbon steel flange joint due to stress from road placement and backfilling (Figure 20). The leak at the mechanical joint at the pipe bend of the outside fire water supply pipe was determined to have been caused by the same reason (Figure 20). The pipe bend and joint were replaced, and the hold time of the jockey pump was extended from 35 seconds to 15 minutes.

On 1 January 2013, during a field walk-down, steam was observed rising from the outdoor gravel field between the fire water pump room and the water treatment room. On 5 January, after excavating around the leak area it was determined that the leak was caused by corrosion failure of a section of the oily waste separator pipe running from the auxiliary boiler room drain line to the oily waste separator. The root cause analysis attributed the failure to flow assisted corrosion acting on the 45 degree elbow, and external corrosion of the buried pipe also took place due to the degraded condition of the anti-corrosion tape. The failed portion of the existing carbon steel elbow and pipe (6 inch diameter, wall thickness 7.1 mm, Schedule 40) were replaced with stainless steel SUS 316 pipes. The newly replaced pipe was connected to the remaining section of the buried pipe using pipe coupling, and anti-corrosion taping was applied to protect the external pipe surface (Figure 21a).

Figure 20: The leaking flange joint of fire water supply pipe.

Figure 21: a) Corroded Elbow, b) Leak Area Wall Thickness Measurement, c) Underground Buried Pipe Coupling Connection, d) Anti-Corrosion Tape

	
(a)	(b)

(c) (d)

4.3.8 Slovak Republic (SK)

There are two operating nuclear power plants in the Slovak Republic, Jaslovské Bohunice and Mochovce, each with two reactor units. Each unit is a 6-loop PWR, Type VVER 440. At both plants, underground BP is primarily used in the circulating cooling water (CCW) system (cooling water to the main condenser) and ESW system. Both systems run below ground between the central pump station and the reactor building. The CCW system has BP at both plants, but the ESW piping system layouts differ. In comparison with Bohunice NPP, where ESW piping is completely buried, the ESW piping at the Mochovce NPP is placed in culverts. A large portion of the ESW underground piping at the Bohunice NPP is encased in concrete.

Chronology of BP failures in Bohunice NPP:

- 1999 – leak on discharge pipe DN800 on the ESW system I., locally repaired by metal welded patch.
- 2009 – 3 leaks discovered on the return pipe DN800 on the ESW system I., near the ESW cooling tower; section of pipe in the length of about 8 metres was replaced with new ones (Figure 22).
- 2011 – two local external leaks on the discharge pipe DN800 on ESW system I; these leaks were temporarily repaired using threaded sleeve anchors.
- 2013 – leaks on the pipeline providing additional water into the ESW system between the chemical water treatment building and the central pumping station.

Figure 22: The Leaking on the Return pipe DN800 on the ESW System I Near the ESW Cooling Tower.

Based on analyses, the following causes of ESW pipes failures were identified:

- Degradation of the pipe outer surface hydroinsulation.
- Mechanical damage due to improper backfill (not according to design).
- Chemical and biological processes under damaged insulation over the lifetime.
- Original hydroinsulation end-of-lifetime.
- Lack of CP.

Activities related to BP carried out in Bohunice NPP from 2009 to 2011:

- Studies on the degradation mechanisms causing perforations.
- Seismic inspections and inspection excavations to map the status of ESW piping.

In 2013, a technical survey of the concrete monolith and piping was carried out. It consisted of geo-radar geophysical inspection, core drilling to determine concrete compressive strength, absorbency concrete carbonation level in order to assess the further ability of passivation of steel reinforcement and pipe, concrete waterproofing and absorbency, and pH of concrete. Ultrasonic measurements of the pipe wall thickness were also performed. Based on the above, it was demonstrated that the assessed concrete structure was not damaged after 30-years of operation and exposure to climatic and geological effects not damaged and under current conditions it can be in the service for the next 30 years.

In 2014, the ESW modification was approved except for the concrete monolith. Modification was divided into two parts: a project for pipeline rehabilitation and a project for pipe replacement. The ESW return pipe from cooling towers to the pumping station inlet (gravitation pipes) was rehabilitated (sequential excavation of pipes during operation, insulation replacement, application of cold sleeve in corroded areas with wall thickness loss, application of hot sleeve when leaks detected). Pipes rehabilitation was carried out in 2015 and 2016.

The ESW pipeline sections from the central pump station to the concrete monolith and return ESW pipeline from the concrete monolith to the cooling towers were replaced. Replacement was carried out during a common outage of both units at Bohunice NPP in May 2016. The piping replacement project included the installation of CP.

4.3.9 *Spain (ES)*

According to the Spanish Nuclear Safety Council (CSN) Mandatory Instruction IS-22 (1 Jul 2009), the nuclear power plant owners are required to comply with the ageing management principles of

NUREG-1801 [21]. Consequently, all Spanish plants have in place an Ageing Management Plan, which includes Section XI.M41 "Buried and underground piping and tanks". It is a programme designed to manage ageing of external surfaces of buried and inaccessible pipes and deposits/tanks, which includes prevention and monitoring of material loss caused by the corrosion on the outer surface of the buried/underground pipes. However, the inspection of buried tanks does not apply in Spanish NPPs as there are no buried tanks in the scope of the Ageing Management Plan. Also, the external accessible pipes are handled with AMP-XI.M36 "External Surfaces Monitoring[26]". Preventive measures include anti-corrosion protection. The activities included in this programme are:

- Hydrostatic and leak tests of buried pipelines.
- Visual Inspection[27] (VT-1) (through testings) of the buried pipe systems.
- Opportunistic VI (testing) of buried pipelines[28].
- Monitoring of the cathodic protection system (CPS; only two Spanish NPP have CPS).
- Pressurising Jockey Pump Monitoring of the FPS (if chosen).

This AMP uses activities owned by the ISI Programme or specific surveillance programme of structural integrity of systems susceptible to corrosion degradation similar to those detected in the service water system of Vandellos II NPP in 2004 (VT-2 and VT-3).

Regarding monitoring/inspections, in general, it can be said that there are no direct inspections of buried pipes regularly, but inspection should be done if possible (there are opportunistic inspections to check the status of the external surfaces of buried pipelines) but some systems have their own planned visual inspection technique (VT) inspections rather than an opportunistic inspection triggered by a visibly degraded condition.

Regarding testing of specific systems and opportunistic inspections, any damage caused to the coating and/or the pipe by filling material is unacceptable. Coatings are acceptable if they continuously cover the surface (no exposed base metal) and welds/joints. Any signs of corrosion or cracks in steel piping, or changes in the material properties of plastic piping (discoloration, cracking, hardening, etc.) is unacceptable. The results of the inspection of the protective coating are used to determine if additional inspections are needed:

- VT-3 of the outer surface of the pipe: in case of signs of degradation detected in the coating that would have allowed contact between metal pipe with the ground.
- Measurement of thickness (UT or RT) of the pipe: if the results of a visual inspection identify a loss of material, thickness measurements will be performed of the damaged area.
- Visual inspections of the pipe elements (manholes and hydrant connections) exposed to air are performed at intervals of 5 years.

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26. This programme visually inspects the outer surface of the mechanical components (including pipes) within its scope and tracks of the outer surfaces of the metallic components of the systems subject to Ageing Management Review about the loss of material and leakage.

27. Visual inspection (VI): based on observation of the exposed surfaces of the inspection components, detecting and evaluating anomalies. It is typically the first step before any subsequent evaluation.

  - VT-1: detects discontinuities and imperfections in the surface of the components, including cracks, wear, erosion and corrosion.
  - VT-2: detects evidence of leakage in pressure retaining components during pressure testing.
  - VT-3: determines the general condition, mechanically and structurally, of the components. Detects discontinuities and imperfections, such as loss of flanged joints and integrity of welded joints, loss of parts, wear or erosion.

28. Any maintenance or similar that unearth or do a testing in one of the buried pipes within the scope of AMP-41 will conduct to an inspection of the external surface of that pipe.

- In the inspection guided by indications, performing a complete transmission route in the field of buried pipes is done at intervals of 3 years.
- In the sampling inspection, the programme includes inspection of samples of the lines defined in the scope of the maintenance rule at intervals of 3 years

Concerning staff qualification, personnel performing visual inspections on pipelines are qualified at least to Level I for VT and technical staff responsible for monitoring and evaluating the results are qualified to a minimum of Level II.

The current approach to below ground/BP ageing management in Spain has been tempered by the regulatory and industry actions in response to the 2004 ESW pipe break at Vandellos II (Figure 23). On 25 August 2004, when the plant was operating at 100% power, a break occurred in the below ground ESW system – a Bonna® pipe system. Specifically, an 800 mm diameter standpipe failed in the manhole area EF-18-I. On the following day, the plant staff decided to make a non-scheduled shutdown in order to proceed with the repair of the affected standpipe. A visual inspection was carried out before declaring the system operable. ESW Train B was returned to service on 27 August 2004.

During the visual inspection that followed the start-up of Train B, a small leak was detected through one of the previously inspected manhole areas. In this case, it concerned the area where the standpipe connects to the Train B main header in manhole area EF-32-Z3. Subsequently, all Train ‘A’ standpipes were inspected and minimum wall thickness calculations were performed.

In response to this event an independent root cause analysis was performed under the auspices of the IAEA and with contractor support. It was confirmed that the ESW pipe rupture occurred as a result of severe external corrosion of the standpipe. The analysis also revealed that the ESW system had been exposed to pervasive corrosion and exfoliation in the outer part of the manhole necks since 1993. This corrosion was due to inadequate protection of the steel against the erosive environment inside the hatches. Despite these findings, maintenance activities had not been improved. In the year 2000, no measurements were taken after a licensee internal inspection report had recommended an urgent measure of the thickness of EF-18-I manhole neck. On 10 May 2004, an oozing was identified in EF-18-I, the manhole neck that broke on 25 August 2004, and the utility did not declare a non-conforming status of the plant. Figure 24 shows the general arrangement of the ESW system and details of the affected section of below ground ESW piping are shown in Figure 25[29].

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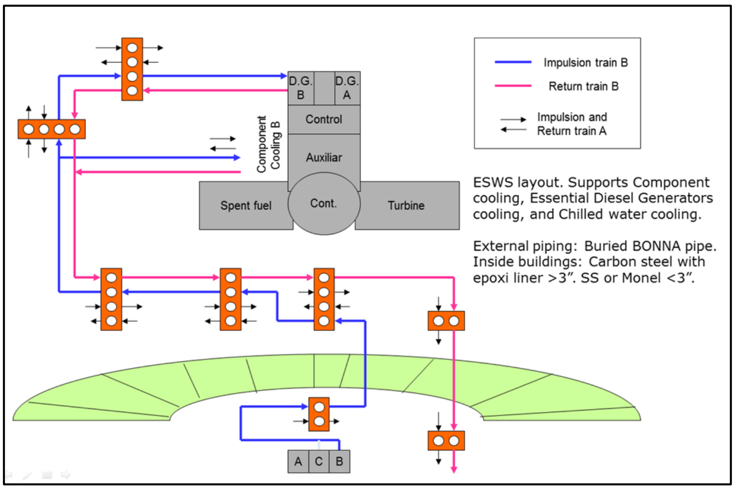
[29] Figures 23-25 are courtesy of the Spanish Nuclear Safety Council.

Figure 23: Arial View of Vandellos II Ultimate Heat Sink & ESW Intake Structure

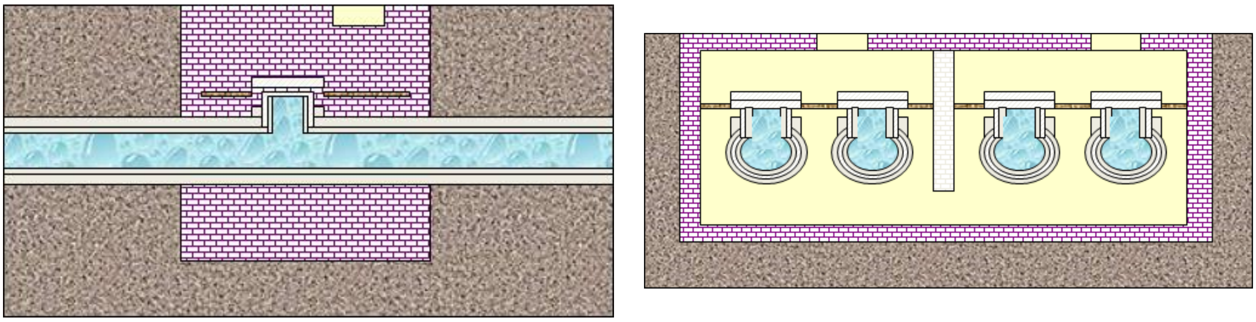
Figure 24: ESW System General Arrangement



ESWS layout. Supports Component cooling, Essential Diesel Generators cooling, and Chilled water cooling.

External piping: Buried BONNA pipe. Inside buildings: Carbon steel with epoxi liner >3”. SS or Monel <3”.

Figure 25: Details of Below Ground ESW Piping



The utility did not perform any thickness measurements of the manhole necks. Nor did the utility respond to earlier ESW system health reports that had warned about a process of pervasive corrosion. In response to the event[30]:

- The Spanish plants have developed, or are currently developing, augmented inspection programmes in order to maintain periodic surveillance of the below ground/BP systems.
- Different corrective actions have been established to eliminate or reduce problems of accessibility for the inspection of certain sections of underground piping.
- Most of the Spanish plants do not have CP systems for their underground piping or have ceased to use them. Those plants that still use such systems consider them to be a complementary method to ensure effective passive corrosion protection. Nevertheless, in the view of the Spanish regulator, the plants that have these systems in service should assess their effectiveness on a periodic basis.

4.3.10 Switzerland (CH)

Switzerland has five operating commercial nuclear power plants at four sites; two units at Beznau, and single reactor units at Gösgen-Däniken, Leibstadt and Mühleberg, respectively. The following below ground systems are found at the four plants sites:

- Service Water – Non-Safety-Related
- Service Water – Safety-Related, Safety Class 3[31]
- Fire Protection, Safety Class 424
- Drain System for Nuclear Buildings, Safety Class 424

The SW systems as well as the fire protection system contain only river and groundwater, respectively. The pipes are either buried in soil or within non-accessible concrete channels. The buried pipe in the Drain System for Nuclear Buildings is not accessible for direct inspection but is equipped with a shield tube (double-walled piping). Leaks from this pipe could be detected via the drain system of the shield tube.

The ISIs are performed according to the Swiss Directive SVTI-NE14 Rev. 6 [37]. Generally, the operating experience with the below ground piping systems has been good and as demonstrated through ISI and periodic performance tests of the systems. The outside diameter (OD) condition of the BP can and has been assessed though local VT whenever sections of the piping have been exposed during excavation activities within the owner controlled areas. The inside diameter (ID) material condition can to a certain degree be assessed by NDT of the easily accessible areas of the piping.

The following maintenance activities have been implemented for the below ground safety-related SW system piping:

- Coating of the inner surface of several buried carbon steel pipes with an Epoxy-coating.
- Replacement of a buried carbon steel pipe with a stainless steel pipe.
- Coating of the inner surface of several buried carbon steel pipes with a Polyethylene Inliner.
- Local assessment of OD piping condition by excavation of a representative area during maintenance of the road above the BP.

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[30] 2006 Spanish Nuclear Safety Council Report to the Parliament: "Lessons Learnt by the Test of the Plants as a Result of the Vandellós II Nuclear Power Plant Event," pp 18-19.

[31] As defined in Swiss Directive ENSI-G01, "Sicherheitstechnische Klassierung für bestehende Kernkraftwerke" (January 2011).

For the fire protection water system the following maintenance measures have been implemented:

- Selective replacement of carbon steel piping with Polyethylene piping whenever small leaks have been detected. Polyethylene piping replacements have also been performed as a preventive measure when larger sections of the piping have been exposed during excavation work done as part of road maintenance.

4.3.11 United States (USA)

This section describes notable BP leakage events in the United States and efforts by the US NRC and its licensees to address them, particularly leaks that involve the discharge of tritiated water. In 2009, BP leaks released water that contained low levels of tritium at Dresden, Oyster Creek and Peach Bottom nuclear plants. The levels of tritium did not exceed any NRC limits (that would be applicable on-site) and, after additional dilution and decay that would occur as a natural consequence of migration towards the site boundary, would not exceed any NRC limit off-site. Although these leaks did not exceed any NRC limits, either on-site or off-site, the level of tritium triggered the licensees to initiate voluntary communications with local and state officials.

In response to these leakage events, the NRC performed a collective significance review of BP degradation. In September 2009, the NRC Chairman issued a tasking memorandum that required the NRC staff to review the adequacy of regulations, codes, standards and industry activities related to degradation of BP. In response to the Chairman tasking memorandum, the NRC staff prepared SECY 09-0174, “Staff Progress in Evaluation of Buried Piping at Nuclear Reactor Facilities,” [38] which concluded that no immediate regulatory changes were necessary to address degradation of BP because a) leakage from BP was of low safety significance with respect to structural integrity of the piping, and b) the amount of radioactive material that has been released has been a small fraction of regulatory limits. Additionally, SECY 09-0174 described a number of ongoing NRC staff codes and standards, and industry activities. The NRC staff identified plans to review operating experience to continue to validate conclusions in the SECY paper and indicated it would continue its participation in codes and standards organisations efforts to incorporate changes in the state-of-the-art with respect to maintenance and evaluation of BP. On 14 September 2010, the NRR action plan on BP (i.e. the action plan) [39] was issued which outlined a plan to track the action items in SECY 09-0174. The action plan also tracked interaction with industry to understand whether, by 2015, their Buried Piping and Underground Piping and Tanks Integrity Initiatives (discussed below) ultimately reduced the incidence of degradation and leaks.

Independent of the NRC actions, in November 2009, the nuclear industry issued their “Buried Piping Integrity Initiative,” an executive level inter-utility agreement to address degradation of BP. The NRC staff identified actions necessary to understand the breadth of implementation and effectiveness of this initiative. Additionally, the NRC staff identified actions related to licence renewal, new reactors and the need to communicate about BP issues with licensees and other stakeholders

In September 2010, the industry developed the “Underground Piping and Tanks Integrity Initiative,” which extended the objectives and actions in the Buried Piping Integrity Initiative to all buried and underground piping and tanks that are not inside buildings regardless of whether or not they are in direct contact with soil. Actions in this plan that previously applied only to the Buried Piping Integrity Initiative applied to the full scope of both industry initiatives. The NEI report, “Guideline for the Management of Underground Piping and Tank Integrity,” [40] establishes the goals and requirements of the Underground Piping and Tanks Integrity Initiative (i.e. the Initiative). The goals of the Initiative are to (1) proactively assess and manage the condition of in-scope piping and tanks, (2) share operating experience within the industry, (3) guide the development of technologies to improve available inspection and analysis techniques and (4) “Improve regulatory and public confidence in the industry's management of the material condition of its underground tanks and piping systems." To meet the goals of the Initiative, industry agreed to implement certain measures deemed as requirements and others deemed as recommendations outlined in four elements:

1. Procedures and Oversight: (a) Ensures clear roles and responsibilities including senior level accountability and (b) Develops and maintains an Underground Piping and Tank Integrity Programme document and implementing procedures.
2. Risk Ranking and/or Prioritisation: (a) Requires risk ranking of in-scope items and provides risk-ranking categories, and (b) Prioritises items for inspection.
3. Inspection Plan: Requires the development and maintenance of an inspection plan that provides reasonable assurance of piping and tank integrity.
4. Asset Management Plan: Requires the development of an asset management plan based on inspection results.

A plan of action and milestones was established to complete the four elements of the Initiative above, including the execution of the inspection plans. As of 2016, all four elements were completed by all operating plants and the Initiative has transitioned into ongoing plant asset management programmes based on the asset management plans developed in element #4 above [41].

During 2010-2011, the Government Accountability Office (GAO) performed a review of NRC activities related to buried and underground piping. On 3 June 2011, the GAO issued GAO-11-563, "Oversight of Underground Piping Systems Commensurate with Risk, but Proactive Measures Could Help Address Future Leaks" [18], which contained a recommendation for the NRC staff to keep abreast of emerging inspection technology. A milestone was added to Revision 2 of the action plan in November 2011 to specifically address the GAO recommendation.

On 15 August 2011, the Commission issued a staff requirements memorandum (SRM) for SECY 2011-0019 [42] that approved the NRC staff's continued efforts to work with industry initiatives and consensus standards organisations. This SRM also stated, "If, based on its participation in consensus standard activities the staff determines that revisions to the agency's regulations are necessary to incorporate changes to the American Society of Mechanical Engineers (ASME) codes related to groundwater protection, the staff should seek Commission approval via a notation vote paper." An action item was added to Revision 2 of the action plan to address this requirement. Furthermore, the NRC completed activities associated with Temporary Instruction TI-182 and verified all plants were following the industry's Buried Piping Integrity Initiative and Underground Piping and Tanks Integrity Initiatives [43]. By November 2015, the NRC had completed all action items and closed the action plan.

Over the course of the six years while the action plan was in place, leakage associated with BP and underground tanks, when it has occurred, a) has been of low safety significance with respect to structural integrity, and b) the amount of radioactive material that has been released has been a small fraction of regulatory limits. Furthermore, over that time period rates of significant leakage events as tracked by the INPO initially increased and has since exhibited a decreasing trend consistent with improved maintenance and inspection practices. Reported significant leaks, those in safety-related piping or in piping containing environmentally hazardous material, increased from 8 to 15 from 2009 to 2010, but have since decreased to 8 in 2011, 5 in 2012, 4 in 2013 and 3 in 2014. Reporting of BP degradation and failure is done through:

- ASME XI ISI Owner Activity Reports: include information on repair/replacement activities associated with buried Code Class 3 piping.
- NRC Inspection Reports (IRs).

- NRC Event Notification Reports.
- Licensee Event Reports.
- INPO Consolidated Events Database/Equipment Performance Information Exchange (ICES/EPIX) database: this information is proprietary; data is input by each utility in the United States; the amount of data provided varies by utility.
- Licence Renewal Process: extensive operating experience data available on BP, but with focus on buried Condensate system piping, fire protection water system piping and SW system piping.

The US operating experience with BP is summarised in Figure 26 (below ground piping failures by system and time period), Figure 27 (below ground piping failures by plant type and calendar year) and Figure 28 (below ground piping failures by degradation mechanism). The ongoing licence renewal activity has generated a significant body of information regarding the below ground operating experience and ageing management activities. Examples of US plant below ground/BP corrosion failures include:

- In February 2005 (CODAP Event #4883), a leak was detected in a 4-inch condensate storage supply line. The cause of the leak was microbiologically influenced corrosion (MIC) or under deposit corrosion. The leak was repaired in accordance with ASME Section XI, "Repair/Replacement Plan."
- In October 2007 (CODAP Event #4053), degradation of ESW piping (ASME Code Class 3) was reported. The riser pipe leak was caused by a loss of pipe wall thickness due to external corrosion induced by the wet environment surrounding the unprotected carbon steel pipe. The corrosion processes that caused this leak affected all eight similar locations on the ESW riser pipes within vault enclosures and had occurred over many years. This event caused the plant owner to declare the ultimate heat sink for both units inoperable.
- In September 2008 (CODAP Event #4898), a malfunction in the turbine-generator (TG) led to high vibrations and a subsequent manual reactor trip. A TG hydrogen fire resulted when high TG vibration apparently caused TG hydrogen seals to fail. Portions of the Unit 1 TG fire suppression system automatically actuated. About 90 minutes into the event, a fire system low pressure alarm signalled a problem with the system. Operators stopped the site's three fire pumps. A section of fire protection system DN300 buried yard loop piping had failed early in the event resulting in the loss of at least 2 000 m^3 of water from the north fire water storage tank. The ruptured pipe was located under a large concrete pad that was resting against the Turbine Building wall on one side and sandy soil on the other. The water-based fire protection capability was lost for approximately four-and-a-half hours until the fire protection yard loop piping break had been isolated and fire protection water system pressure had been restored. The root cause analysis of the ruptured FP pipe determined that an unknown buried DN200 pipe located above the failed DN300 FP pipe may have inflicted a significant bending moment on the failed pipe.
- In February 2009 (CODAP Event #3261), a leak was discovered on an 8-inch return line to the condensate storage tank. The cause of the leak was coating degradation potentially due to rock impingement from the piping backfill. Rocks up to 8 inches in diameter were allowed in the original backfill specification in use at the time of construction. The licensee specified the use of high quality backfill for future BP excavation activities that does not contain objects damaging to protective coatings on piping.
- In April 2009 (CODAP Event #4884), a leak was discovered in a concrete encased aluminium pipe where it went through a concrete wall. The piping was for the condensate transfer system. The failure was caused by vibration of the pipe within its steel support system. This vibration led to coating failure and eventual galvanic corrosion between the aluminium pipe and the steel supports.

- In April 2010 (CODAP Event #1531), portions of the Unit 1 and Unit 2 auxiliary feedwater system (AFW) system piping is BP and had not been visually inspected since the plant began operation in 1977 for Unit 1 and since 1979 for Unit 2. This piping is safety related, 4.0" ID, ASME Class 3 piping. In April 2010, approximately 680 ft. (340 ft. of the Steam Generator No. 12 AFW supply and 340 ft. of the Steam Generator No. 14 AFW supply) of piping between the pump discharge manifold and the connection to the main feedwater piping to the affected SGs was discovered to be corroded to below minimum wall thickness (0.278") for the 13.4 MPa design pressure of the AFW System. The discovery was noted by the owner during a planned excavation to implement site-specific buried pipe inspection programme. The lowest wall thickness measured in the affected piping was 0.077". The pipe wall thinning was attributed to degraded pipe coating and corrosion.
- In November 2015 (CODAP Event #4899), following a smoke alarm caused by overheating some food in a kitchen area (no fire occurred), the B electric fire pump started. Once the B electric fire pump started, a large break developed in a 14 inch section of the buried high pressure fire system piping between the Unit 1/2 diesel generator building and the off gas treatment building. Due to a loss of system pressure caused by the leak, the A and C electric fire pumps and the diesel driven fire pump started in their expected sequence. The required system pressure of 300 feet of head could not be maintained with all four fire pumps running. The leak was not able to be isolated effectively for approximately 1 hour due to its location. The last successful test of a fire pump at rated system pressure occurred on 1 November 2015. The material used for the buried fire piping is susceptible to selective leaching and there were signs of selective leaching on the failed portion. The causal analysis determined the failure was caused by heavy vehicles driving over the pipe. The area near this piping did not have heavy vehicle traffic controls. The piping was buried deep enough where the heavy vehicles should not have caused the failure, but the combination of selective leaching and heavy vehicles caused the failure. The licensee has since updated their selective leaching programme for increased monitoring and placed restrictions on heavy vehicle traffic. The owner had experienced another pipe break due to heavy vehicle traffic during cooling tower construction in January 2014. The 2014 fire piping break did not cause a complete loss of high pressure fire protection system pressure. TS 5.4.1.d was the regulatory requirement covering operation of the owner’s fire protection programme at the time of the event. The licensee obtained a licence amendment to shift to the requirements of NFPA 805 effective 21 May 2016. The NRC determined that the owner’s failure to maintain the integrity and thus system pressure in the high pressure fire system piping was a performance deficiency.
- In March 2017 (CODAP Event #4961), Unit 1 experienced a sudden low alarm for the non-safety-related open loop cooling system. Operations personnel had been monitoring leakage from the open loop piping system since January 2017. Following a failure of the open loop cooling system piping (which is located in a below ground pipe tunnel), a controlled manual reactor shutdown ensued. It was estimated that over 1 000 m^3 of cooling water was released.

Figure 26: Below Ground Piping Failures by System & Time Period

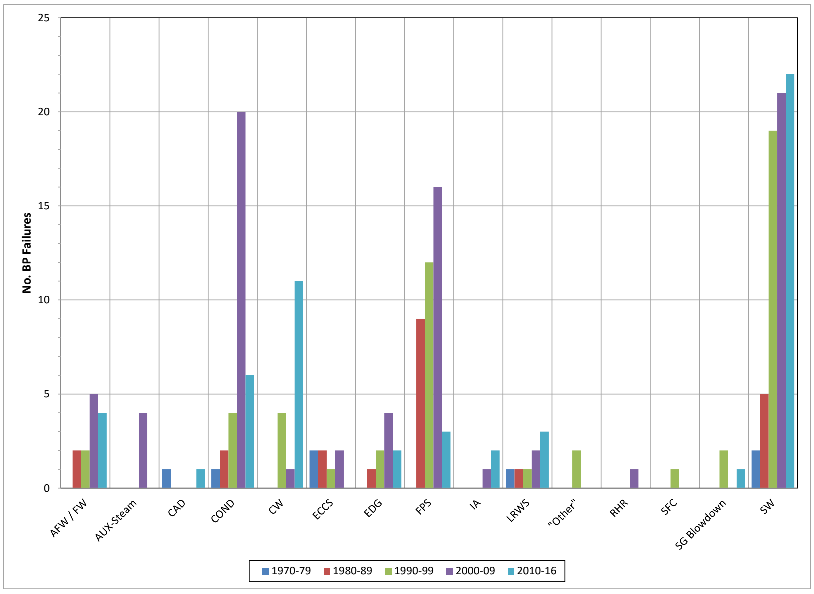


Figure 27: Below Ground Piping Failures by Plant Type & Year of Occurrence

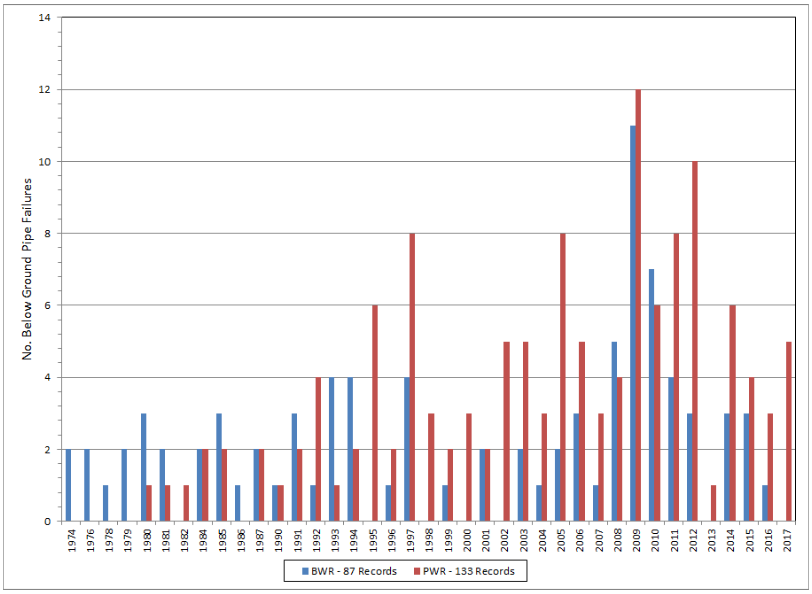
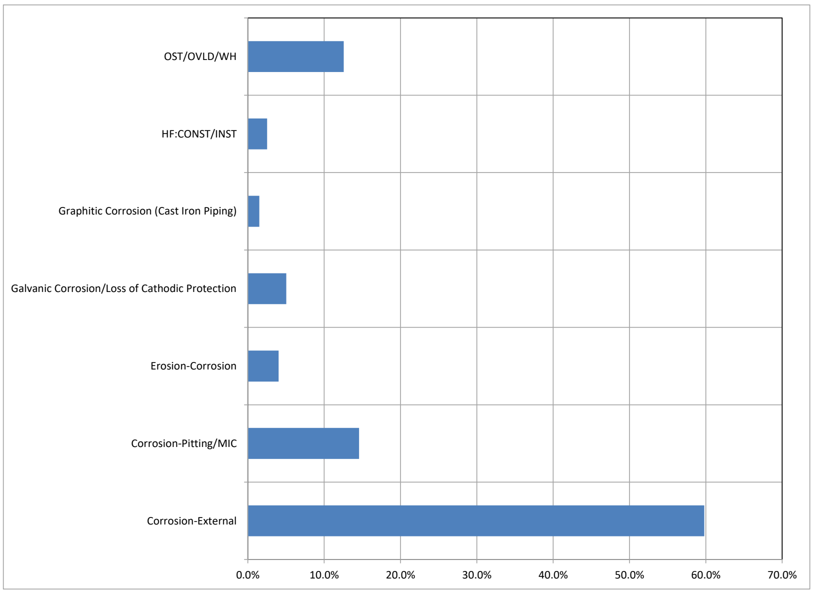


Figure 28: Below Ground Piping Failures by Damage/Degradation Mechanism



4.4 OE data analysis insights

This section presents an example of how the CODAP event database can be applied in support of below ground piping reliability analysis. The example is concerned with an assessment of below ground service water (SW) piping failure rates and break frequencies on the basis of the corresponding worldwide operating experience as recorded in CODAP. A technical approach to estimating the frequency of a pipe break on the basis of operating experience data is expressed by Equations (1) and (2). The magnitude (i.e. size of a pressure boundary breach) is expressed by an equivalent break size (EBS) “x” and corresponding peak through-wall flow rate. The parameter x is treated as a discrete variable representing different EBS ranges.

$$F(IE_x) = \sum_i m_i \rho_{ix} \qquad (1)$$

$$\rho_{ix} = \sum_k \lambda_{ik} P(R_x | F_{ik}) I_{ik} \qquad (2)$$

Where:

$F(IE_x)$ = Frequency of pipe break of size *x*, per reactor operating year, subject to epistemic (or state of knowledge) uncertainty calculated via Monte Carlo simulation.

m_i = Number of pipe welds (or fittings, segments or inspection locations of type i; each type determined by pipe size, weld type, applicable damage or degradation mechanisms, and inspection status (leak test and non-destructive examination). For the buried ESW piping the parameter m_i corresponds to the total length of piping being analysed.

ρ_{ix} = Frequency of rupture of component type *i* with break size *x*, subject to epistemic uncertainty calculated via Monte Carlo simulation (100 000 trials were used in this analysis).

λ_{ik} = Failure rate per "location-year" for pipe component type *i* due to failure mechanism *k*, subject to epistemic uncertainty; Equation 3 below. In this analysis the failure rate is calculated on the basis of per linear metre and reactor operating year. A lognormal distribution was used to characterise the a priori failure rate.

$P(R_x|F_{ik})$ = Conditional rupture probability (CRP) of size *x* given failure of pipe component type *i* due to damage or degradation mechanism *k*, subject to epistemic uncertainty. This parameter may be determined on the basis of probabilistic fracture mechanics, expert elicitation or service experience insights. This term was not utilised in this example because of the form of the operating experience data.

I_{ik} = Integrity (RIM) management factor for weld type i and failure mechanism k, subject to epistemic uncertainty determined by Monte Carlo simulation and Markov modelling. This parameter is not explicitly addressed in this example.

For a point estimate of the failure rate of piping component type i and degradation mechanism k:

$$\lambda_{ik} = \frac{n_{ik}}{\tau_{ik}} = \frac{n_{ik}}{f_{ik} N_i T_i} \qquad (3)$$

Where:

n_{ik} = Number of failures in pipe component of type *i* due to degradation mechanism *k*. The component boundary used in defining exposure terms is a function of the susceptibility to certain damage or degradation mechanisms. CODAP provides the number of failures of below ground large-diameter SW piping.

τ_{ik} = Component exposure population for welds of type *i* susceptible to degradation mechanism *k*.

f_{ik} = Estimate of the fraction of the component exposure population for piping component type *i* that is susceptible to degradation mechanism *k*, estimated from results of a formal degradation mechanism evaluation. In this example, it is assumed that each section of SW piping is equally susceptible to degradation; i.e. $f_{ik} = 1$.

N_i = Estimate of the average number of pipe components of type *i* per reactor in the reactor operating years of exposure for the data query used to determine n_{ik}. Determined from isometric drawings reviews for a population of plants and expert knowledge of degradation mechanisms. In this analysis, N = linear meter of SW piping on a per plant basis. The plant-to-plant variability is accounted for using three estimates for the component populations and subjectively assigning probabilities to weight the best estimates and upper and lower bounds. The best estimates are derived from a sample of plants for which details on the linear meter of SW piping is available. The upper and lower bounds were set at percentages above and below these estimates based on engineering judgement. The following values were used as input:

- Best estimate = 1 098 m
- Lower bound = 549 m
- Upper bound = 1 528 m

T_i = Total exposure in reactor-years for the data collection for component type *i*. CODAP event database provides the number of reactor operating years that produced the operating experience data. In this example, the SW failure population resulted from 3 042 reactor operating years (U.S. and non-U.S. operating experience).

For a Bayes' estimate, a prior distribution for the failure rate is updated using n_{ik} and τ_{ik} with a Poisson likelihood function. The formulation of Equation (2) enables the quantification of conditional failure rates, given the known susceptibility to the given damage or degradation mechanism. When the parameter f_{ik} is applied, the units of the failure rate are failures per piping component susceptible to the degradation mechanism of concern.

The above calculation format has been implemented in a Microsoft® Excel spreadsheet with two add-in programmes for Bayesian reliability analysis[32] and Monte Carlo simulation, respectively. Correlating an event population with the relevant plant and component populations that produced these failure events enables the estimation of reliability parameters for input to a calculation case. The information contained in a database must be processed according to specific guidelines and rules to support reliability parameter estimation.

This analysis accounts for two sources of uncertainty: 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). In the Bayesian reliability analysis, a lognormal prior distribution is assumed, and with a range factor (RF) of 100 and mean value of 1.0×10^{-7} per meter of piping and reactor operating year. The source of uncertainty that is attributed to varying pipe lengths is treated by using three estimates for the component populations and subjectively assigning probabilities to weight the best estimates and upper and lower bounds. The best estimates are derived from a sample of plant for which details on the piping component populations have been published. The upper and lower bounds were set at percentages above and below these estimates based on engineering judgement.

The Bayes' updating process was applied not once but three times to cover the range of estimates in the component populations. That process by its standard elements accounts for the uncertainty due to the scarcity of data by the use of a Poisson likelihood function; and Bayes' theorem itself performs the task of defining the proper weights between the prior and the likelihood functions in defining the final form of the posterior distributions. The selection of a large RF for the lognormal prior distribution provides results that have only a minor influence on the posterior distributions. The three Bayes' estimates are probabilistically combined in a Monte Carlo sampling process.

A first step in this data processing involves querying the event database by applying data filters that address the conjoint requirements for pipe degradation and failure. These data filters are an integral part of a database structure. Specifically, these data filters relate to unique piping reliability attributes and influence factors with respect to piping system design characteristics, design and construction practice, in-service inspection (ISI) and operating environment. A qualitative analysis of service experience data is concerned with establishing the unique sets of calculation cases that are needed to accomplish the overall analysis objectives and the corresponding event populations and exposure terms.

Illustrated in Figure 29 are the results of the SW piping reliability analysis based on service experience data as of 31 December 2016 and as a function of through-wall flow rate threshold values:

- Equivalent Break Size Class (EBSC) >1 corresponds to a very small, perceptible leakage. This calculation case captures all events of EBSC > 1, from very small to very large through-wall flow rates.
- EBSC > 6 corresponds to a relatively small leak; greater than 0.06 kg/s. Over time, this would be a leak of sufficient magnitude to cause soil erosion adjacent to leak site with the potential of propagating to a large leak.
- EBSC > 10 corresponds to a significant mass flow rate greater than 60 kg/s.

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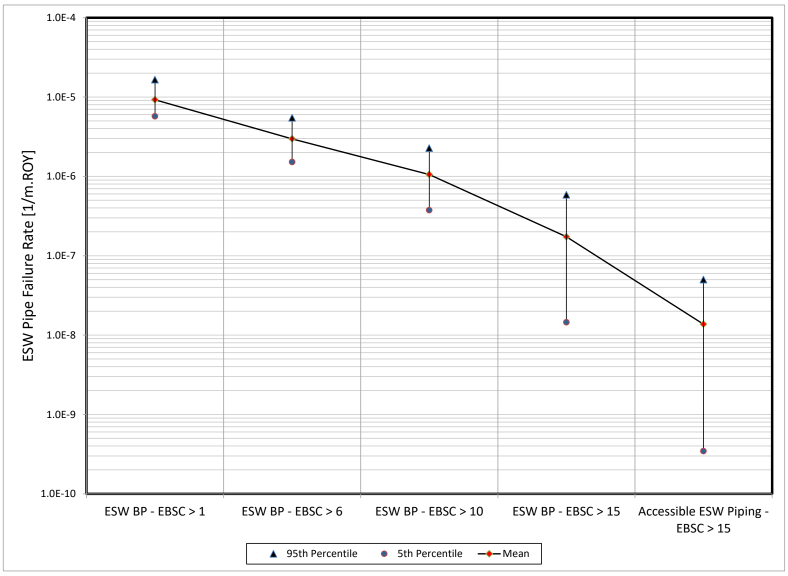
[32] In this example the stand-alone software R-DAT Plus was utilised (http://www.prediction-technologies.com/rdat.html) together with Oracle Crystal-Ball (http://www.oracle.com/us/products/applications/crystalball/overview/index.html) for Monte Carlo simulation.

- EBSC > 15, finally, corresponds to a very significant buried ESW pipe failure with a through-wall mass flow rate greater than 6 000 kg/s.

Included in Figure 29 for comparison is the calculated safety-related SW pipe failure rate for accessible, in-plant piping for EBS > 15 based on US operating experience [44][33]. These results account for the available operating experience data at the end of 2016. The difference in reliability of inaccessible (below ground) versus the accessible SW piping is attributed to differences in damage/degradation susceptibility and ageing management programme. References [44] [45] document the technical details of the calculation format for the herein documented piping reliability analysis example. Following on an evaluation of new below ground SW piping operating experience, including one significant pipe failure that occurred during the first quarter of 2017, the analysis was expanded to perform a new Bayesian update. The results of the expanded analysis are shown in Figure 30, which represents the state of knowledge as of mid-2017.

Figure 29: Comparison of Calculated Mean Cumulative SW Large-Diameter (≥ DN600) Pipe Failure Rates as a Function of Break Size – End of 2016 State of Knowledge



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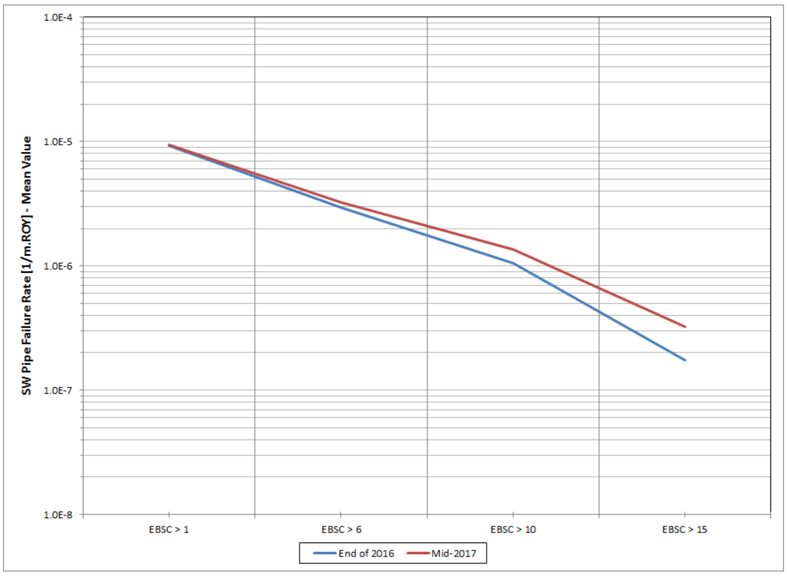
[33] From Table 3-23 of Reference [44].

Figure 30: Cumulative Below Ground SW Large-Diameter Pipe Failure Rate as a Function of Break Size – Mid-2017 State of Knowledge



4.5 HDPE piping operating experience

At some nuclear power plants, continued issues with pin-hole leaks, pitting, and other localised forms of pipe wall degradation due to MIC have resulted in the replacement of portions of or the entire buried carbon steel piping of the safety-related ESW systems, with high density polyethylene (HDPE). This material has demonstrated a high resistance to abrasion, fouling and general corrosion. Summarised in Table 6 are examples HDPE below ground piping applications.

Table 6: Selected HDPE Buried Piping Applications Plant

Plant	Application	In-Service Date	Length of Piping [m]
Callaway	Original cooling tower blowdown/discharge re-inforced plastic mortar (Techite®) BP replaced with 36-inch diameter HDPE pipe.	2006	11 400
	Original essential service water (ESW) carbon steel BP replaced with 36-inch (ESW supply/discharge) and 4-inch (ESW strainer backwash) HDPE piping.	2008	600
Catawba-1	Emergency Diesel Generator heat exchangers DN300 SW piping.	2011	1 200
Catawba-2		2010	
Catawba-1/2	Non-safety-related Service Water piping – 32-inch piping.	1995	6 600
Sizewell ‘B’	Replacement of original carbon steel safety-related SW piping with DN600 HDPE pipe.	2005	150

The rationale for using HDPE (PE 4170) materials is to eliminate the corrosion and erosion (or abrasion) susceptibilities. Furthermore, this material has high flexibility, ductility and resistance to soil movement. The non-nuclear industry experience with HDPE piping is very extensive (References [46] through [53]). The mechanical properties of HDPE material are summarised in Reference [48].

Examples of buried HDPE piping degradation mechanisms include stress cracking, creep and buckling. Reference [47] includes a detailed documentation of HDPE material characteristics including its seismic resistance and with reference to the 1995 Kobe (Japan) earthquake where "… the HDPE pipe for potable water piping used in this region performed 'very well with few failures', when compared to other pipe materials". It has also been reported that the toughness, ductility and flexibility of HDPE pipes, combined with their fully restrained butt-fused joints, make it well suited for installation in dynamic soil environments and in areas prone to earthquakes [52].

From December 2012 through March 2015, a total of 14 leaks and breaks occurred on the HDPE fire water supply piping system at Shin Kori Units 3 and 4[34], which were under construction and commissioning, respectively. The root cause analysis determined that the incompleteness of the system installation and inadequate venting led to the accumulation of air in some sections of the piping, which then caused a water hammer transient with ensuing pressure pulse in excess of the allowable pressure of the HDPE piping. Rapid crack growth occurred due to the water hammering at the location where the material quality had been degraded. The flaw developed in the axial direction and the ruptured surface analysis showed that it was an embrittlement rupture developed from the inside and out (Figure 31). It was a rapid crack propagation (RCP) S-shaped failure, an indication of air presence inside.

The leak occurred at a section of the fusion zone of the pipe because the incomplete fusion was not sufficient to withstand the system pressure. The leak area observation confirmed that the fusion was incomplete at most of the surface except the end (Figure 32 – showing the crack propagation path into the pipe). Evaluation of the water hammer transient showed that a large amount of stationary air is left in the T-section when performing a gravity make-up in a condition where the piping network is partially turned over. Under this condition, the opening of the hydrant at the end of the pipe system make-up caused a large water hammer (Figure 33). In response to this event, the entire length of the piping of the fire water supply system was replaced with a stainless steel material.

Figure 31: Ruptured Buried HDPE Fire Water Pipe and Cross Section.

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[34] Advanced Power Reactor-1400 (APR-1400). Unit 3 was connected to the grid on 15 January 2016.

Figure 32: Incomplete Fusion Zone.

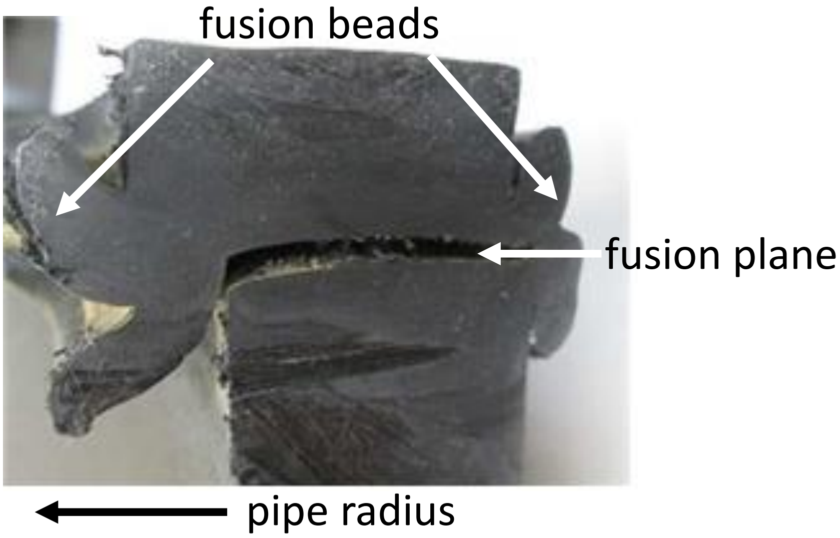
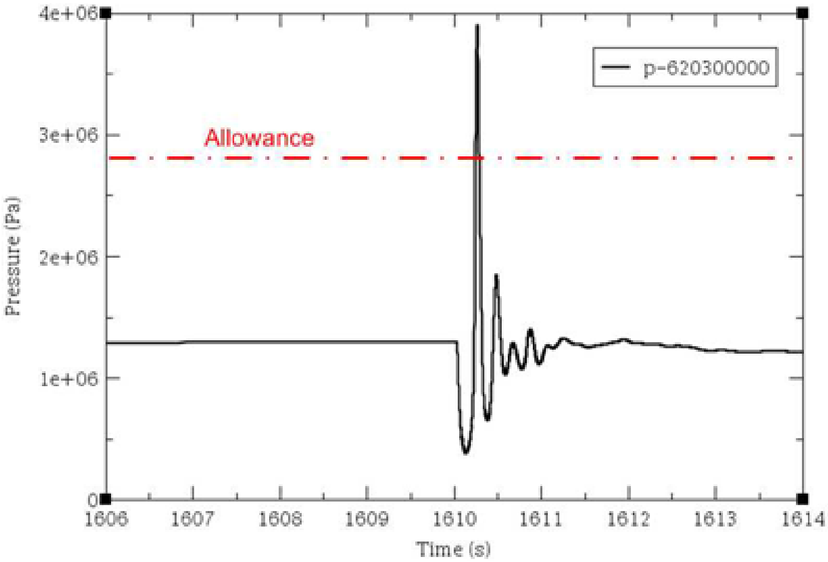


Figure 33: Pressure Behaviour when Opening T-section Outdoor Hydrant.



5. SUMMARY AND CONCLUSIONS

This report represents the fourth Component Operational Experience, Degradation and Ageing Programme (CODAP) topical report and it focuses on the operating experience with below ground piping systems in commercial nuclear power plants. Through an examination of the operating experience as recorded in the CODAP event database, the field experience with the different below ground piping systems is evaluated in order to draw qualitative and quantitative insights about the damage and degradation mechanisms and their potential plant operability and safety impacts. The report includes an example of how to assess below ground pipe failure probability on the basis of the CODAP event database.

5.1 Summary

Consequences of a below ground pipe failure on plant operation can have direct impacts (as in flow diversion and loss of the affected train or system or an initiating event as analysed in probabilistic safety assessment studies) or indirect impacts (e.g. the failure results in depletion of a tank and loss of the systems supplied by the tank). The operating experience as recorded in the CODAP event database includes examples of below ground pipe failures that have had multi-unit impacts as well as caused flooding of equipment areas and utility tunnels. An example of an initiating event could be the loss of Service Water (SW) or dual-unit loss of SW due to a below ground pipe failure. Another example of significant buried piping (BP) failure includes the loss of fire protection water due to a fire protection header break coincident with a fire suppression demand.

Since its inception in 2002, operating experience with below ground piping has been an intrinsic aspect of the technical scope of the CODAP database project. Specifically, CODAP collects data on below ground pipe failures with operational impacts as well as potential safety impacts. The scope of the CODAP event database is to collect, evaluate and exchange operating experience data on metallic passive components. In the database the earliest recorded buried pipe failure dates from April 1976 when a significant (ca. 3 kg/s) through-wall leak developed in a buried SW system pipe line at a US boiling water reactor (BWR) plant.

The report includes an example of how the CODAP event database can be used to obtain quantitative estimates of below ground piping reliability. Specifically, this example addresses the reliability of buried (or inaccessible) essential service water (ESW) piping and includes a quantitative comparison of inaccessible versus accessible ESW piping reliability.

5.2 Conclusions

Most, if not all commercial nuclear power plants have extensive below ground piping systems that transport cooling water to and from the plant, fire protection system water, emergency diesel generator fuel oil, instrument air and water containing radioactive isotopes (e.g. tritium). The amount and type of below ground piping systems vary significantly among nuclear power plants. As nuclear power plants age, their below ground piping systems tend to corrode, and since these systems are largely inaccessible it can be challenging to determine their structural integrity. The report includes the results of a survey of below ground piping systems in CODAP Project Review Group (PRG) member countries.

Some CODAP member countries (e.g. Canada, France and the United States) have implemented a risk-ranking methodology to identify the specific below ground piping locations that are most susceptible to degradation and failure. This risk-ranking methodology has been developed by the Electric Power Research Institute (EPRI) with support from plant operators and the American Society of Mechanical Engineers (ASME). A software implementation of EPRI's risk-ranking methodology was released in 2008.

The PRG identified on the order of 300 below ground pipe failures. Of the total data subset, ca. 75% represents the US operating experience. It is recognised that this 3:1 ratio is not a true reflection of the status of the below ground ageing management practices across the CODAP member countries but more a reflection of the generally greater accessibility to information about US events. The project member countries are responsible for making data submissions in an equitable manner. Except for "significant" failure events, information on degraded below ground piping is not generally available to regulators and its technical support organisations.

Based on the operating experience review, below ground SW system piping has produced the largest event population including several significant events with major operational impact. This system group includes non-safety-related and safety-related SW.

5.3 Recommendations

With respect to the continued database development and maintenance (i.e. data submissions and validation), it is recommended that the following items be considered in the ongoing data submission activities by the CODAP-PRG Members as well as in the current programme for an enhanced version of the online database ("CODAP Option 2" Project)[35]:

- Encourage the PRG membership to more actively share below ground piping operating experience insights. As a standing action, future working group meetings should expand the focus on technical discussions regarding how to utilise CODAP and how to share data analysis insights with the nuclear safety community.
- Within the PRG membership, share insights from ageing management programme audits with focus on below ground piping, including the associated non-destructive examination (NDE) experience.
- On the basis of the CODAP event database, the PRG membership should consider how to perform risk categorisation of below ground piping systems, conditional on different degradation susceptibilities and different reliability and integrity management (RIM) strategies.
- Expand the sharing of operating experience data within the PRG. future working group meetings should include as a standing action: national overviews of recent operational events, including the findings of root cause analyses; the technical as well as organisational factors contributing to material degradation and failures.

The CODAP-PRG faces two important future challenges. Firstly, while efforts have been made to promote CODAP and associated data project products to the nuclear safety community at large, there remain programmatic issues relative to how to make the restricted CODAP event database

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[35] Approved by the CODAP PRG at its 11th Working Group Meeting (May 2015), "CODAP Option 2" entails the development of software requirements specifications for an enhanced web based database.

available to probabilistic safety assessment (PSA) practitioners. Secondly, work remains to be done relative to the development of PSA-centric database application guidelines and associated analytical infrastructure (i.e. piping reliability analysis techniques and tools). Two initiatives are under consideration by the PRG to address the stated challenges:

- The Working Group on Risk Assessment (WGRISK) of the Committee on the Safety of Nuclear Installations (CSNI) is planning the "Joint Workshop on Use of NEA Data Project Operating Experience Data for Probabilistic Risk Assessment." It is recommended that the CODAP-PRG membership actively support this initiative and present insights from database application such as the buried ESW piping reliability assessment as documented in Section 4.4 of this report.
- Additionally, a proposal has been made for an international benchmark exercise concerning the use of service experience data to quantify piping reliability parameters for input to a standard problem application (e.g. risk-informed operability determination[36]). One possible first step could be to actively pursue the development of recommended guidelines for risk characterisation of below ground pipe failures.

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[36] The topic of an international benchmark exercise has been under discussion since the inception of the NEA Pipe Failure Data Exchange (OPDE)/CODAP Project.

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APPENDIX B

NUCLEAR PLANT SYSTEMS CROSS-REFERENCE TABLE

Table B-1: Plant Systems Cross-Reference Table

CODAP Generic(1)	Description	Czech Republic	France	Germany (7)		Finland (8) / Sweden
				AKZ	KKS	
ADS	BWR Primary Depressurization System (BWR)	N/A	N/A	TK, RA		314
AFW	Auxiliary Feedwater System		ASG	RQ		327
CC	Component Cooling Water System	TF	RRI	TF	LA	711/712
COND	Condensate System			RM, RN	LC	414/430 (3)
CRD	Control Rod Drive (Insert/Removal/Crud Removal)	--	RGL			354
CS	Containment Spray System	TQ	EAS			322
CVC	Chemical & Volume Control System (PWR)		RCV	TA, TC, TD	KB	334
Make-up Water	Water Inventory Control Function of the CVC System (PWR)		REA			
CW	Circulating Water System / Intake Cooling Water (ICW)		CRF			443
EHC	Electro Hydraulic Control System					442
EXT	Steam Extraction System		CEX			419/423
FPS	Fire Protection Water System	C-52	JPx		SGA	762
FW	Main Feedwater System		ARE	RL	LA	312/415 (4)
HPCS	High Pressure Core Spray (BWR)	N/A	N/A	TJ		--
HPSI	High Pressure Safety Injection (PWR)	TJ	RIS	TH	JN	--
IA	Instrument Air System	US	CAS			484
LPCI	Low Pressure Coolant Injection (BWR)	N/A	N/A			323 (5)
LPCS	Low Pressure Core Spray (BWR)	N/A	N/A	TK, TM		323
KC	Demineralised Water Storage & Transfer		SED			736
LK	Nitrogen Supply System		RAZ			754
LPSI	Low Pressure Safety Injection (PWR)	TH	RIS	TH	JN	--
MS	Main Steam System		VVP	RA	LB	311/411 (6)
MSR	Moisture Separator Reheater System		GSS	RB	LB	422

CODAP Generic(1)	**Description**	**Czech Republic**	**France**	**Germany** (7)		**Finland** (8) **/ Sweden**
				AKZ	**KKS**	
RCS	Reactor Coolant System (PWR)		RCP	YA, YB,	JA, JE	313
RHR	Residual Heat Removal System	(2)	RRA	TH	JN	321
RR	Reactor Recirculation System (BWR)	N/A	N/A			313
RPV-HC	RPV Head Cooling System (BWR)	N/A	N/A	TC		326
RVLIS	Reactor Vessel Level Indication System (BWR)	N/A	N/A			536
RWCU	Reactor Water Cleanup System (BWR)	N/A	N/A	TC	KB	331
S.A.	Service Air System	TL	SAT	TL	KL	753
SFC	Spent Fuel Pool Cooling System	TG	PTR	TG	FA	324
S/G Blowdown	Steam Generator Blowdown System (PWR)		APG	RS	LA	337
SLC	Standby Liquid Control System (BWR)	N/A	N/A			351
SW	Service Water System	VF	SEC	VE	PE	712/715

Notes:

1. See IEEE Std 805-1984 (IEEE Recommended Practice for System Identification in Nuclear Power Plants and Related Facilities) for information on system boundary definitions and system descriptions.
2. No dedicated RHR system in WWER-440 (decay heat removal is through natural circulation).
3. 414 for F1/F2/R1/R2/R3/R4 and 430 for O1/O2/O3.
4. 312 for O1/O2/O3 and 415 for F1/F2/R1/R2/R3/R4. Also note that 312 is the designation for steam generators in Ringhals-2/3/4.
5. Forsmark-3 & Oskarshamn-3.
6. 311 for O1/O2/O3 411 for F1/F2/R1/R2/R3/R4.
7. AKZ = Anlagen Kennzeichnungs System, KKS = Kraftwerk Kennzeichnungs System.
8. Olkiluoto Units 1 & 2.

APPENDIX C

GLOSSARY OF TECHNICAL TERMS

Backfill. The material used to refill the trench after the pipe and the embedment have been placed[39].

Backing Ring (BR). A backing ring is used to align two pipe sections before welding and eliminate the need for tack welding. Backing ring pins or nubs automatically set the weld gap.

Bayesian Reliability Analysis. In the Bayesian approach a subject matter expert develops a well-informed estimate of the probability of failure distribution – the prior state of knowledge. This probability distribution is then updated as more information is collected about the structural integrity of a certain piping system component.

Below-Grade Piping. Below ground piping with its location given relative to a reference point (e.g. ground level per a plant structure elevation).

Below Ground Piping. Buried piping in contact with soil or concrete and underground piping that is below grade, but is contained within a tunnel or vault such that it is in contact with air and is located where access for inspection is restricted

BONNA® Pipe. A thin steel pipe embedded in reinforced concrete. It has rebar or a heavy wire mesh embedded in the OD concrete.

Buried Piping. Piping that is below grade and in direct contact with soil. Buried piping is provided with corrosion protection such as coating and cathodic protection.

Cathodic Protection (CP). A corrosion protection technique in which the potential difference is applied to buried piping from an external power source or a more anodic material (sacrificial anode) for the purpose of making the piping behave in a cathodic manner. Through the use of CP, the corrosion rate is normally reduced to an acceptable level.

CFRP System: A buried piping rehabilitation and repair technique. It is comprised of high-strength carbon fibre fabrics and/or glass fibre fabrics, fully saturated in a two part 100% solids epoxy matrix. These laminates are bonded both longitudinally and circumferentially to the interior surface of the pipe forming a structural lining within the pipe. This lining can be designed to replace the degraded portions of the existing system without reliance on the degraded piping for the life of the repair, except at the terminal ends of the repair.

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[39] For additional details on buried piping backfill refer to: “Pipe Bedding and Backfill,” Geotechnical Training Manual No. 7, United States Department of the Interior, Bureau of Reclamation, Earth Sciences and Research Laboratory, Denver, CO.

Concrete Encased Piping (CEP). Below ground piping that is embedded in concrete. The piping is not easily extracted nor is the interior pipe surface readily accessible for inspection. The CEP category also includes piping recessed in plant building floors.

Crevice Corrosion. Crevice corrosion occurs in a wetted or buried environment when a crevice or area of stagnant or low flow exists that allows a corrosive environment to develop in a component. It occurs most frequently in joints and connections, or points of contact between metals and nonmetals, such as gasket surfaces, lap joints and under bolt heads. Carbon steel, cast iron, low-alloy steels, stainless steel, copper and nickel base alloys are all susceptible to crevice corrosion. Steel can be subject to crevice corrosion in some cases after lining/cladding degradation.

Cured-in-Place-Pipe (CIPP). A BP temporary repair method. A resin-saturated felt tube made of polyester, fibreglass cloth or a number of other materials suitable for resin impregnation, is inverted or pulled into a damaged pipe. It is usually done from the upstream access point (manhole or excavation).

Dealloying (Selective Leaching). As defined by NACE, "dealloying" or "selective leaching" refers to the selective removal of one element from an alloy by corrosion processes. A common example is the dezincification of unstabilised brass, whereby a weakened, porous copper structure is produced. The selective removal of zinc can proceed in a uniform manner or on a localised (plug-type) scale. It is difficult to rationalise dezincification in terms of preferential Zn dissolution out of the brass lattice structure. Rather, it is believed that brass dissolves with Zn remaining in solution and Cu replating out of the solution. Graphitic corrosion of grey cast iron, whereby a brittle graphite skeleton remains following preferential iron dissolution is a further example of selective leaching. During cast iron graphitic corrosion the porous graphite network that makes up 4-5% of the total mass of the alloy, is impregnated with insoluble corrosion products. As a result, the cast iron retains its appearance and shape but is weaker structurally. Testing and identification of graphitic corrosion is accomplished by scraping through the surface with a knife to reveal the crumbling of the iron beneath.

Double-Walled Pipe. A double-walled pipe is a secondary contained piping system. It is a pipe-within-a-pipe, or encased in an outer covering, with an annulus (interstitial space) between the two diameters. The inner pipe is the primary or carrier pipe and the outer pipe is called the secondary or containment pipe.

Epistemic Uncertainty. It is scientific uncertainty in the piping reliability model. It is due to limited data (or completeness of the database) and knowledge. The epistemic uncertainty is characterised by alternative models. For discrete random variables, the epistemic uncertainty is modelled by alternative probability distributions.

Equivalent Break Size (EBS). The calculated size of a hole in a pipe given a certain through-wall flow rate and for a given pressure.

Frazil Ice. A collection of loose randomly oriented needle-shaped ice crystals in water that is too turbulent to freeze solid. It resembles slush and has the appearance of being slightly oily when seen on the surface of water.

Fusion (or Heat Fusion). In the context of HDPE piping design and installation, fusion techniques are used to join pipes together. It is a welding process used to join two different pieces of a thermoplastic. This process involves heating both pieces simultaneously and pressing them together. The two pieces then cool together and form a permanent bond

Holiday in Pipe Coating. A holiday is a hole or void in the coating film which exposes the buried piping to corrosion.

JRC Operating Experience Clearinghouse (CE-OEF). Located in Petten, The Netherlands, the Clearinghouse gathers nuclear safety experts performing the following technical tasks in support to the EU Member States:

- “Topical Studies” providing in-depth assessment of either particularly significant events or families of events. These studies are drafted by experts on the topic and based on an analysis of usually hundreds of event reports.
- Trend analysis of events in order to identify priority areas.
- Improvement of the quality of event reports submitted by the EU Member States to the International Reporting System jointly operated by the NEA and the IAEA.
- Reporting every three months the main events having occurred in NPPs.
- Database: a European central OE repository being developed in order to ensure long-term storage of OE and to facilitate information retrieval.
- Further to these activities, the EU Clearinghouse is participating to several international co-operation projects on OE, mainly through the IAEA and the NEA working groups.

Limiting Condition for Operation (LCO). According to the Technical Specifications[40], an LCO is the lowest functional capability or performance level of a piece of equipment required for safe operation of a nuclear plant. When an LCO cannot be met, the reactor must be shut down or the licensee must follow any remedial action permitted by the Technical Specifications until the condition can be met.

Pipeline Inspection Gauge (PIG). In-line inspection pigs or smart pigs, gather information about the pipeline from within. The type of information gathered by smart pigs includes the pipeline diameter, curvature, bends, temperature and pressure, as well as corrosion or metal loss. Inspection pigs utilise two methods to gather information about the interior condition of the pipeline: magnetic flux leakage (MFL) and ultrasonics (UT). MFL inspects the pipeline by sending magnetic flux into the walls of the pipe, detecting leakage, corrosion, or flaws in the pipeline. Ultrasonic inspection directly measures the thickness of the pipe wall by using ultrasonic sounds to measure the amount of time it takes an echo to return to the sensor

Selective Leaching. Also referred to as dealloying, demetalification, parting and selective corrosion, is a corrosion type in some solid solution alloys, when in suitable conditions a component of the alloys is preferentially leached from the material. The less noble metal is removed from the alloy by a microscopic-scale galvanic corrosion mechanism. The most susceptible alloys are the ones containing metals with high distance between each other in the galvanic series (e.g. copper and zinc in brass).

TECHITE® Pipe. Fibreglass (or Fibre Reinforced Polymer) reinforced mortar pipe. This type of piping has found very limited use in cooling tower blowdown/discharge applications. This material can be affected by the environment, becoming brittle or soft, and breaking or leaking.

Tritium. Tritium is a naturally occurring radioactive form of hydrogen that is produced in the atmosphere when cosmic rays collide with air molecules. As a result, tritium is found in very small or trace amounts in groundwater throughout the world. It is also a by-product of the production of electricity by nuclear power plants. Tritium emits a weak form of radiation, a low-energy beta particle similar to an electron. The tritium radiation does not travel very far in air and cannot penetrate the skin.

Tritium in Nuclear Power Plants. Most of the tritium produced in nuclear power plants stems from a chemical, known as boron, absorbing neutrons from the plant's chain reaction. Nuclear reactors

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[40] “Betriebshandbuch” in German.

use boron, a good neutron absorber, to help control the chain reaction. Towards that end, boron either is added directly to the coolant water or is used in the control rods to control the chain reaction. Much smaller amounts of tritium can also be produced from the splitting of Uranium-235 in the reactor core, or when other chemicals (e.g. lithium or heavy water) in the coolant water absorb neutrons. Like normal hydrogen, tritium can bond with oxygen to form water. When this happens, the resulting "tritiated" water is radioactive. Tritiated water (not to be confused with heavy water) is chemically identical to normal water and the tritium cannot be filtered out of the water.

Type A Sleeve (Reinforcing). Used for the repair of non-leaking defects (e.g. pitting, wall thinning) of below ground pipelines. Such a sleeve provides reinforcement for the defective area.

Type B Sleeve (Pressure Containing). A type of steel sleeve used to make pipeline leak repairs. The ends of a Type B sleeve are fillet welded to the carrier pipe.

Unified Numbering System. An alloy designation system in use in North America. It consists of a prefix letter and five digits designating a material composition. For example, a prefix of S indicates stainless steel, C indicates copper, brass or bronze alloys.

Yoloy Pipe. A high-strength low-alloy steel with enhanced corrosion resistance (ASTM A-714).

VT-1 Examination. A limited visual examination specific to ASME Section XI which is the observation of exposed surfaces of a part, component, or weld to determine its physical condition including such irregularities as cracks, wear, erosion, corrosion, or physical damage.

VT-2 Examination. Per ASME XI, VT-2 is a visual surface examination to locate evidence of leakage from pressure-retaining components.

VT-3 Examination. A limited visual examination specific to ASME Section XI which is the observation to determine the general mechanical and structural condition of components and their supports, such as the verification of clearances, settings, physical displacements, loose or missing parts, debris, corrosion, wear, erosion, or the loss of integrity at bolted or welded connections. The VT-3 examinations shall include examinations for conditions that could affect operability of functional adequacy of snubbers, and constant load and spring type supports. The VT-3 examination is intended to identify individual components with significant levels of existing degradation. As the VT-3 examination is not intended to detect the early stages of component cracking or other incipient degradation effects, it should not be used when failure of an individual component could threaten either plant safety or operational stability. The VT-3 examination may be appropriate for inspecting highly redundant components (such as baffle-edge bolts), where a single failure does not compromise the function or integrity of the critical assembly.

Visual Examination. The oldest and most commonly used non-destructive examination (NDE) method is Visual Testing , which may be defined as “an examination of an object using the naked eye, alone or in conjunction with various magnifying devices, without changing, altering, or destroying the object being examined.” Per ASME XI, there are three different VT methods; VT-1, VT-2 and VT-3.

WEKO-SEAL®. A flexible rubber leak clamp that ensures a non-corrodible, tight seal around the full inside circumference of the pipe joint area. The design incorporates a series of proprietary lip seals that create a leak proof fit on either side of the joint.

Weldolet. The most common of all branch connections, and is welded onto a larger-diameter pipe. The ends are bevelled to facilitate this process, and therefore the “weldolet” is considered a butt-weld fitting. Weldolets are designed to minimise stress concentrations and provide integral reinforcement.