IAEA Nuclear Energy Series

No. NR-T-3.34

Basic Principles

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Management of Ageing and Obsolescence of Instrumentation and Control Systems and Equipment in Nuclear Power Plants and Related Facilities Through Modernization

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MANAGEMENT OF AGEING AND OBSOLESCENCE OF INSTRUMENTATION AND CONTROL SYSTEMS AND EQUIPMENT IN NUCLEAR POWER PLANTS AND RELATED FACILITIES THROUGH MODERNIZATION

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IAEA NUCLEAR ENERGY SERIES No. NR-T-3.34

MANAGEMENT OF AGEING AND OBSOLESCENCE OF INSTRUMENTATION AND CONTROL SYSTEMS AND EQUIPMENT IN NUCLEAR POWER PLANTS AND RELATED FACILITIES THROUGH MODERNIZATION

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology. While the guidance provided in IAEA Nuclear Energy Series publications does not constitute Member States' consensus, it has undergone internal peer review and been made available to Member States for comment prior to publication.

The IAEA safety standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA safety standards are referred to as the current boundary conditions for the application of nuclear technology.

A significant number of nuclear power plants around the world employ instrumentation and control systems and equipment (including cabling) that have been in service for many years. As a result, equipment ageing and obsolescence issues are becoming increasingly prevalent.

The ageing of instrumentation and control equipment has the potential to degrade the performance and reliability of such systems, which in turn can lead to a reduction in safety margins and an increase in operating and maintenance costs. The obsolescence of instrumentation and control equipment (hardware and software) can compound matters by making it difficult to source suitable replacements and to maintain adequate levels of replacement parts. Therefore, robust ageing and obsolescence management of this equipment is vital.

In 2019 the IAEA Technical Working Group on Nuclear Power Plant Instrumentation and Control recognized that information was needed to develop a strategy for managing instrumentation and control system and equipment ageing and obsolescence when it comes to replacing old technology with modern smart technology. This publication provides such information, which is based on recent operator experience.

The information in this publication builds on other IAEA publications on the topic of ageing management issued in the IAEA Safety Standards Series, the Safety Reports Series and the IAEA Nuclear Energy Series and in IAEA Technical Documents (TECDOCs).

The IAEA wishes to acknowledge the valuable assistance provided by the contributors and reviewers listed at the end of the publication, in particular the contribution of R.C. Green (United Kingdom) as the Chair of the authoring group. The IAEA officer responsible for this publication was J. Eiler of the Division of Nuclear Power.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

A significant number of nuclear power plants (NPPs) around the world employ instrumentation and control (I&C) systems and equipment (including cabling) which have been in service for many years. As a result, equipment ageing and obsolescence issues are becoming increasingly prevalent.

The ageing of I&C equipment has the potential to degrade the performance and reliability of I&C systems, which in turn can lead to a reduction in safety margins and an increase in operating and maintenance (O&M) costs. Obsolescence of I&C equipment (hardware and software) can also compound matters by making it difficult to source suitable replacements and to sustain adequate levels of spares. Therefore, robust ageing and obsolescence management of I&C equipment is vitally important.

There are three main top level ageing and obsolescence management strategies that can be employed to increase the operating lives of systems (see Fig. 1):

(1) Retain and sustain equipment;
(2) Wholesale equipment replacement;
(3) A combination of (1) and (2).

Figure 1 is a simplified graphical representation of the ‘reliability bathtub curve’ and does not therefore take into account the potential for strategies (2) and (3) to introduce ‘infant mortality’ failures.

In relation to strategies (2) and (3), replacing old technology with modern technology (especially with smart technology) can permit system performance improvements to be made. Examples of such improvements include the addition of improved accuracy and configurability, integrated controls and fault monitoring/logging/reporting as well as diagnostic capabilities. Furthermore, an appropriate, fault tolerant, design can have benefits such as increasing system reliability and reducing O&M costs.

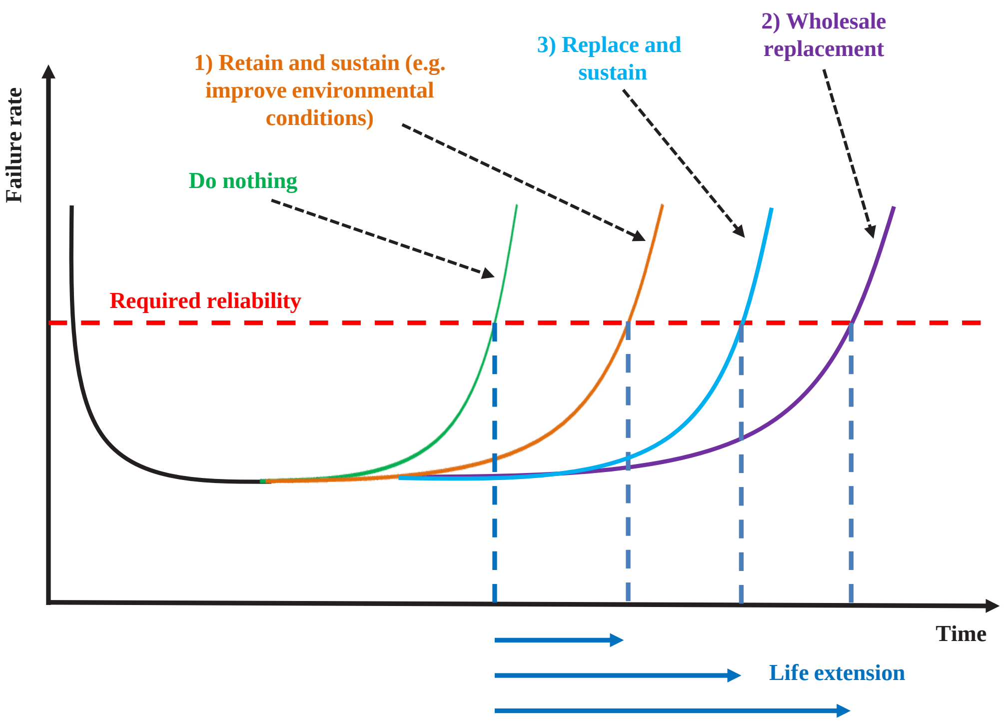


FIG. 1. Main top level ageing and obsolescence management strategies.

However, the modernization of I&C systems/equipment can bring with it a number of challenges, such as the need to:

— Identify suitable replacement equipment technology.
— Determine how to replace systems/equipment while maintaining required operating capabilities and adequate safety margins.
— Establish how to integrate replacement systems with older systems that are based on different technologies.
— Ensure that all reasonably foreseeable ageing equipment degradation mechanisms and effects have been identified, understood and accounted for in the design of the equipment.
— Obtain sufficient and suitable evidence to support software integrity claims.
— Ensure that personnel are trained and qualified to use and maintain the replacement systems/equipment.
— Ensure that potential cybersecurity vulnerabilities associated with modern smart technologies are appropriately managed.

This publication provides information on strategies for managing I&C system and equipment ageing and obsolescence based on the experience of NPP operators in overcoming these challenges.

1.2. OBJECTIVE

The objectives of this publication are to highlight:

— Pertinent IAEA recommendations and guidance on I&C system/equipment ageing and obsolescence management and relevant good practice.
— Key ageing and obsolescence related issues that need to be taken into consideration when modernizing I&C systems/equipment.
— Strategies that could be employed to address such issues.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE

This publication provides ageing and obsolescence management information in relation to I&C systems and equipment, and is applicable to:

— I&C systems/equipment used by, and intended for use, in:
  - All types of NPPs;
  - Spent fuel storage and radioactive waste management facilities that are related to NPPs.
— All phases in the life cycle of NPPs/facilities;
— All phases in the life cycle of I&C systems/equipment.

This publication does not provide guidance regarding the structure and implementation of an ageing management programme, nor does it provide guidance in relation to the qualification of I&C equipment, as these topics are covered in detail in other IAEA publications. Although this publication takes the NPP operator’s viewpoint and is aimed at existing NPPs and related facilities, the information provided is also considered relevant to I&C systems/equipment vendors and new-build programmes.

Regulatory bodies can use this publication when preparing regulatory requirements, codes, standards and guidance, and when verifying that effective ageing and obsolescence management arrangements have been implemented at NPPs and related facilities. Note that the term ‘equipment’ in the context of this publication also includes components and cables.

This publication builds on information already published by the IAEA, such as IAEA Safety Standards Series No. SSG-48, Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants; Safety Reports Series No. 82 (Rev. 1), Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL); IAEA-TECDOC-1147, Management of Ageing of I&C Equipment in Nuclear Power Plants; IAEA-TECDOC-1389, Managing Modernization of Nuclear Power Plant Instrumentation and Control Systems; IAEA-TECDOC-1402, Management of Life Cycle and Ageing at Nuclear Power Plants: Improved I&C Maintenance; and IAEA Nuclear Energy Series No. NP-T-3.6, Assessing and Managing Cable Ageing in Nuclear Power Plants.

1.4. STRUCTURE

This publication is organized into six major sections (including the introduction in Section 1), one Appendix and six annexes. Section 2 lists relevant IAEA safety requirements and guidance applicable to the subjects covered in the publication. Section 3 discusses I&C equipment ageing management, including ageing related degradation mechanisms and effects, ageing identification techniques, data capture and trending, life cycle considerations and maintenance strategies that can be employed to prevent/mitigate equipment ageing.

Section 4 outlines I&C equipment obsolescence management, including the relevant phases of the related processes. Section 5 introduces assessment methodology for the choice of modernization strategies, including the decision making process and the justification of the selected solutions. Section 6 covers I&C modernization issues and strategies to cope with equipment obsolescence.

The Appendix describes a specific case of cable ageing management using condition monitoring (CM) techniques. The six annexes provide case studies of Member State practices related to I&C system/equipment modernization.

2. RELEVANT IAEA SAFETY REQUIREMENTS, RECOMMENDATIONS AND GUIDANCE

2.1. RELEVANT IAEA SAFETY REQUIREMENTS FOR MANAGING AGEING AND OBSOLESCENCE

Specific safety requirements for the design, commissioning and operation of NPPs have been established in the following IAEA safety standards publications:

— IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design [1].
— IAEA Safety Standards Series No. SSR-2/2 (Rev. 1), Safety of Nuclear Power Plants: Commissioning and Operation [2].

The importance of systematically managing the ageing and obsolescence of structures, systems and components (SSCs) is recognized in the IAEA safety standards publications cited above, which contain the following relevant safety requirements:

— IAEA Safety Standards Series No. SSR-2/1 (Rev. 1) [1].

“**Requirement 30: Qualification of items important to safety.**

A qualification programme for items important to safety shall be implemented to verify that items important to safety at a nuclear power plant are capable of performing their intended functions when necessary, and in the prevailing environmental conditions, throughout their design life, with due account taken of plant conditions during maintenance and testing.

5.48. The environmental conditions considered in the qualification programme for items important to safety at a nuclear power plant shall include the variations in ambient environmental conditions that are anticipated in the design basis for the plant.

5.49. The qualification programme for items important to safety shall include the consideration of ageing effects caused by environmental factors (such as conditions of vibration, irradiation, humidity or temperature) over the expected service life of the items important to safety. When the items important to safety are subject to natural external events and are required to perform a safety function during or following such an event, the qualification programme shall replicate as far as is practicable the conditions imposed on the items important to safety by the natural external event, either by test or analysis, or by a combination of both.

5.50. Any environmental conditions that could reasonably be anticipated and that could arise in specific operational states, such as in periodic testing of the containment leak rate, shall be included in the qualification programme.

“**Requirement 31: Ageing management.**

The design life of items important to safety at a nuclear power plant shall be determined. Appropriate margins shall be provided in the design to take due account of relevant mechanisms of ageing, neutron embrittlement and wear out and of the potential for age related degradation, to ensure the capability of items important to safety to perform their necessary safety functions throughout their design life.

5.51. The design for a nuclear power plant shall take due account of ageing and wear out effects in all operational states for which a component is credited, including testing, maintenance, maintenance outages, plant states during a postulated initiating event and plant states following a postulated initiating event.

5.52. Provision shall be made for monitoring, testing, sampling and inspection to assess ageing mechanisms predicted at the design stage and to help to identify unanticipated behaviour of the plant or degradation that might occur in service.”

— IAEA Safety Standards Series No. SSR-2/2 (Rev. 1) [2].

“**Requirement 14: Ageing management.**

The operating organization shall ensure that an effective ageing management programme is implemented to ensure that required safety functions of systems, structures and components are fulfilled over the entire operating lifetime of the plant.

4.50. The ageing management programme shall determine the consequences of ageing and the activities necessary to maintain the operability and reliability of structures, systems and components. The ageing management programme shall be coordinated with, and be consistent with, other relevant programmes, including the programme for periodic safety review. A systematic approach shall be taken to provide for the development, implementation and continuous improvement of ageing management programmes.

4.51. Long term effects arising from operational and environmental conditions (i.e. temperature conditions, radiation conditions, corrosion effects or other degradations in the plant that may affect the long term reliability of plant equipment or structures) shall be evaluated and assessed as part of the ageing management programme. Account shall be taken in the programme of the safety relevance of structures, systems and components.

“**Requirement 16: Programme for long term operation.**

Where applicable, the operating organization shall establish and implement a comprehensive programme for ensuring the long term safe operation of the plant beyond a time-frame established in the licence conditions, design limits, safety standards and/or regulations.

4.53. The justification for long term operation shall be prepared on the basis of the results of a safety assessment, with due consideration of the ageing of structures, systems and components. The justification for long term operation shall utilize the results of periodic safety review and shall be submitted to the regulatory body, as required, for approval on the basis of an analysis of the ageing management programme, to ensure the safety of the plant throughout its extended operating lifetime.

4.54. The comprehensive programme for long term operation shall address:

(a) Preconditions (including the current licensing basis, safety upgrading and verification, and operational programmes);
(b) Setting the scope for all structures, systems and components important to safety;
(c) Categorization of structures, systems and components with regard to degradation and ageing processes;
(d) Revalidation of safety analyses made on the basis of time limited assumptions;
(e) Review of ageing management programmes in accordance with national regulations;
(f) The implementation programme for long term operation.”

2.2. IAEA RECOMMENDATIONS AND GUIDANCE FOR MANAGING AGEING AND OBSOLESCENCE

To help Member States meet the requirements described , the IAEA has produced the following generic (i.e. non-I&C specific) publications which provide guidance on the ageing and obsolescence programmes and associated activities that need to be undertaken during each phase of an NPP’s life cycle:

— IAEA Safety Standards Series No. SSG-48, Ageing Management and Development of a Programme for Long Term Operation of Nuclear Power Plants [3];
— IAEA Safety Standards Series No. SSG-69, Equipment Qualification for Nuclear Installations [4];
— Safety Reports Series No. 82 (Rev. 1), Ageing Management for NPPs: International Generic Ageing Lessons Learned (IGALL) [5].

In addition to the above, the IAEA has also produced the following I&C specific ageing and obsolescence related publications:

— IAEA-TECDOC-1402, Management of Life Cycle and Ageing at Nuclear Power Plants: Improved I&C Maintenance [6];
— IAEA-TECDOC-1389, Managing Modernization of Nuclear Power Plant Instrumentation and Control Systems [7];
— IAEA-TECDOC-1147, Management of Ageing of I&C Equipment in Nuclear Power Plants [8];
— IAEA Nuclear Energy Series No. NP-T-3.6, Assessing and Managing Cable Ageing in Nuclear Power Plants [9].

This publication is intended to supplement the IAEA publications mentioned above and can be considered along with these publication.

3. AGEING MANAGEMENT OF I&C EQUIPMENT

3.1. INTRODUCTION: DEFINITION OF AGEING EQUIPMENT

In the context of this publication, ‘ageing equipment’ is equipment which is degrading at such a rate that its ability to deliver its required function(s) within its specified operating life could be threatened. Thus, it is important to recognize that ‘ageing equipment’ and ‘degrading equipment’ are not always synonymous.

Furthermore, there are many examples where the integrity of equipment that has been in service for many years has remained high, while the integrity of equipment which has been in service for just a few years has significantly decreased. Therefore, it is important to note that the rate of degradation can be affected by many factors and is not always a linear function of time. Thus, it also needs to be recognized that ‘ageing equipment’ and ‘old equipment’ are not always synonymous.

3.2. AGEING RELATED DEGRADATION MECHANISMS AND EFFECTS

I&C equipment can be affected by a wide range of degradation mechanisms, the impact of which will vary due to a number of factors, such as:

— How the equipment has been designed, fabricated and installed.
— The materials used to manufacture the equipment.
— The equipment’s tolerance to drift and failure.
— The equipment’s operating environment (i.e. its exposure to degradation mechanisms).
— How the equipment is maintained.
— The potential for the degradation mechanisms to interact with each other.
— The duty cycle of the equipment (i.e. continuous or intermittent use). Equipment designed for intermittent use is likely to degrade at a greater rate if used for continuous operations.

It is therefore important to recognize that the identification of degradation mechanisms and the assessment of their impact may not be a straightforward activity and is likely to require inputs from a wide range of competent personnel with specialist skills and knowledge.

3.2.1. Examples of ageing related degradation mechanisms

Ageing related degradation mechanisms are phenomena that cause the physical integrity of equipment to degrade and which, left unchecked, may eventually affect the equipment's ability to deliver its required function(s). Appendix IV in Ref. [5] provides a list of ageing related SSC degradation mechanisms that have been identified by NPP operators around the world. The following are examples of degradation mechanisms that may affect I&C equipment:

— Temperature;
— Moisture/humidity;
— Thermal and humidity cycling;
— Erosion;
— Thermomechanical and/or thermodynamic constraints during the manufacturing process;
— Vibration;
— Repetitive rapid acceleration/deceleration (e.g. a seismic event);
— Repetitive mechanical shock;
— Handling (that may lead to electrostatic discharge (ESD) for instance);
— Radiation exposure;
— Chemical exposure;
— Electromagnetic interference (EMI)/radiofrequency interference (RFI) exposure;
— Ultraviolet light exposure (this mainly has an impact on polymers);
— Surface contamination (e.g. dust, dirt, sand, fluff, mould);
— Wear;
— Electrical stress (e.g. power surges);
— Salt fog (this degradation mechanism is pertinent to NPPs on coastal sites);
— Fatigue.

3.2.2. Examples of ageing effects

Appendix IV in Ref. [5] also provides a list of the SSC ageing effects which have been identified by NPP operators around the world. The following are examples of ageing effects that have an impact on I&C equipment as a result of degradation mechanisms:

— Calibration drift and deviation of set points;
— Accuracy and reproducibility degradation;
— Changes in equipment response time(s);
— Changes in equipment signals (amplitude and frequency);
— Output data corruption;
— Introduction of signal noise;
— Loss of output signals/data;
— Changes in switching voltages;
— Changes in resistance (e.g. insulation, coil, loop and contact);
— Corrosion of equipment supports, housing and components;
— Loss of conductor mechanical strength;
— Cracking of equipment supports, housings, seals, coatings and solder joints.

In addition to the above, the following are some specific examples of ageing effects:

— Elevated ambient temperatures, which will increase the rate at which electrolytic capacitors lose their liquid electrolyte as a result of degraded end cap seals (e.g. through evaporation), which in turn can result in the capacitors drying out and failing to open, or causing a short circuit.

— Exposing cables to high temperatures can cause their insulation polymers to degrade, which can lead to the cables failing and causing a short circuit (see Fig. 2).
— Thermal cycling can cause circuit boards and components to expand or contract at different rates, which can place solder joints under mechanical stress. This can lead to fatigue in the solder joints and failure.
— Thermomechanical and/or thermodynamic constraints during the manufacturing process can lead to the growth of metal 'whiskers' (see Figs 3–4), which can lead to short circuits.
— Ionizing radiation can cause fibre optic cables to darken, which can affect the propagation of optical signals through the cables.
— High levels of ionizing radiation can cause semiconductor 'bulk damage', which can cause electronic equipment to fail.
— I&C equipment located on or next to rotating equipment can experience high levels of vibration, which can lead to fatigue in component connections and failure.
— Chemicals, such as grease, oil, acids and cleaning fluids, can degrade the integrity of cable insulation polymers, which can lead to cable failure and short circuits.
— Periodic removal of I&C equipment for inspection, test or overhaul can result in mechanical damage to connectors (e.g. wear, fatigue). This can lead to a loss of continuity or arcing between contacts (see Fig. 5).
— Chemical degradation of neoprene rubber insulation sleeves can result in hygroscopic salts forming within the rubber, which can absorb moisture from the air and lead to highly conductive droplets forming on the outsides of the insulation sleeves (the sleeves will appear to be sweating) (Fig. 6). This can lead to the insulation sleeves becoming conductive and short circuits occurring between the touching of sleeves to earth through metal structures. This issue has been identified at NPPs in the United Kingdom, leading to an extensive replacement programme of the neoprene rubber insulation.

Reference [8] provides further examples of I&C equipment ageing effects.

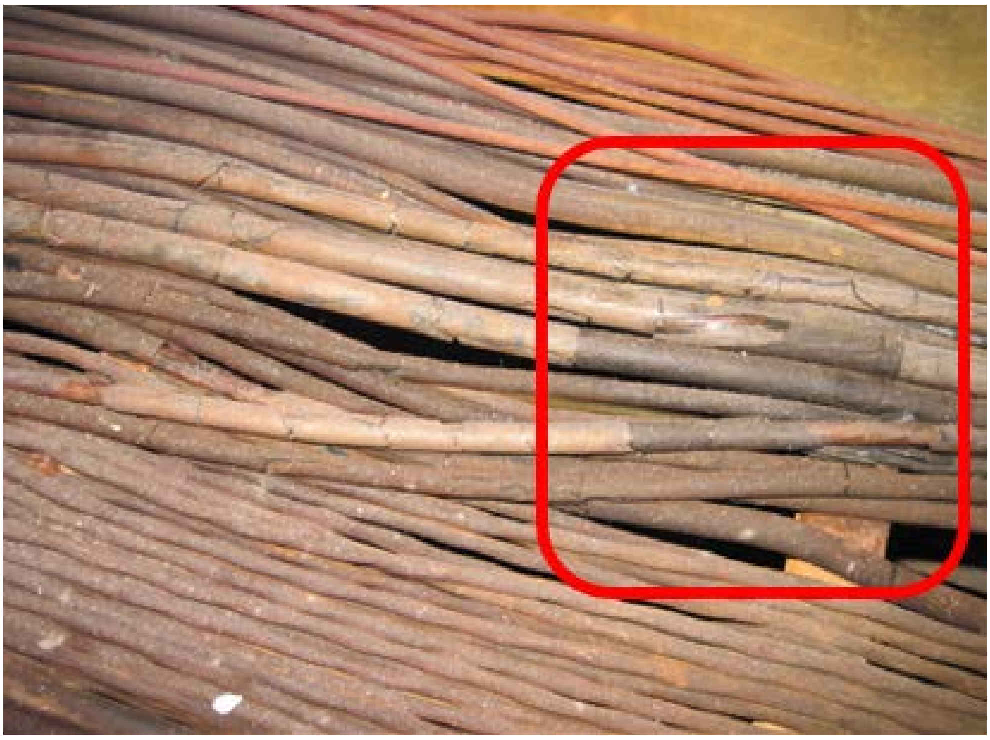


FIG. 2. Cables with degraded insulation after being exposed to high temperatures.

FIG. 3. Silver 'whiskers' growing from a silver plated feedthrough capacitor.

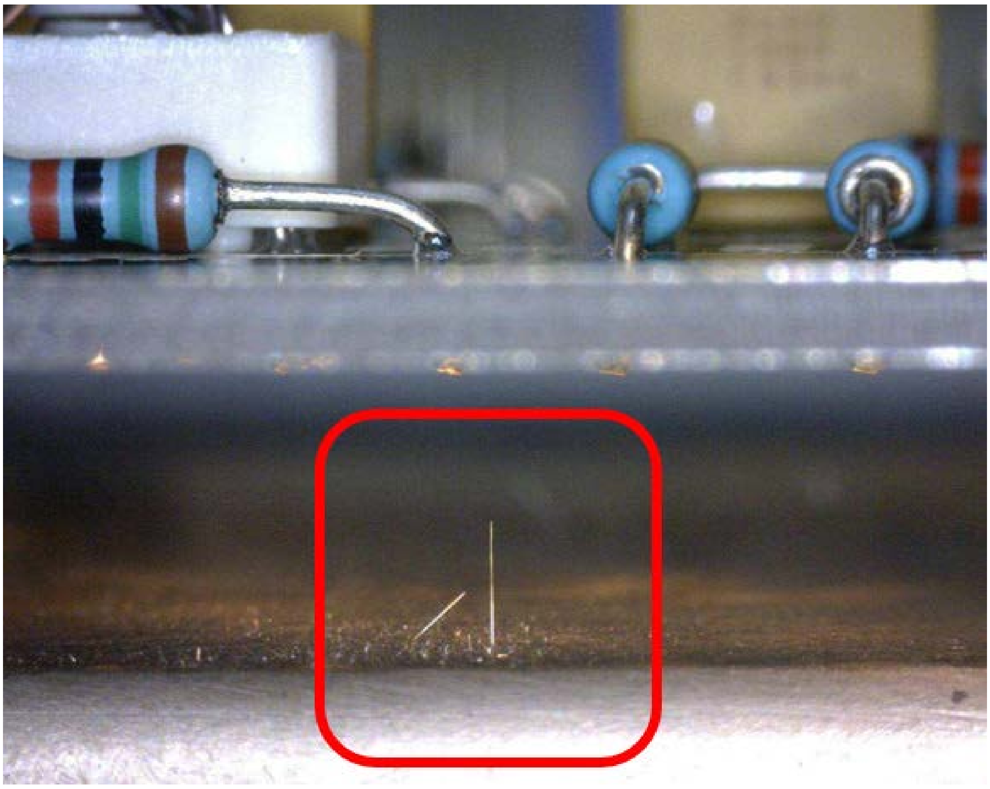


FIG. 4. Tin whisker (approximately 4 mm in length) growing on a tin plated screening can.

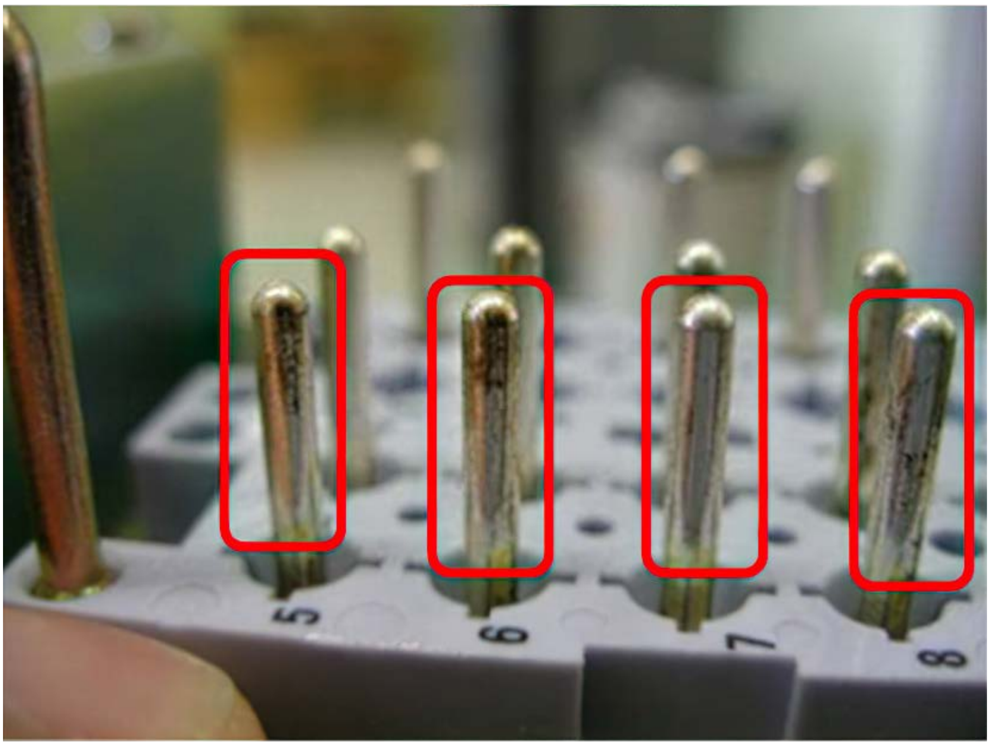


FIG. 5. Worn connector pins.

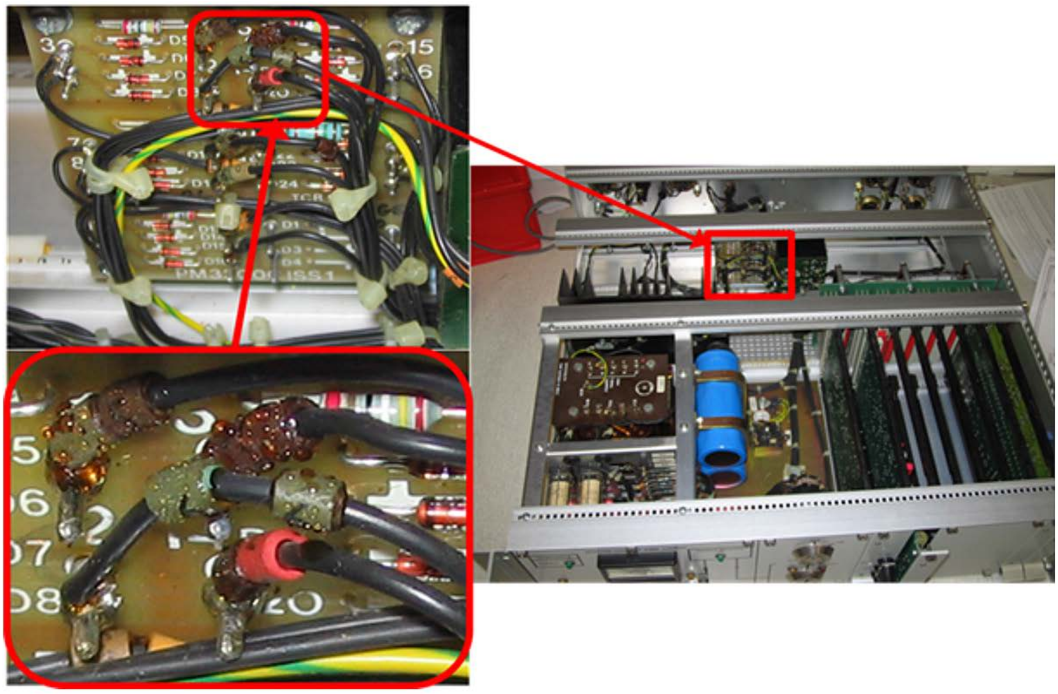


FIG. 6. Degraded (sweating) neoprene rubber insulation sleeves.

3.3. METHODS AND TECHNIQUES TO IDENTIFY AGEING I&C EQUIPMENT

3.3.1. Visual inspections

Visual inspections are one of the most practical ways of identifying ageing effects in I&C equipment (especially for analogue devices and cabling). Therefore, it is advisable that they are included in all system health/performance monitoring programmes.

While the removal of equipment will maximize the coverage of any visual inspection (internal/external), the disadvantages of doing so needs to be considered, such as the potential to damage the equipment and/or surrounding equipment. Where it is not practicable or desirable to remove equipment for inspection, the use of specific tools needs to be considered (e.g. magnifying glasses, endoscopes, inspection mirrors and torches).

There may also be limited scope to remove or gain access to equipment for inspection during normal operations. Therefore, such inspections have to be scheduled during routine plant outages. Conducting opportunistic equipment inspections when systems have had to be shutdown following a fault is also necessary.

Visual inspections are undertaken by competent personnel (i.e. by trained personnel who have a good working knowledge of typical I&C equipment degradation mechanisms and ageing effects).

For the condition of equipment to be trended, a detailed description of the ‘as found condition’ of the equipment has to be recorded, along with photographs. To ensure that trending is meaningful (i.e. ageing effects are identified and mitigated before they can threaten the equipment’s required function(s)), it is advisable that visual inspections are undertaken on a regular basis. In the United Kingdom, for example, non-disruptive plant walkdowns of advanced gas cooled reactor nuclear safety related systems need to be undertaken at least twice a year.

To increase the likelihood of ageing related degradation being detected, adequate lighting needs to be provided and maintained in the areas where I&C equipment is located. The following are examples of issues to look out for when undertaking visual inspection of I&C equipment:

- Corrosion.
- Water patination.
- Condensation.
- Cracking of:
  - Equipment component coatings;
  - Solder joints;
  - Circuit board tracks;
  - Equipment housings;
  - Equipment supports;
  - Seals;
  - Cable insulation (see Fig. 2).
- Lifted circuit board tracks.
- Metal whiskers (see Figs 3, 4).
- Delaminated or bowed circuit boards.
- Bulged components (e.g. electrolytic capacitors, lithium ion batteries).
- Equipment discolouration (i.e. indicating localized ‘hotspots’).
- Damaged/worn connectors (see Fig. 5).
- Degraded (sweating) neoprene rubber insulation sleeves (see Fig. 6).
- Surface sooting and spot welds (indicating arcing has occurred) (see Figs 7, 8).
- Missing connector caps/covers.
- Contamination (e.g. dust, dirt, sand fluff, oils, mould, salt crystals) (see Fig. 8).
- Excessively dirty filters.
- Darkened optocouplers/fibre optic cables.

— Fluid leaking from equipment/components (e.g. leaking electrolytic capacitors, batteries).
— Unusual noise emanating from the equipment.
— Unusual odours emanating from the equipment.
— Missing seals.
— Poor manufacturing quality (e.g. poorly finished surfaces, gaps, indentations and the use of fragile materials can increase the likelihood and rate of equipment degradation).
— Discolouration of equipment surfaces.
— Rodent and insect damage.

However, visual inspections are unlikely to pick up all ageing effects (especially for digital equipment where ageing effects are usually associated with the die of electronic components) and that other methods/techniques may be more effective in identifying certain types of ageing effects. Therefore, when developing a system health/performance monitoring programme, it is important that careful consideration is given as to the most effective methods/techniques to identify ageing effects.

3.3.2. Real time monitoring

Most primary NPP control systems monitor and trend plant operating parameters such as temperature, pressure, flow and neutron flux level. Variations in these parameters over time may indicate the onset of ageing related equipment degradation (for example, a gradual reduction in thermocouple loop resistance would result in a gradual increase in output temperature). However, detailed investigations will often be necessary to establish the exact cause of any such changes.

Modern digital I&C devices (i.e. smart devices) are often able to self-monitor their performance and to automatically report the early onset of issues to operators and vendors before they threaten the delivery of the equipment's required function(s). This in turn has the benefit of enabling timely mitigating measures to be introduced to prevent equipment failures. However, it is important to recognize that the use of such devices can also introduce computer security vulnerabilities and it is vital that this is evaluated and mitigated before such devices are employed.

3.3.3. Infrared thermography

Infrared thermography is a non-invasive process that involves detecting heat radiation and converting it into images that represent the amount of heat that is being radiated (see Fig. 9). Thermography is therefore a useful technique for identifying equipment 'hot spots' that are the result of ageing related degradation (e.g. due to degradation of equipment insulation and increased contact resistance), or heat sources that could cause surrounding equipment to degrade. However, hot spots may only develop during certain system/equipment operating modes, and it is therefore important that infrared thermography is undertaken across the equipment's full operating spectrum.

To identify any increasing heating trends, it is also advisable that infrared thermography pictures are taken under identical conditions and compared. This facilitates proactive mitigating measures that prevent such failures from occurring in the first place.

3.3.4. Cable testing

There are growing concerns that NPP life extension programmes could result in cable and connector ageing issues becoming more prevalent. Therefore, given that NPPs typically have many kilometres of cables, which are generally difficult and costly to replace, the need for robust cable ageing management and testing is assuming greater importance. This is the subject of IAEA Nuclear Energy Series No. NP-T-3.6 [9], which provides an overview of a number of cable ageing testing methods that cover laboratory/in situ and destructive/non-destructive testing.

In addition to the methods covered by the above publication, the following two methods have recently emerged as potential cable insulation (e.g. polymer) degradation testing methods:

(1) Terahertz (THz) imaging;
(2) Ultrasonic testing.

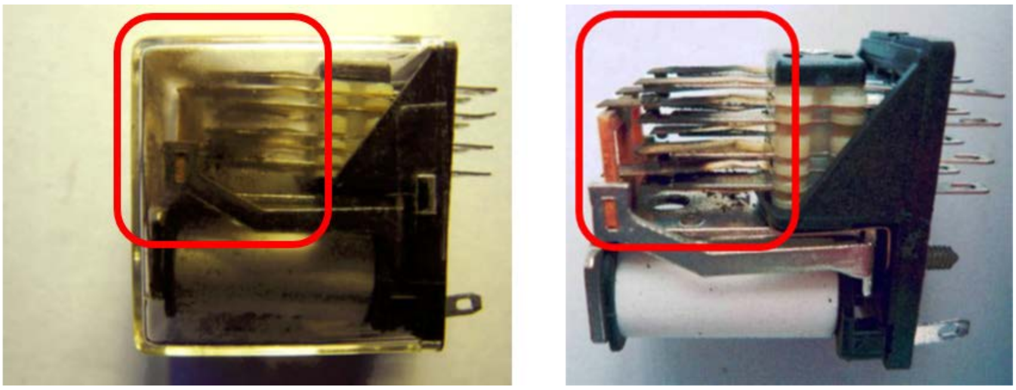


FIG. 7. Relay contact arching (note the sooting on the relay's protective case).

FIG. 8. Connector fluff and dirt contamination.

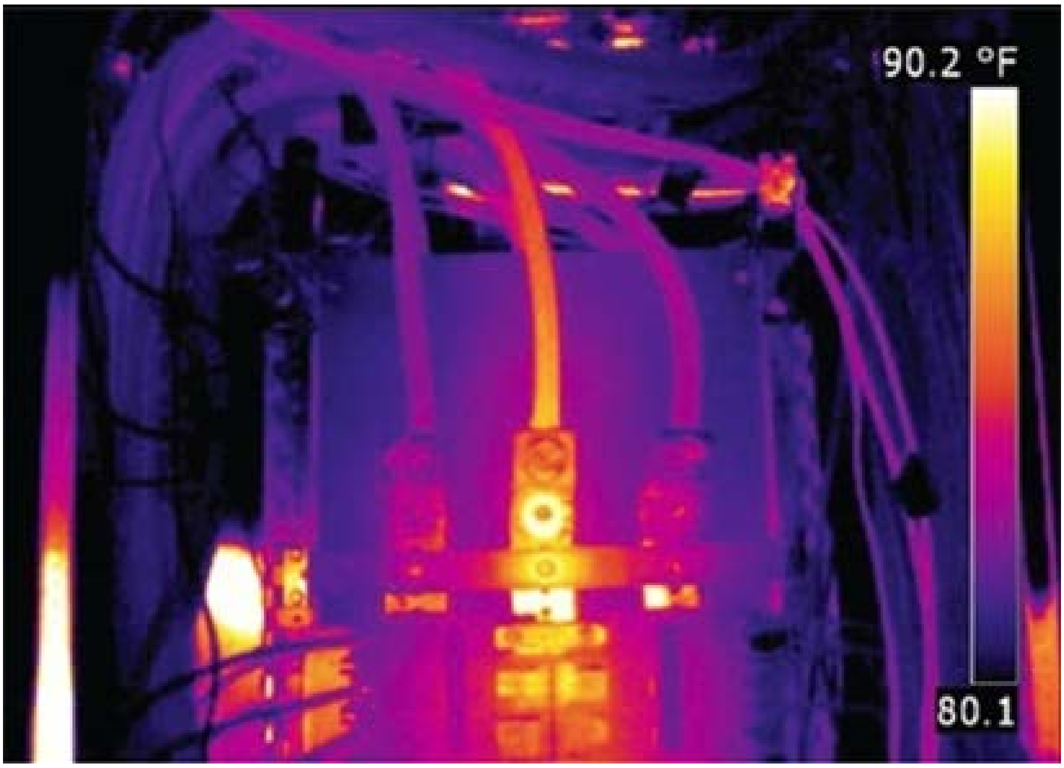


FIG. 9. Heating caused by a degraded equipment cable connector.

These methods have the benefits of being user safe, non-destructive and can be used to test cables in situ. However, their use is currently limited to specific applications due to their high equipment costs and/or the need for highly trained operators. Information relating to cable ageing management through CM is provided in the appendix of this publication.

3.4. AGEING EQUIPMENT SIMULATION AND MODELLING

3.4.1. Ageing equipment simulation

I&C equipment can be affected by a wide range of degradation mechanisms, which can have a detrimental impact on performance. It is therefore important to predict the impact of these mechanisms. One of the ways of doing this is to perform accelerated life/ageing testing.

3.4.1.1. Accelerated life/ageing testing

Accelerated life/ageing testing is the process of determining equipment's response to normal operating conditions over a long time by subjecting it, in a laboratory, to conditions in excess of those conditions during a significantly shorter time. However, it needs to be noted that only dominant depredation mechanisms are normally simulated. Predictions about the operational life and maintenance intervals can then be made by analysing the test results. The following are the degradation mechanisms that are normally simulated:

— Elevated temperature (accelerated thermal ageing, thermal cycling, etc.);
— Radiation (accelerated radiation ageing);
— Elevated humidity (humidity or humidity cycling ageing);

— Mechanical stress;
— Vibration ageing/seismic event;
— Thermodynamic simulation (e.g. loss of coolant accident (LOCA) simulation);
— Electrical stress.

It needs to be noted that accelerated life/ageing testing can be conducted under constant ‘stress’ conditions or increasing stress conditions. In addition, the duty cycle of the equipment can be altered (e.g. omitting low/unpowered periods). However, it is important not to overexpose equipment to stress conditions such that the accelerated life/ageing test results equate to ‘real time’ degradation. Furthermore, excessive accelerated ageing might underestimate ageing effects in some cases or could put the equipment in unrealistic conditions (e.g. thermal ageing where the physical properties of some materials might start changing at higher temperatures).

Moreover, synergistic effects (e.g. between thermal and irradiation ageing tests) have to be taken into account when establishing the sequence of the ageing tests, especially in the presence of organic materials. In these cases, performing the irradiation test first, followed by the thermal ageing test, may be more challenging, albeit more realistic, than following the reverse order.

The definition of the test conditions needs to be based on the model most appropriate to the case in hand (these are typically the Arrhenius or Eyring models). Arrhenius plots can be used to determine the appropriate stress condition levels. However, accelerated ageing can be used for equipment in mild as well as harsh environments. An example of accelerated ageing on equipment located in a mild environment is provided in Annex V.

3.4.1.2. Accelerated life/ageing test plan

The accelerated life/ageing test plan has to define the number of test objects, the degradation mechanisms to be simulated and their parameters, dealing with failures, and ending the test. The test plan is usually produced by the testing laboratory in cooperation with the end user (NPP operator), and preferably also with the original equipment manufacturer (OEM).

The basic set-up of the accelerated life/ageing test/qualification test can be found in international standards. However, international standards are not precise enough to define all the test conditions (e.g. temperatures used for accelerated ageing, number of cycles, accelerograms).

3.4.1.3. The pros and cons of accelerated ageing simulation

There are a number of advantages of undertaking accelerated ageing simulation:

— Accelerated life/ageing testing typically provides more accurate results than mathematical simulations;
— Accelerated life/ageing testing provides useful reliability data such as time to failure;
— Accelerated life/ageing testing can enable failures to be analysed (e.g. it can provide information on the weak point in the design), which in turn can facilitate improvement of the equipment’s design before it is put into final production.

However, there are disadvantages of undertaking accelerated ageing simulation:

— Accelerated life/ageing testing is expensive and time consuming and is typically employed for items of equipment that are required to perform a safety related or high reliability role.
— It can be difficult to accurately specify the degradation mechanisms to be simulated, their ‘stress’ levels and combinations of these. Failure to do so will reduce the accuracy of the test results.
— A small number of units/items of equipment (typically between one and three) are only tested at any time.

- The results of the accelerated testing are specific to the equipment, the environmental conditions and operational states tested. Extrapolation of these results to other equipment is not advisable. The results of each test are also valid only for devices for which the tested sample is representative (i.e. they are manufactured in the same way and contain the same materials). This presents an issue for commercial off the shelf (COTS) equipment.
- One of the biggest problems of the ageing and qualification test is to formulate the correct acceptance criteria. Acceptance criteria are not mentioned in any standard, though they are related to each component and to every position within an NPP.

3.4.2. Ageing equipment modelling

3.4.2.1. The need for modelling

As stated in Section 3.4.1.3, there are a number of disadvantages associated with accelerated life/ageing testing. Therefore, ageing equipment modelling may provide a useful alternative, supplementary or confidence building measure.

3.4.2.2. Initial data for modelling

The main source of initial data for modelling the ageing of I&C equipment can be operating experience (OPEX), technical documentation, data from international reference books and organizations. Preference has to be given to OPEX, since it takes into account the actual operation of the I&C equipment, as well as the operating conditions it has been exposed to. Therefore, it is important to maintain a database of equipment failures, replacements and repairs in a format that can be statistically processed. Particular attention needs to be paid to identifying the failure modes and effects.

3.4.2.3. Choosing a method for assessing reliability and modelling

During operation, technical equipment goes through three phases:

(1) Burn-in: The failure rate decreases with time;
(2) Normal operation: The failure rate is considered constant;
(3) Ageing: The failure rate increases with time.

When modelling the reliability characteristics of the I&C equipment, the time heterogeneity of the failure rate needs to be considered.

3.4.2.4. Analysis of results

Reliability models of I&C equipment can be used for the following purposes:

- Forecasting the reliability of the I&C equipment and planning repairs, maintenance and replacement of components;
- Assessing the level of reliability to extend the service life.

Considering the complexity and heterogeneity of reliability models, it is advisable to verify the model by carrying out modelling in several ways and comparing the results obtained. An assessment of the significance and uncertainty of the input data also needs to be carried out to determine the boundaries and potential errors of the model.

3.5. DEGRADATION ACCEPTANCE CRITERIA

3.5.1. Degradation acceptance criteria for I&C equipment (excluding cables)

There are many factors that can influence the severity and rate of I&C equipment degradation. In addition, the point at which such degradation will affect the equipment's ability to deliver its required function(s) will depend on how the equipment is used. For example, a change in a parameter (e.g. resistance, switching voltage, response time) by ten per cent over the operational life of a part of I&C equipment may be acceptable for one application, but not acceptable for another.

As a result, it is not possible to define a generic set of acceptable acceptance criteria for I&C equipment. Furthermore, it may not be practicable (from a time or cost perspective) to determine the exact correlation between equipment degradation and parameter change for a custom made item of equipment (e.g. X amount of corrosion equates to a Y per cent drift in contact resistance).

However, it may be possible to identify a measurable set of parameters and determine cut-off points for them at which the equipment can no longer be relied upon to deliver its required function(s) (e.g. a relay may not operate if its coil resistance drops below X ohm). Therefore, where practicable, it is advisable that a programme of regular equipment parameter monitoring, recording and trending is implemented to determine if these limits are being approached, and thus allow appropriate and timely mitigating measures to be taken. The identification of such parameters is more of a challenge for digital devices than for analogue devices.

3.5.2. Degradation acceptance criteria for cables

A number of cable ageing testing methods have been developed and been successfully applied in NPPs around the world (see Section 3.3.4 and the Appendix). These plants often have criteria for CM tests, such as insulation resistance, that are used to help determine if a cable will operate normally when placed in service. Unfortunately, recognized acceptance criteria do not currently exist for CM tests used to trend the age related degradation of insulation polymers. However, work is currently under way in the United States of America (USA), under a research project commissioned by the United States Department of Energy, to address this. Details of the project are provided in the Appendix.

3.6. AGEING MANAGEMENT OF SPARE PARTS

If I&C equipment fails in-service, it is important that it is exchanged for fully functional equipment in a timely manner. Therefore, managing the ageing of I&C equipment spares is as important as managing the ageing of in-service equipment.

The following are general guidelines for mitigating the potential for I&C equipment to degrade while in storage:

- Equipment storage conditions need to be commensurate with OEM recommendations and are monitored and carefully controlled. Also, heating, ventilation and air conditioning (HVAC) systems have to be kept in good working order.
- Equipment storage facilities need to afford adequate protection from external environmental conditions (e.g. wind, rain, snow, ice, salt fog, dust and dirt), industrial airborne contaminants (e.g. chemicals/vapours), electromagnetic sources and radiation.
- The packaging of the equipment needs to be commensurate with the recommendations of the OEM, as incorrect storage packaging can cause equipment degradation. For example:
  - Hygroscopic packaging materials can absorb moisture out of the air and cause corrosion.
  - Chemical compounds can leach from plastic packaging or cardboards and cause corrosive compounds to form on the equipment being stored.

- Inadequate packaging could enable dust and dirt to contaminate the stored equipment.

— OEMs often specify a 'shelf life' for equipment due to the inclusion of perishable components (e.g. rubber seals), or consumables (e.g. batteries). Therefore, equipment is not to be left in storage longer than this period.

— Equipment has to be installed as soon as practicable after it has been removed from its protective packaging. In the event that the installation work is delayed, the equipment has to be repacked within the same protective packing material.

— Spares have to be inspected, maintained and functionally tested on a periodic basis, as I&C equipment spares can be affected by degradation mechanisms even when stored in a strictly controlled environment. Periodically powering up the equipment also has the benefit of reforming the capacitors.

3.7. DATA CAPTURE AND TRENDING

3.7.1. Monitoring, recording and trending

To effectively manage the ageing of I&C equipment, the following issues are monitored, recorded and trended throughout the life of the NPP (including decommissioning):

— Environmental conditions (this includes EMI/RFI);
— Equipment degradation;
— Equipment failures;
— Equipment parameters (where practicable to measure).

3.7.1.1. Environmental conditions

For the design of new I&C equipment to be correctly specified, it is important that the environmental conditions that the equipment will be exposed are fully understood. It is therefore advisable that:

— Environmental conditions where the equipment is to be installed are monitored and recorded, and that this is undertaken over a prolonged period to enable seasonal variations (e.g. winter to summer), equipment duty cycles and plant operating states (e.g. plant shutdowns) to be accounted for.

— If the equipment is to be located within existing enclosures, the conditions inside the enclosures also need to be monitored and recorded (e.g. the internal ambient temperature of the enclosures may be significantly higher than the external ambient temperature due to heat being dissipated by the equipment inside).

Changes to the location of the equipment (e.g. the introduction of partitions or new equipment) can significantly alter the environmental conditions to which the equipment is exposed. Therefore, monitoring and recording of environmental condition have to be undertaken throughout the lifetime of the NPP to enable timely actions to be taken to keep the equipment within its specified environmental condition design limits.

The impact that equipment could have on other equipment also has to be considered during the design phase (e.g. could waste heat or radiofrequency emissions affect other equipment? Is spacing between the equipment sufficient to enable adequate cooling air flow? Are filters and shields needed?).

Where the reliability of in-service equipment is known to be sensitive to certain environmental conditions or changes, it is advisable that real time monitoring systems are introduced to alert staff of the approach of such levels and thus enable timely mitigating measures to be introduced (e.g. opening of enclosure doors, introduction/operation of chiller/dehumidifier/fans).

3.7.1.2. Equipment degradation

It is a fact that all things decay with time. However, whether or not ageing related I&C equipment degradation is considered to be a significant issue will depend on the potential for it to threaten the equipment's ability to deliver its required function(s) within its specified operational life.

Therefore, for ageing related degradation to be identified and addressed in a timely manner (i.e. before it can threaten the delivery of the equipment's required function(s)), it is advisable that the physical condition of I&C equipment is regularly inspected for signs of degradation (e.g. corrosion patch growth and colour changes of components). Furthermore, for the condition of equipment to be trended, a detailed description of the 'as found condition' of the equipment needs to be formally recorded along with photographs.

3.7.1.3. Equipment failures

A trait of all effective organizations is that they regularly review OPEX data and ask themselves: 'Does the data indicate that we have an issue and, if so, what do we need to do to resolve it?' Therefore, it is advisable that equipment failures are recorded, trended and investigated to determine whether they were caused by ageing related degradation mechanisms. This is important to enable mitigating measures to be introduced to prevent such failures from reoccurring.

It is common practice to return failed equipment to the OEM for repair. However, when doing so it is advisable that the OEM is requested to produce a cause of failure report to enable the NPP operator to determine whether mitigating measures can be introduced to prevent similar failures. In Canada, it is also common practice to utilize independent specialist facilities and personnel to undertake forensic examinations of failed equipment to provide an impartial assessment of the cause of failure.

Where a 'replace and discard on failure' approach is taken, it is advisable that the equipment is examined before it is discarded, as this may reveal useful OPEX that can be used to develop strategies to mitigate/eliminate degradation mechanisms.

3.7.1.4. Equipment parameters

Changes in I&C equipment parameters (such as insulation/loop/coil resistance, switching voltage and response time) (see Fig. 10) and increasing set point drift (see Fig. 11) could indicate that the equipment is degrading and heading towards failure. Therefore, it is advisable that such parameters are recorded (where practicable), trended and any changes investigated to determine whether they are caused by ageing related degradation mechanisms. This is important to enable proactive mitigating measures to be introduced to prevent such failures from occurring in the first place.

3.7.2. Data capture

3.7.2.1. Data recording

The transposing of equipment parameters from paper records to electronic databases can be a labour intensive and time consuming process. Therefore, consideration has to be given to introducing arrangements to enable maintenance personnel to directly record such data electronically. This also has the benefit of enabling data to be easily manipulated.

3.7.2.2. Database use

To enable I&C equipment OPEX (e.g. equipment parameter/condition/failure data) to be efficiently interrogated and trended, databases need to be established to capture such data as soon as possible after the equipment enters service. Setting up databases late in the operational lives of NPPs without populating

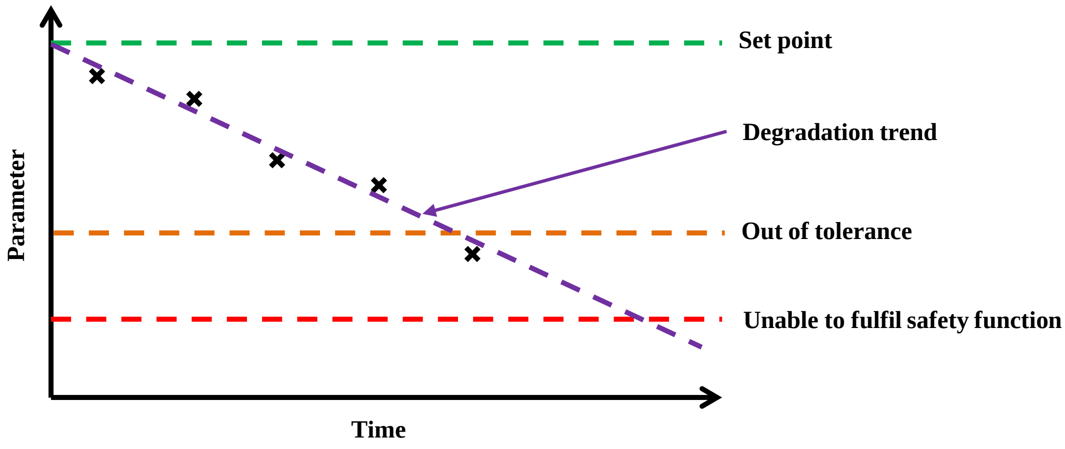


FIG. 10. Parameter drift.

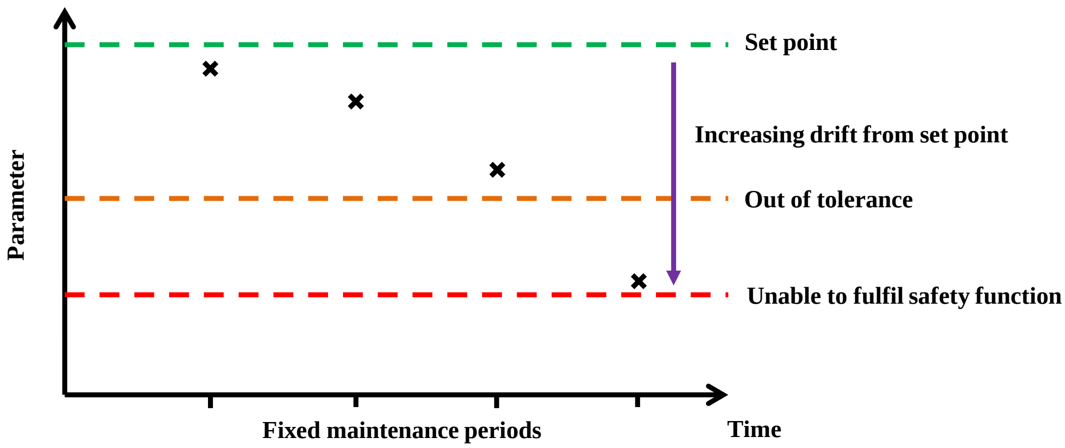


FIG. 11. Set point drift.

them with historic data (if available) may serve little purpose, as the data that is captured during the remaining operational life of the equipment may not be sufficient to allow useful trends to be identified. However, it is recognized that the retrospective entry of data into databases can be labour intensive and time consuming, and may not therefore be practical.

3.7.2.3. Data storage

Consideration also has to be given to the means for storing I&C equipment OPEX data for the duration of an NPP's life (including the decommission phase). Sufficient storage will need to be provided to hold the vast amount of data that will be generated during an NPP's life, which will need to remain secure and retrievable during this period.

3.7.3. Review of data

3.7.3.1. Data point comparison

System owners need to regularly review I&C equipment parameter/condition/failure data to enable ageing related issues to be identified and addressed in a timely manner. Simply comparing the most recent and penultimate data sets may not identify gradual degradation. Therefore, several data sets have to be compared to enable degradation trends to be identified (see Fig. 12). Equipment parameter and failure data needs to be input into databases to enable data to be easily manipulated and to permit effective data trending to be undertaken (e.g. data can be filtered and graphically displayed).

3.7.3.2. Comparing like with like

I&C equipment operating parameters may vary significantly with operating conditions (e.g. thermocouple loop and insulation resistance vary with temperature). Therefore, to permit like for like comparisons to be made with previous data sets, it is advisable that equipment operating parameters are recorded under the same environmental conditions and that details of these conditions are recorded.

3.7.4. OPEX and solution sharing

Operators need to share details of emergent ageing related degradation mechanisms and effects with relevant stakeholders to enable lessons to be learned and timely mitigative actions to be taken. Therefore, NPP operators need to implement arrangements to share such information, which may include the production and distribution of learning briefs, inclusion of OPEX data in training material, establishing company/fleetwide OPEX databases and establishing OPEX 'wikis'.

In addition, NPP operators need to encourage OEMs and equipment repair organizations to share details of new ageing related degradation mechanisms and the effects that they have identified or been informed of by other equipment operators. They have to also make arrangements to share details of mitigative measures and design solutions with relevant stakeholders, especially those that employ the same equipment, to avoid costly duplication of time and effort.

3.7.5. Use of modern digital technology

One of the benefits of replacing old technology with modern digital technology (i.e. smart devices) is that a self-diagnostic functionality is often included, which can record and report the onset of undesirable changes in equipment parameters. This in turn has the benefit of enabling timely mitigating measures to be introduced to prevent equipment failures. However, the use of such devices has disadvantages

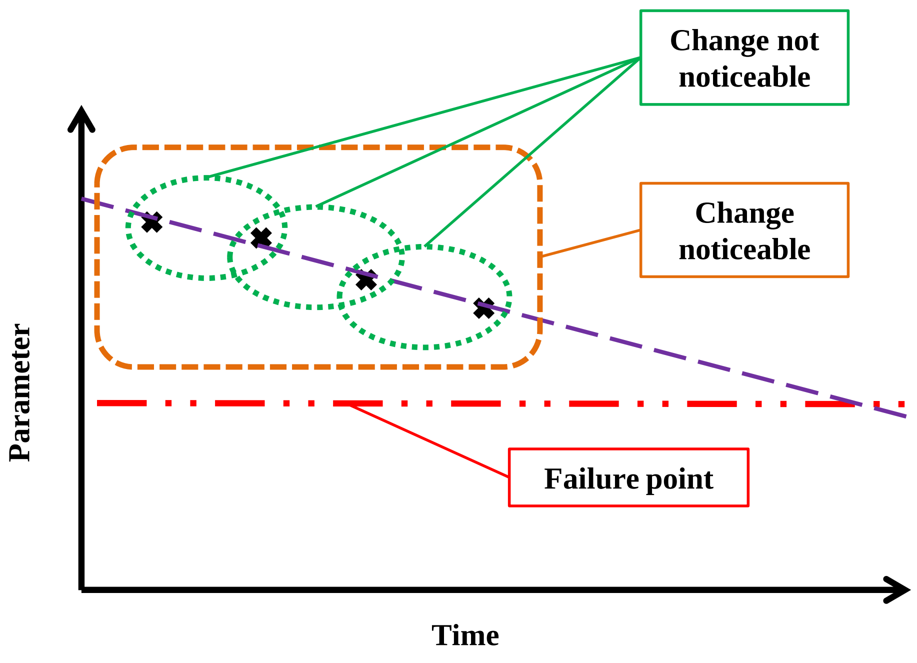


FIG. 12. Data point comparison.

such as being able to demonstrate that the device’s software and hardware have the required integrity and the potential for them to become obsolete within a short period compared with analogue devices. Such devices can also introduce computer security vulnerabilities and it is vital that this is taken into consideration (i.e. evaluated and mitigated) before they are employed. Annex VI provides an example of the fit, form and function (FFF) replacement of analogue valve positioners with digital positioners at the Darlington Nuclear Generating Station in Canada.

Artificial intelligence is an emerging technology that shows promise in efficiently analysing large data sets and identifying subtle data trends. A good example of the use of innovative data collection and intelligent advanced pattern recognition software is PRiSM, which is being used in Canada. PRiSM is an anomaly detection software tool used in monitoring and diagnostics to identify early signs of degradation. It uses historical data to model the normal behaviour of a system and continuously compares current values of the running systems against historical values. The PRiSM system consists of two main modules: PRiSM Client and PRiSM Web. PRiSM Client is the desktop application of PRiSM that is used to build and edit operational profiles. PRiSM Web is a browser based application that displays high level information from all of the equipment and systems currently being monitored, including basic tools for managing alarms, visualization of trends and analytics to identify areas for further investigation.

3.8. GENERAL SPECIFICATION, DESIGN, MANUFACTURE AND IN-SERVICE LIFE CYCLE PHASE CONSIDERATIONS

It is important to identify the degradation mechanisms that could affect the new I&C equipment and understand their impact. This information then has to be used to support decisions to eliminate, mitigate, or even accept the impact of the identified degradation mechanisms. The following sections provide examples of measures that can be taken during I&C equipment specification, design, manufacture and in-service life cycle phases to eliminate or minimize the impact of degradation mechanisms.

3.8.1. Safety case

All ageing related degradation mechanisms, effects, degradation limits and mitigative measures need to be recorded in top level safety case documentation, kept up to date (e.g. to capture emergent ageing related issues), and be readily accessible for review. Safety case ageing related claims, argument and evidence have to also be reviewed whenever operating conditions change.

3.8.2. Specification considerations

A margin needs to be built in when specifying the operating conditions envelope for new I&C equipment. For example, it would not be sensible to specify the equipment’s maximum operating temperature to be the same as that which it could experience in service (see Fig. 13).

The specified operating condition envelope for new I&C equipment needs to take into account the following factors:

— Changes in environmental conditions due to climate change;
— Changes in environmental conditions due to seasonal variations (e.g. winter to summer);
— Changes in environmental conditions due to prolonged plant outages/permanent plant shutdowns;
— Changes in environmental conditions during construction, installation and commissioning;
— Changes in environmental conditions due to HVAC performance degradation (e.g. due to blocked filters and ‘clogged’ heat transfer fins) and failures;
— Changes in environmental conditions due to EMI/RFI from other new equipment nearby;
— Changes in environmental conditions due to leakage of corrosive gases and liquids from nearby equipment.

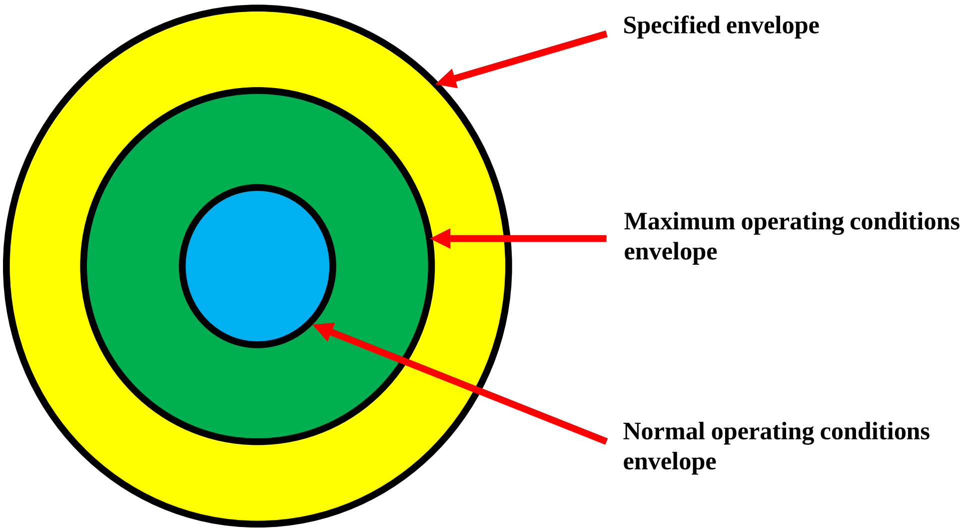


FIG. 13. I&C equipment operating envelope specification.

As stated in Section 3.4.2.2, the specified operating condition envelope for new I&C equipment needs to based on OPEX data, as original plant design operating conditions limits, which were likely based on theoretical data, may no longer be representative of actual conditions. For example, heat soak from adjacent plant/equipment rooms may be greater than originally anticipated, and modifications to room layouts and the introduction of additional equipment may have significantly changed operating conditions over time.

3.8.3. Design and manufacture considerations

Where practicable, the impact of degradation mechanisms on new I&C equipment needs to be eliminated or mitigated by design, for example, through:

- The selection of quality and reliable components;
- Following recognized good design practices and standards;
- The use of EMI/RFI shielding, filters and earth straps;
- The selection of degradation resistant materials/components;
- Ensuring that the equipment is appropriately sealed;
- The provision of heat sinks, cooling vents and cooling fans;
- The provision of anti-vibration mounting;
- Separating heat generating components and equipment to ensure adequate cooling air flow.
- Selection of overrated components;
- Undertaking environmental qualification testing that covers the equipment's operating envelope (see Ref. [4]);
- Undertaking accelerated ageing testing.

Equipment needs to be procured from reputable OEMs and component suppliers with a proven track record of designing and manufacturing quality and reliable components. The equipment has to be designed in such a way that it can be easily installed/removed, inspected and maintained.

3.8.4. In-service considerations

Where it is not practicable to eliminate degradation mechanisms by design, consideration needs to be given to mitigating them in service. This could involve the introduction of:

- HVAC;
- Radiation shielding;
- Robust power supplies (unstable power supplies can lead to the associated equipment failing);
- Covers;
- Foreign material exclusion inspections;
- Maintenance arrangements to ensure that air vents, fans and equipment surfaces are kept free from contaminants (e.g. dirt, dust and fluff) and that air filters are periodically changed.

Also, when introducing new I&C equipment, consideration needs to be given as to whether it could have a detrimental impact on local environmental conditions and in turn adversely affect the ageing of surrounding equipment. For example, what impact waste heat from the equipment could have on surrounding equipment. This is especially important when new equipment is to be installed inside existing equipment enclosures. A thermal assessment needs to be undertaken in such circumstances.

Similarly, it is necessary to check whether changing maintenance practices/periodicity could lead to new degradation mechanisms arising or existing mechanisms becoming more prevalent. For example, seeking to mitigate thermal degradation by increasing the air flow through an enclosure by removing its air filters could adversely lead to increased equipment corrosion due to contaminants being able to enter the enclosure.

The equipment has to be installed in such a way that it can be easily inspected for signs of degradation and be maintained without causing damage to the equipment (this includes the use of ESD provisions by maintenance personnel) or surrounding equipment.

It is important to appreciate the key ageing related equipment management roles that support systems (e.g. HVAC, lighting and power supply systems) often play. HVAC systems, for example, have a major role in mitigating ageing related degradation mechanisms (e.g. temperature extremes, thermal cycling, moisture/humidity and surface contamination), while lighting systems are important in enabling ageing effects to be identified. Therefore, these systems have to be kept in good working order.

3.9. MAINTENANCE ARRANGEMENTS AND STRATEGIES

If unmitigated, ageing related degradation can occur within a very short period of I&C equipment entering service. Therefore, effective ageing management maintenance arrangements have to be in place when the equipment enters service. The following sections outline some of the actions that need to be considered when developing such arrangements.

3.9.1. Ageing related degradation mechanism training

All personnel required to test and inspect I&C equipment need to be made aware of the potential ageing related degradation mechanisms associated with the equipment, the effects of such mechanisms and the appropriate mitigative action needed. Therefore, it is advisable that all such personnel are provided with training, and that refresher training is also undertaken on a regular basis to avoid ‘knowledge fade’. The importance of adequately addressing degradation mechanisms and effects in a timely manner also needs to be explained during such training.

Staff members need to be made aware of their potential to damage the equipment and surrounding equipment during maintenance activities. This also includes the need for them to take appropriate equipment handling precautions (e.g. the wearing of ESD straps).

3.9.2. Proactive ageing equipment management

Even with the best efforts, it may be difficult to determine the precise nature of each identified degradation mechanism or to identify every degradation mechanism before the equipment enters service. For example, the use of novel materials, changes in environmental conditions, changes in operation and maintenance (O&M) practices and equipment modifications could affect the aggressiveness of degradation mechanisms or introduce new degradation mechanisms. Therefore, a programme of regular environmental condition, physical condition and equipment parameter monitoring, recording and trending need to be introduced when the equipment enters service to enable the early identification of such mechanisms and to enable appropriate measures to be taken before the delivery of the equipment's required function(s) is threatened.

3.9.3. Maintenance schedule considerations

Ageing related I&C equipment maintenance intervals need to be sufficiently short to enable degradation mechanisms to be eliminated, or their effects to be mitigated to an acceptable level. I&C equipment can be affected by a wide range of degradation mechanisms and their impact will vary due to a number of factors. Therefore, OPEX data (e.g. inspection, test and failure data) have to be reviewed regularly to ensure that the derived intervals are appropriate and remain so.

If OPEX data reveal that there is no or limited ageing related degradation, it does not automatically mean that the maintenance intervals can be extended, as they may actually be in the 'Goldilocks zone' (i.e. just right). If, after due consideration, it is concluded that maintenance intervals can be extended, a conservative approach needs to be taken and OPEX data regularly reviewed thereafter.

If analysis indicates that degradation effects may become more prevalent after a specific period, inspections/testing have to be undertaken more frequently, along with modifying/undertaking additional maintenance activities. This advice applies equally if reliability analysis indicates the equipment is approaching the 'end of life'/'wear out' side of the reliability bathtub curve (see Fig. 14).

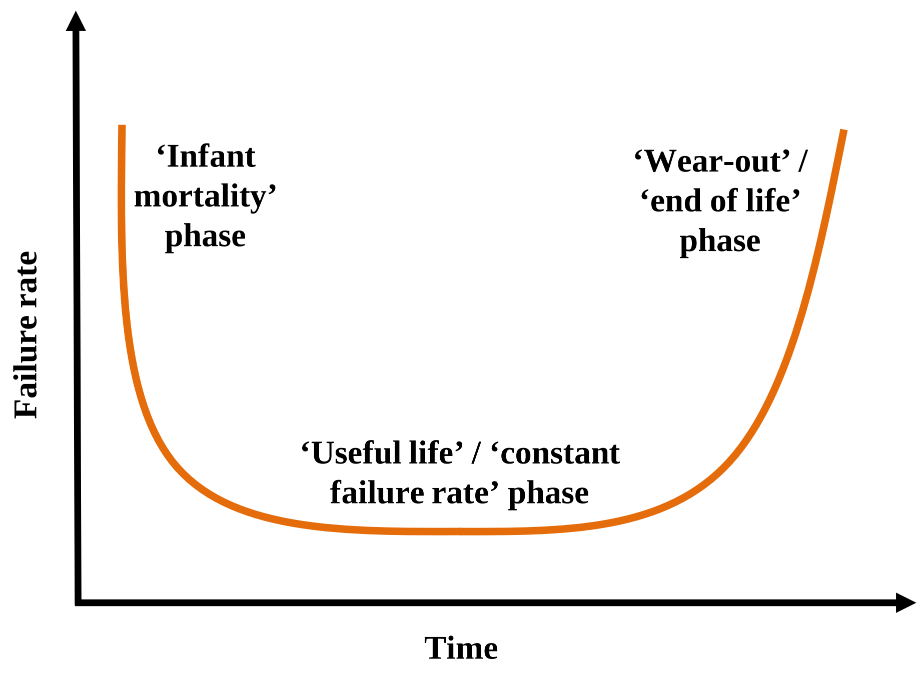


FIG. 14. Reliability bathtub curve.

3.9.4. Ageing related equipment maintenance strategies

3.9.4.1. Preventive maintenance strategy

Preventive maintenance involves undertaking periodic maintenance activities that will prevent equipment degradation or mitigate it to an acceptable level, and thus prevent equipment failures or significant defects. One of the key pillars of this strategy is the need to capture, and trend, sufficient equipment condition/parameter/performance data to enable early signs of equipment ageing to be identified and in turn enable the cause(s) to be eliminated or adequately mitigated in a timely manner. This strategy is highly advisable for I&C systems/equipment that implement a safety function(s).

3.9.4.2. Predictive maintenance strategy

Predictive maintenance involves performing periodic or continuous monitoring of the equipment's condition, with the purpose of using these data to predict the most cost effective time to undertake maintenance before unacceptable levels of equipment degradation or failures can occur. Two of the main challenges associated with this strategy, from an I&C equipment perspective, are the selection of appropriate parameters to monitor and the ability to extrapolate data with sufficient confidence that appropriate maintenance is undertaken before the equipment's ability to deliver its required function(s) is threatened.

3.9.4.3. Maintain and replace on condition strategy

'Maintain and replace on condition' is an ageing related equipment maintenance strategy that is employed by many NPP operators around the world (also known as condition based maintenance). This involves monitoring items of equipment, either continuously or at set intervals, for signs of degradation (either physical or functional) and replacing them when degradation reaches a specified level. This needs to be set below the level where equipment failure can result. 'Replace on condition' does not mean 'replace on failure' and 'maintain and replace on condition' is therefore not a 'fit and forget' strategy.

One of the challenges with this strategy is that it is not always easy to specify degradation replacement limits with sufficient margin before failure occurs. Failure to successfully do so could result in a spike in equipment failures occurring in a short period of time, which in turn could potentially challenge holdings of equipment spares. Another challenge with this strategy is that the mixing of new and old items of equipment can result in incompatibility/interface issues. For example, there may be subtle differences in the timing of digital circuits where drift has occurred over many years, which may only become apparent when new components are introduced with old. Similarly, the new equipment may be less tolerant to signal noise or voltage supply ripples than the original equipment.

3.9.4.4. Wholesale periodic equipment replacement

Wholesale periodic equipment replacement is another ageing related equipment maintenance strategy that is employed by NPP operators around the world. This involves replacing in-service equipment with new equipment, regardless of its condition, before the equipment reaches the end of life/wear out phase of the reliability bathtub curve (see Fig. 15).

One disadvantage with this strategy is that it has the potential to introduce 'infant mortality' failures, which in turn could potentially challenge equipment spares holdings. The risk of this can be reduced by undertaking a 'burn-in' programme before the equipment is installed for operational use.

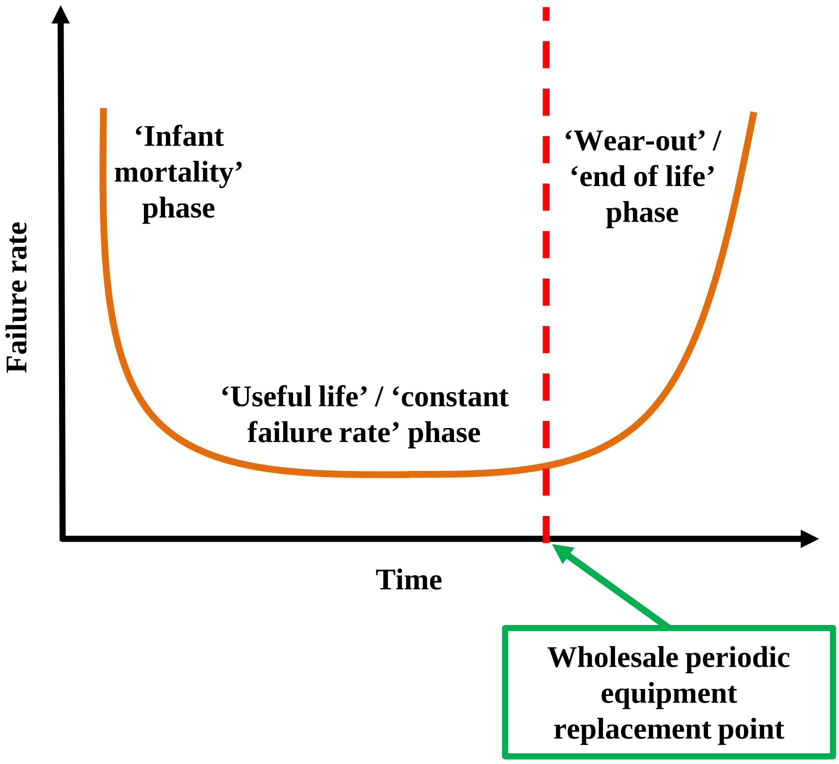


FIG. 15. Wholesale periodic equipment replacement point.

4. I&C EQUIPMENT OBSOLESCENCE MANAGEMENT

4.1. INTRODUCTION

Although the principles of obsolescence management are generally common to all engineering disciplines, the I&C area requires a greater focus on the issue of obsolescence due to the high rate of technology change. This section builds on previous IAEA obsolescence management requirements, recommendations and guidance and concentrates on topics specific to I&C systems/equipment, such as obsolescence of software, semiconductor based components and COTS products.

It is important that operators of new-build NPPs understand the obsolescence status of the equipment they have selected as the equipment may have become obsolete by the installation and commissioning phases. It is therefore vital that NPP operators implement a robust obsolescence management process as soon as practicable, certainly before the NPP enters the operational phase of its life cycle. The consequences of not doing so can be:

— Reduction of safety margins;
— Safety equipment not being available when needed, leading to unplanned shutdown of the plant;
— Equipment or station outage duration extensions;
— Planned work not being completed on schedule;
— Computer security vulnerabilities arising.

In addition, there are some more subtle consequences, such as:

- Loss of equipment configuration management. One of the key objectives of any NPP obsolescence management process is to ensure that the configuration of systems/equipment important to safety and power generation is carefully controlled and managed.
- Costly engineering work may be undertaken unnecessarily if the obsolescence status of equipment is not fully understood.

4.2. DEFINITION AND SCOPE

4.2.1. COTS products

COTS products can be purchased as either components, subsystems or full systems and they will likely form the majority of all NPP I&C systems. However, it is important to recognize that the manufacturers of COTS products will typically own the design rights to their products and can without consultation:

- Make modifications (hardware and/or software) to a product;
- Withdraw a product from the marketplace;
- Withdraw support for a product.

Common reasons for modifying COTS products include: the need to address component obsolescence; make updates to hardware/firmware/software to fix design flaws/bugs; or to add functionality. COTS manufacturers may also deliberately declare a product to be obsolete to encourage users to upgrade to a new product. It is therefore important that NPP operators regularly engage with their supply chain to receive timely notification of product modifications and product/service withdrawals, and to gain an understanding of how long versions of products are likely to remain available.

The availability of COTS products may also be affected by manufacturer takeovers, mergers and liquidation. Thus, NPP operators also have to understand the economic health of COTS manufacturers in their supply chain.

COTS manufacturers are not allowed to change their product serial numbers when they make minor hardware or software changes. Thus, NPP operators also have to record the product’s hardware and software versions in their asset management system (AMS) to ensure that configuration management is maintained.

4.2.2. Custom I&C equipment

If I&C equipment has been manufactured specifically for an NPP, and the equipment has not been manufactured for some time, the components that were originally used may have become obsolete by the time the equipment is next required to be manufactured. There is a reasonable likelihood of this if the design of the equipment is not under continual review by the OEM. This also includes COTS equipment that was specifically adapted for use within NPP I&C systems.

In such a case, the remanufacture of this equipment with alternative components and additional design features will also require its fit, form and functionality, as well as integrity, to be re-evaluated, which may have significant lead time implications. The future availability of custom made equipment may also be affected by:

- The commercial status of the company that designed and manufactured the original equipment.
- The availability of original design documentation.
- The availability of specific manufacturing jigs and tools.

— The availability of specialist personnel (e.g. designers, suppliers, or installers with key knowledge and skills).
— The need to undertake new or additional testing. The original equipment may have been designed and tested to specific standards that may no longer be adequate.

A decision has to be made whether such equipment needs to be recorded as obsolete by default unless the current design status of the equipment is known to be otherwise.

4.2.3. Externally maintained I&C equipment

Many NPP operators send items of equipment to specialist repair organizations (also known as specialist repair houses) for repair/overhaul. As part of this process, it is likely that the specialist organization will identify obsolete components. However, arrangements are needed to prevent them from replacing obsolete components with alternative components without prior approval from the NPP operator. Failure to do so could lead to significant configuration management issues and safety case claims being undermined.

NPP operators need to establish what the impact of using alternative components would be before approving their use. It is also advisable that operators consider the following:

— Is the alternative component appropriately rated?
— Is the alternative component qualified for the environment in which it will operate?
— Is the accuracy/tolerance of the alternative component sufficient?
— Is the performance of the alternative component adequate?
— Will the alternative component affect the equipment’s functionality?
— Will the alternative component affect the equipment’s reliability?
— Will the alternative component introduce new failure modes?

This analysis is not to be deferred to the specialist repair organizations unless they are the OEM, as it is likely that they will not have knowledge of the equipment’s design and qualification requirements or appreciate their importance.

4.2.4. I&C equipment software obsolescence

There are several factors that can cause software to become obsolete. These include:

— *Operating system obsolescence:* The operating system is no longer sold or supported.
— *Tool chain obsolescence:* The tool chain used to develop, modify, or test a specific version of software is no longer available or supported.
— *Software version obsolescence*: A specific version of software is no longer available or supported. This may be due to hardware changes, bug or security fixes, the addition of extra functionality or due to suppliers deliberately making their software obsolete to encourage users to upgrade to new software/equipment.
— *Software no longer supported:* The software supplier stops supporting and providing patches/updates to the software as required for maintenance and security.
— *Hardware obsolescence:* New hardware does not support the original software. This may be due to hardware component obsolescence that leads to a forced hardware change.
— *Communication protocol obsolescence:* A proprietary protocol may be unsupported.
— *Poor documentation/media control:* Documentation/media is not revised/backed up such that future software updates cannot be supported.

— *Competent personnel:* There are not enough people with adequate experience and knowledge of the software application, tools or programming language to support its use and maintenance into the future.

Evidence is needed to verify supplier claims that software developed for a specific hardware version will operate correctly on the next generation of hardware. Such claims are not to be taken on trust; the new version of the hardware is not to be accepted unless they can be verified.

4.3. I&C EQUIPMENT OBSOLESCENCE MANAGEMENT PROCESS

4.3.1. Overview

I&C equipment obsolescence is one of the main issues that all NPP operators will face throughout the lifetime of the NPP. Thus, it is important that operators establish a robust obsolescence management process early on in their NPP's life cycle.

Obsolescence management is primarily targeted at ensuring that existing systems will continue to operate and deliver their functionality throughout their specified life. Modernization is a process of replacing existing equipment with new/modern equipment, which may also add functionality.

It is important that procurement and engineering disciplines work closely to ensure that obsolescence issues are identified and resolved in a timely manner. Many NPP operators have an obsolescence management process that is led by the procurement/supply chain discipline, with the engineering discipline playing a key supporting role. However, the reverse (i.e. the obsolescence management process led by the engineering discipline) can work just as effectively provided that there is clear ownership of all necessary activities.

For an obsolescence management process to be truly effective NPP operators need to engage regularly with their supply chain to receive timely notification of when products will be discontinued and/or when their support will be withdrawn.

The obsolescence management process is an information driven process and it will fail without the capture and analysis of sufficient high quality data in a timely manner. Therefore, sufficient resources (competent personnel and tools) are needed to ensure that data are captured and analysed throughout an NPP's life cycle (including decommissioning).

The acquisition of an adequate number of spares is also an important part of any obsolescence management process. Sufficient resources are also needed to ensure that spares are always readily available for use throughout an NPP's life cycle.

4.3.2. Phase 1: I&C equipment identification, data collection and recording

For an obsolescence management process to be effective, the obsolescence status of the equipment in the plant needs to be known, which in turn requires the capture of the details of the equipment. These details have to include equipment manufacturer, model/part number and hardware/firmware/software serial numbers.

A typical AMS will hold a large quantity of equipment data and, as a result, there is potential for data input errors or omissions. Thus, when seeking to implement a new obsolescence management process, the quality and completeness of the data in the AMS needs to be established.

Furthermore, data quality improvement programmes will need to be targeted at equipment of the highest priority. This will likely require the use of dedicated and knowledgeable resources and will require careful planning to determine the amount of effort and resources needed to complete the activity. Once the activity has been completed, the data in the AMS needs to be kept up to date, which in turn will require resources to be made available.

It is good obsolescence management practice to also record the details of alternative/equivalent items, as this will reduce the time taken to identify suitable alternatives if an obsolete item of equipment needs replacing.

4.3.3. Phase 2: I&C equipment obsolescence status identification

As stated above, the effectiveness of an obsolescence management process depends on the quality of information that has been captured in an AMS. For various reasons, an AMS may not hold information at the correct level of detail. For example, where an AMS does not deconstruct a subsystem into individual items of equipment, then the obsolescence status of those items is unlikely to be proactively tracked. Thus, such items would likely only reactively be revealed to be obsolete (e.g. upon the need to replace them following a fault).

A proactive approach is a better way to identify the obsolescence status of equipment in an NPP. This approach uses multiple methods to gain information from the OEM/supplier as to the ongoing availability of equipment and any important product life cycle dates. Formal agreements with the OEM/supplier to inform the NPP operator of planned equipment obsolescence would also be considered a proactive approach.

A proactive approach may not always be sufficient since several events may quickly change the obsolescence status of the equipment (e.g. simplification of the product catalogue, loss of means of production). Hence, a reactive approach also needs to be taken. Possible sources of information that can result in the obsolescence status of I&C equipment being revealed include:

— Information received from suppliers and manufacturers;
— Information from specialist repair organizations;
— Spares' requirements audits;
— NPP personnel who identify obsolescence issues during the course of their daily activities;
— Data and OPEX from other NPPs or other external sources;
— Preventive vulnerability assessments (e.g. walkdowns to identify ageing problems in advance);
— Technical assessment reports;
— Results of performed maintenance;
— Results of reliability analysis;
— Existing equipment, suppliers, spare parts database.

4.3.4. Phase 3: Prioritization of I&C equipment obsolescence issues

A systematic methodology is required to rank, and thus prioritize, those obsolete items of equipment that present the highest risk with respect to maintaining nuclear safety. To determine this, it is advisable that the following factors be taken into consideration:

— Equipment with a high failure rate (and which will require a large quantity of spares);
— Equipment with low available spares level;
— Equipment safety Class 1;
— Equipment that is a single point vulnerability to plant operation;
— Equipment where there is a high demand (a five-year usage profile);
— Equipment critical to the delivery of outage or specific maintenance tasks;
— Amount of equipment in the storage warehouse and storage history (ageing of equipment in the warehouse).

Each factor can be weighted in relation to the significance placed on it by an NPP operator, which in turn will raise those items of equipment to which the most 'significant' factors apply in the obsolescence prioritization ranking list.

The above information is relevant to all engineering disciplines. However, the following factors typically have a notable impact in relation to I&C equipment and need to be taken into consideration:

- Equipment that has high nuclear safety claims will be required to meet modern standards (possibly more onerous than the existing equipment) and therefore undergo rigorous qualification activities (associated time and cost implications have to be considered).
- Custom made equipment where there is no OEM or technical support available.
- Equipment that has not been manufactured for many years.
- Equipment that is part of a wider system where ongoing modification to the system would solve the obsolescence issue.
- The potential for using spares from a lower safety class system.
- The availability of sufficient spare parts to allow time to develop solutions for potentially complex problems.

This phase needs to involve all relevant stakeholders, such as maintenance, engineering and procurement/supply chain specialists, to ensure that all relevant factors are taken into consideration and that the output of this activity is usable. This phase needs to be undertaken in a reasonably short time to avoid the information that the judgements were based on from becoming obsolete.

4.3.5. Phase 4: Resolution of I&C equipment obsolescence issues

4.3.5.1. Informed decision making

When an obsolescence issue has been prioritized, the optimum solution may not always be obvious. Further analysis to determine the optimum solution may therefore be required, which needs to consider all credible options. Failure to do so could result in work starting on an expensive reengineering project only to find that another NPP operator had spare unused stock that would have been sufficient to last to the end of the NPP's operating life.

The following are examples of some of the information that is needed to support this analysis. If this information is not available, then a plan will need to be developed to obtain it. Some of these questions may have been asked during the previous phases; however, all of the following options need to be fully evaluated:

- What is the full usage profile for the equipment (including forward predictions)?
- How many items of the equipment are employed by the NPP?
- What is the spares policy for the equipment?
- What safety case claims are made on the function of the equipment? (Are there different claims depending on where the equipment is employed?)
- What is the extent of the documentation held for the equipment?
- Are the technical requirements available in enough detail such that a replacement or modern equivalent can be specified with little additional investigation into the required characteristics of the equipment? For example, where analogue equipment is to be replaced, characteristics, such as response time, may be essential to be known.
- What was the history of the OEM (still operating, closed down, renamed)?
- What is the qualification level of the equipment (e.g. seismic, temperature, humidity)?
- When is the solution required? (What is the realistic date? Are there specific outage requirements?)
- What is the reliability history of the equipment? (Is the same component really to be put back in the system?)
- What constitutes completion of the task?
- Have any other organizations already solved this obsolescence issue? Solutions to difficult obsolescence problems can be expensive and time consuming. Collaborating with other organizations who have solved or partially solved an issue, or have experience of a certain technique of use can

be very efficient, especially when working within the bounds of intellectual property (IP), nuclear sensitive information and export controls.

These questions need to be addressed to define the true scope of the obsolescence problem that needs to be solved. The risk of not answering the questions is that the solution will only partially resolve the obsolescence issue and further work may be required.

The optimum solution to an obsolescence issue may be a hybrid of more than one solution type, depending on the urgency of the need. Moving directly to a long term solution may not be possible for a number of reasons. Therefore, there may be a time where a temporary (time limited) strategy is necessary. This may include making some modifications on one system to free up spares for a second system.

Figure 16 lists potential solutions that need to be considered on a case by case basis. This section highlights the main advantages and drawbacks for each solution type; but does not detail how to implement them. The solution types can appear to have a relationship to the cost and engineering resource effort, though this is not always true.

Decision making does not simply take into consideration the cost of making replacement equipment available (e.g. by reverse engineering), but also has to take into consideration the cost of training relevant stakeholders and of updating and producing new supporting documentation. The likelihood of success also has to be taken into consideration.

These solutions have been classified under non-modernization and modernization solutions.

4.3.5.2. Non-modernization solutions

Non-modernization solution (e.g. replacing an analogue based system with another analogue system) tend to be informed by lifetime requirements and are typically driven by procurement/supply chain specialists, with less input from engineering specialists. These solutions do not represent a change to plant, and they claim to produce identical equipment.

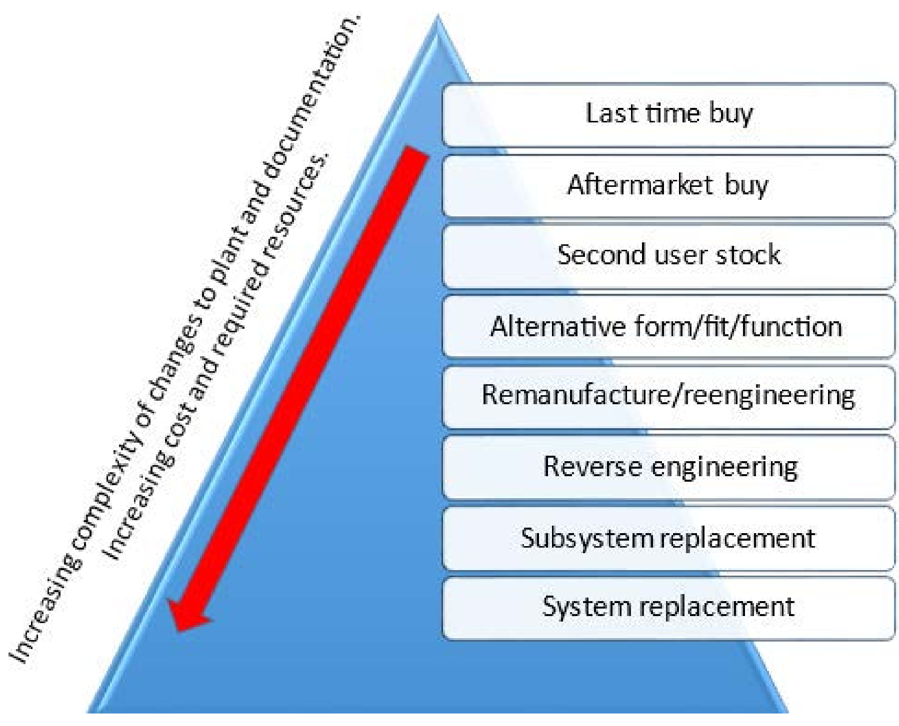


FIG. 16. Potential obsolescence solutions for I&C with reference to complexity, plant change and cost.

The reason that remanufacturing/reengineering of the original design is not included here is because experience shows that remanufactured units are usually manufactured in a very small batch using tooling that is not original and by personnel who do not necessarily have full design knowledge of the original equipment. Also, minor modifications, such as alternative components, are likely to be needed. There are risks in remanufacturing equipment when the original, well established production line has been dismantled. However, remanufacturing or reengineering equipment will still be required to undergo requalification.

Last time buy and component storage

The offer of a last time buy from an OEM to cover any future need for a specific part can be useful and very resource efficient. It can also be a useful strategy to employ until an alternative part is qualified for use or the system is replaced. It is sometimes offered by the OEM prior to making the product obsolete and before tooling for the product is dismantled.

In a proactive approach, it is not necessary to wait for the notice of a last buy offer to stock spares at a level to mitigate obsolescence (for a defined time period based on the measured usage rate).

The advantages of a last time buy solution include:

— No change to the plant or plant documentation;
— Costs are relatively low (provision needs to be made for long term storage costs need to be included);
— Low use of specialist engineering resources;
— Low lead time to availability;
— Storage costs are usually much lower than the costs incurred if no spares are available.

The disadvantages of a last time buy solution include:

— Acquiring funding to make the last time purchase:
  - The funding may be outside the budget or not accounted for within the operator’s business plan.
  - This may stop other work from progressing due to the diversion of funds.
— Need for requirements to increase storage provision (space) or additional requirements.
— Long term storage considerations:
  - The component may have ageing considerations to be taken into account while in storage.
  - The product may have no further support once the last time buy is complete.
  - Adequate storage conditions (environmental) will need to be maintained.

Aftermarket buy

This covers stock obtained from a company holding original new stock after the OEM has made the product obsolete. It tends to have the same advantages and disadvantages as the last time buy option. However, other disadvantages include:

— Additional testing/requalification may be required prior to placing it in stores and in the plant;
— No knowledge of previous storage conditions (poor previous storage conditions may lead to a shorter equipment life than expected);
— Potential unidentified damage;
— Fraudulent equipment checking (counterfeit equipment);
— Potential security risks (introduction of viruses, software updates not having been applied);
— Cost of the spares (often much more expensive than in last time buy);
— Detailed understanding of any warranty issues is needed.

Consequently, the purchase of equipment where the traceability of the product history may not be clear (grey market) needs to be avoided (especially for safety related functions, or for items of equipment which, if they fail, can result in a loss of generation). Even when purchasing such equipment from a well known supplier, it is important that extensive functional, physical and reliability checks are undertaken to ensure the integrity of the equipment.

Second user stock

Potentially valid sources of second user stock equipment can come from a number of places such as:

- From an on-site modification where spares are released (sometimes referred to as 'cannibalization');
- From a different industrial plant (possibly even another NPP) where the equipment was installed and can be removed;
- From a company holding original used stock after the manufacturer has made the product obsolete and the user has released the stock.

It needs to be noted that any equipment being removed from service has potential value as a source of strategic spares. Therefore, it is vital that I&C equipment is not disposed of by the NPP operator until they can ascertain that the equipment cannot be utilized for strategic spares (e.g. they cannot be refurbished and retested).

The advantages of a second user stock solution include: No change to plant.

The disadvantages of a second user stock solution include the items listed below (last time buy and aftermarket buy disadvantages also apply here):

- Additional information is needed relating to its previous use (including length of time the equipment was in service, the environmental conditions over that period and any maintenance repair records, especially if the spares come from another company). The equipment is not to be used without this information.
- Additional testing/requalification will be required prior to using it in the plant and placing it in stores.
- The equipment may need to be refurbished (e.g. cleaning contacts).
- Checking for fraudulent equipment is essential.
- There is a potential for equipment damage to go undetected.

4.3.5.3. Modernization solutions

If the above non-modernization solutions are not appropriate, modernization strategies can be used to solve obsolescence problems. The modernization strategies are presented in Sections 5 and 6.

4.3.6. Solution sharing

Solution sharing, both internal to an organization (across NPPs owned by the same operator) or external to an organization (across NPP operators) can bring benefits in both time (i.e. reduced implementation time) and cost. However, there may be IP implications that prevent the sharing of this information with other companies.

4.4. CONFIGURATION MANAGEMENT

Configuration errors or deficiencies are listed as contributors to approximately 25% of the events that are recorded in the IAEA's Incident Reporting System. Thus, the configuration of I&C systems/equipment needs to be carefully managed. Plant changes/modifications are one of the main ways through which configuration errors and deficiencies can be introduced and I&C systems/equipment are no exception when they have to be modernized to address ageing and obsolescence issues.

It is essential that robust configuration management principles are applied throughout the duration of all I&C modernization programmes. Detailed configuration management guidance is provided in the following IAEA publications, which need to be consulted prior to undertaking such programmes of work:

— Safety Reports Series No. 65, Application of Configuration Management in Nuclear Power Plants [10];
— IAEA-TECDOC-1335, Configuration Management in Nuclear Power Plants [11];
— IAEA-TECDOC-1651, Information Technology for Nuclear Power Plant Configuration Management [12].

Based on the above, the following items typically need to be amended when undertaking an I&C modernization programme:

— Safety and security case documentation;
— System description documents and drawings;
— Operating manuals and instructions;
— Technical specifications;
— Maintenance/testing manuals and instructions;
— Bill of materials/AMS databases;
— Training packages and simulators;
— Equipment support contracts;
— Simulators;
— Ageing and obsolescence plans;
— Software management plans;
— Spares provisions;
— Surveillance frequency.

Careful planning is needed to ensure that the necessary document changes are made and that relevant stakeholders (e.g. operating, maintenance and engineering personnel) are provided with the necessary training before the new system/equipment enters service. If original equipment is replaced with new similar/equivalent equipment, the new equipment needs to be provided with a unique asset/part number. This is especially important when the original equipment is still employed by other systems within the NPP. Failure to do so could result in the original equipment being inadvertently installed in place of the new equipment and vice versa.

It is important that COTS manufacturers not change their product serial/part numbers when they make minor hardware or software changes. Therefore, NPP operators have to be vigilant and also record the product’s hardware and software versions in their AMS. It is also important that the AMS is kept up to date and that all equipment details are carefully recorded.

4.5. SOFTWARE

4.5.1. Planning for software obsolescence

Section 4.2.4 outlines a number of ways in which software/firmware can become obsolete and it is therefore important to recognize that this will need to be carefully managed and planned for. This needs to include maintaining a close, formal relationship with the OEM to ensure that relevant software developments and updates are identified and implemented in a timely manner. This could include bug or security fixes, updates to operating systems, hardware drivers, and communications protocols, as well as application and firmware versions.

It is also necessary to plan the software testing to maintain the required level of software integrity. Planning also needs to consider the supporting documentation that need to be updated (e.g. safety case reports, operating manuals, training material).

4.5.2. Software security

Software security related to obsolescence has two main areas of concern:

- Software vulnerable to attack from existing or new cyberthreats;
- Ability of an NPP operator to recover a system using secure backup copies on secure compatible equipment.

With respect to the vulnerability to cyberattack, new techniques of attack have the potential to make originally secure software vulnerable. Although this may not make the software obsolete in the sense that it may still be available to purchase and install, it would likely conflict with the need for it to be secure from cyberthreats. Software requiring a security patch will mean that it is vulnerable to threats and therefore needs to be considered obsolete and be updated.

The ability of an NPP operator to recover a system from either a system failure or from a security breach requires identification of all resources needed for that recovery procedure. This includes the storage of secure backup versions of the existing system software with all current configuration settings, and will need to be available on appropriate equipment for the recovery process. In addition, competent personnel are needed to initiate the recovery process and recommission the system.

4.5.3. Control of existing software for a system’s operating life

A software management plan needs to be developed for I&C system that contains software. The plan needs to itemize all the individual software related components within the system. This breakdown of software related components needs to include, but is not limited, to:

- Operating systems;
- Hardware drivers;
- Communications protocols;
- Application specific code;
- Display drivers.

Each software related component needs to have clear configuration control records and a full modification history. In addition, software tools used to generate and modify the software code, along with any testing equipment, will also need to be maintained.

The level of software qualification needs to be clearly identified along with the records of testing that has been performed. It is important to retain this information, so that it can be referred to for future modifications and inform the testing or analysis required to maintain the integrity of the software.

For many items of I&C systems that contain software, ongoing maintenance/support is often provided by the OEM. If an OEM provides notice that it intends to remove the maintenance/support for a product, the NPP operator will need to evaluate the impact in terms of being able to support the continued operation of the system. One method of mitigating this can be to sign long term maintenance/support contracts with the OEM. Reviews of the software management plan for each system have to be performed on a regular basis, and ideally these reviews involve the OEM.

4.6. KNOWLEDGE MANAGEMENT OF I&C EQUIPMENT

Loss of I&C systems/equipment design, maintenance, repair and operating knowledge is an issue that needs active management. This is also true in relation to the need to obtain knowledge of evolving technologies that could be incorporated into I&C systems in future modernizations. Each NPP operator, therefore, has to implement a knowledge management plan that clearly identifies the areas of expertise and competence that need to be maintained by its own personnel and in the supply chain.

Knowledge management is usually based on two different elements:

(1) Training and mentorship of relevant stakeholders (e.g. operating, maintenance and engineering personnel). This is particularly important for ‘old’ technologies not part of modern education syllabus.
(2) Succession management of system ownership. It is necessary to ensure that knowledge is not lost when accountability for a system changes (e.g. due to the promotion or retirement of system owners).

Documentation on the concept, specification, design or manufacture documentation has to contain as much detail as possible to allow future modification of the existing equipment to take place. This requires an effective document management system whose potential obsolescence also has to be taken into consideration to avoid loss of documents.

Contractual arrangements, where possible, have to be put in place with OEMs to require them to retain relevant technical knowledge and competency to support/maintain I&C equipment into the future. NPP operators have to also ensure that support personnel (either within their company or from vendors) have clear roles with clearly defined expectations on training and experience. These competencies need to be reviewed periodically, and provision needs to be made to monitor the resilience of support efforts time over.

It is not uncommon to find that system support for a modernized system, while initially good (e.g. in the first few years), gradually declines over time and that towards the end of the life of an I&C system only a small number of individuals retain the necessary knowledge to support it. This can result in premature system obsolescence. Therefore, NPP operators have to take steps to proactively manage this and ensure that sufficient resources are in place to manage the transition of knowledge over successive generations of support personnel.

NPP operators have to maintain system handover documents so that there is a consistent and high quality approach to transferring systems knowledge and ownership between personnel. These typically include:

— Details of the I&C equipment utilized by the system;
— Details of safety case and security case requirements placed on the I&C equipment;
— References to key system description, operation and maintenance documents;
— Details of I&C equipment obsolescence issues and associated management strategies;
— Details of key I&C equipment spares holdings and requirements;
— Details of I&C equipment ageing mechanisms and failure modes, and associated management strategies;
— Details of the environmental operating condition limits specified for the I&C equipment;
— Details of key I&C equipment OEMs, suppliers and specialist repair organizations;
— Details of relevant stakeholders;
— Details of software management plans;
— Details of OPEX;
— Details of relevant I&C equipment related training courses;
— Details of sources of general I&C equipment reliability data.

When new personnel are given responsibility for managing an I&C system, there needs to be a clear handover of knowledge to ensure the long term continued operation of the system. This needs to include details of all equipment ageing and obsolescence issues. Appropriate mentor guides have to be provided to enable new system owners to become competent in all aspects of the system's design, maintenance and operation.

4.7. OTHER I&C EQUIPMENT OBSOLESCENCE CONSIDERATIONS

4.7.1. Monitoring and generation of useful metrics

Monitoring and measuring the effectiveness of the obsolescence management process is necessary. Metrics that can be measured to determine the effectiveness of the process are:

- Total number of plant systems or components reviewed or not reviewed (proactive approach);
- Total number of equipment identified as obsolete;
- Total number of obsolescence issues solved;
- Total number of obsolescence issues unsolved (total and by priority);
- Percent of work orders/requisitions returned owing to obsolescence issues;
- Statistics on obsolescence issues solved categorized by solution type used;
- Number of obsolescence issues categorized by plant systems;
- Number of obsolescence issues categorized by manufacturer;
- Percentage of obsolescence issues resolved before they could affect plant operations;
- Average replacement lead time (weeks or months);
- Number of design or system configuration changes due to obsolescence issues;
- Percentage of purchase requisitions returned for obsolescence reasons;
- Number of temporary modifications or other workarounds necessary for continued operation while waiting for a solution to an obsolescence problem;
- Forced loss rate and outage extension (in days) due to obsolescence.

4.7.2. Obsolescence management tools and organizations

There are a number of proactive obsolescence management tools that have been specifically developed for use in the nuclear power generation industry. There are also obsolescence management organizations from which guidance can be obtained:

- Nuclear Utilities Obsolescence Group;
- International Nuclear Utilities Obsolescence Group;
- International Institute of Obsolescence Management.

5. STRATEGIES FOR I&C SYSTEM/ EQUIPMENT MODERNIZATION

5.1. INTRODUCTION

This section assumes that a modernization solution is to be developed for aged/obsolete equipment and a process for assessing the options is necessary. The section discusses recognized I&C modernization options and highlights their advantages and disadvantages. The section also outlines further considerations within the decision making process and the types of engineering justifications that will be required for the modernization to take place.

If the remaining lifetime of the plant is long, modifications may be needed over the lifetime. Facilitating and preparing for these need to be considered as part of any long term strategy and could influence the choice of modernization solution selected from the options below. For example, a solution that seems easier in the short term may make future modernizations more difficult.

The details for implementation of each of the options is described in Section 6 of this publication, so Section 5 is intended as an introduction. Additional information on many aspects that may serve as bases for initiating modernization projects for process control systems of NPPs are described in other publications, such as IAEA-TECDOC-1389 [7], and the US Department of Energy publication: Light Water Reactor Sustainability Program, Business Case Analysis for Digital Safety-Related Instrumentation & Control System Modernizations [13]. Further information and consideration of different modernization strategies may be found in the World Nuclear Association publication I&C Modernization: Current Status and Difficulties [14].

5.2. STRATEGIES/OPTIONS

5.2.1. Common information for all strategies/options

The following information is needed for each of the modernization strategies discussed in this publication. The information is relevant to both equipment and systems.

Technical requirements

— Detailed technical specifications for the component/system and all interfaces.
— Detailed operational/functional requirements in all plant states.
— Complete performance requirements (e.g. reliability, environmental).
— Details for equipment qualification and certifications.
— Inadequacy of the existing system that need to be corrected by the new system.
— Legal ownership of IP for the original design of component/system and requirements for ownership of the IP for the modernized system. This needs to be made clear in any contract. The IP for the hardware is typically retained by the OEM. However, the NPP operator needs to retain the IP for any applications.

Organizational requirements

— Regulatory requirements (codes/standards/conditions of a licence for operation);
— Issues with the equipment identified during operation.

Planning criteria for assessing the start and end dates of a modernization project

— Trends in system reliability and spares holding (when will the system become unsupportable);
— The necessary plant operating modes for a modernization project (current and future schedules of unit outages);
— The availability and accessibility of competent personnel.

System/component historical records and OPEX

— OPEX of the existing system (e.g. failure trends);
— What it will take to keep the existing system functional to the point of modernization;

— International experience and lessons learned from similar modernization projects.

Knowledge management

— The knowledge to support a modernized system is fundamental to ensuring that it continues to operate as designed. Loss of this knowledge will inevitably lead to increasing failure/departure of the system from its design intent. This could either be revealed or unrevealed, but in either case represents a threat to the safe operation of the plant and also to the sustainability of the product into the future. For example, key knowledge (which could be in the form of documentation, skills or experience) will include design information, supporting tools and software, modification history, fault finding guides and techniques. Loss of knowledge can, therefore, result in a point being reached whereby the newly modernized system is no longer supportable, thus accelerating its replacement.
— On commencement of a modernization project, there has to be a clear definition of all necessary support documentation and databases required to understand, maintain and possibly modify the system in the future. Knowledge management is discussed further in Section 4.6.

5.2.2. Replacement with similar equipment (fit, form and function or like for like)

This strategy focuses on the use of alternative equipment that matches the fit, form and functionality of the original equipment. This term is in common use in the field of obsolescence and has the potential to be misused if care is not taken.

Although replacement items may be physically identical and deliver the same function, it is important that the old and new equipment’s characteristics (e.g. integrity, reliability, performance, how it operated under certain conditions) are also taken into consideration. For example:

— The response time of old analogue equipment may be significantly slower than that of the new digital equipment;
— The old analogue equipment may be more tolerant of signal noise than the new digital equipment.

The above differences could in turn have unexpected functional consequences. In addition to this, digital technology will often have additional functional capabilities, which if inadvertently implemented could have unexpected or unwanted consequences.

Thus, a fit, form and functionality replacement will generally still constitute a design change requiring a full engineering change analysis and substantiation. This form of replacement is not to be confused with an item equivalency evaluation (IEE) which, under some circumstances, can be introduced without the full engineering change processes (see Section 5.4.1 for more details).

These factors need to be carefully assessed by competent personnel to determine true functional equivalence.

The advantages of this strategy include the following:

— Only minor changes to plant and plant documentation are needed;
— Justification for use has to be straightforward;
— Compared with a last time buy solution, the new equipment will be supported into the future, although the duration of support also has to be investigated.

The disadvantages of this strategy include the following:

— Engineering resources are needed to confirm that the specification has been met and supporting evidence is complete and sufficient;
— Compared with a last time buy solution, the new equipment may require a period of specific testing to demonstrate that equipment qualification requirements have been met;

— It may be difficult to engage with the OEM if a significant amount qualification/testing evidence is required and the intention is only to purchase a small number of low cost items.

A detailed assessment of this option is provided in Section 6.4.

5.2.3. Remanufacturing/reengineering

This strategy involves remanufacturing of the equipment without making any fundamental design changes (except for very minor component changes). This can be completed by the OEM or by a new supplier (providing appropriate account of IP is taken). To achieve this, it is expected that the vast majority of original design documentation will still be readily available. If a significant amount of this documentation is unavailable, remanufacturing of the equipment would fall under the category of reverse engineering where the design documentation would be required to be generated from the start.

It could be argued that this method does not constitute a modernization solution as it simply reimplements the equipment's original design. The reason that it is discussed here is that remanufacturing an item where production has ceased (potentially for a few years) may mean that production line tooling (including test facilities) is no longer available and that some level of expertise or documentation is no longer available. Therefore, although the item may be the same, the processes used to manufacture it may not be. In addition, manufacturing small batch quantities of a product compared with originally manufacturing larger quantities when in its original production line has the potential to introduce new manufacturing errors not seen in the original.

The advantages of this strategy include the following:

— No changes, or only minor modifications, to the plant and plant documentation are needed.

The disadvantages of this strategy include the following:

— The remanufactured units may require requalification and testing. This can take significant time and resources.
— Minor changes (e.g. onboard simple components that were obsolete) will need justification.
— Funding the one-off engineering works to put production tooling back in place.
— The product may have no further support once the remanufactured production run is complete.

5.2.4. Reverse engineering

Reverse engineering is characterized by the need to take the original equipment, without a complete set of original design documentation, and reproduce the functionality of the equipment within the original form and fit. This may necessitate changes to the original technology, for example with the use of devices such as field programmable gate arrays (FPGA).

When embarking upon reverse engineering as a solution, it is essential that the systems/equipment being reverse engineered are thoroughly understood in both their operation and functional requirements; especially in relation to aspects of safety or interfaces with other equipment. It is also important to distinguish between the 'as found' operation/performance of the equipment and the design requirements, which can often be difficult to do. Changes in the performance of electronic components over time can mean that there is a significant difference between the current performance and the original design intent. Therefore, the objective of reverse engineering is to re-establish design intent rather than 'lock-in' degraded performance in a newly reengineered component. This can be difficult to ascertain in the absence of original design documents.

When considering this as an option, there is the potential to reverse engineer specific parts of a system where the stock of spares is low and where the rest of the system can be appropriately supported with no further engineering effort. A complete life cycle design project will be required for this type of activity. At completion, a complete set of design documentation is required to have been produced.

The advantages of this strategy include the following:

— FFF criteria can be met with minimal other changes to plant;
— Some simple enhancements are possible, such as additional diagnostics or even removal of unused functions of the original equipment (simplification);
— Long term sustainability of equipment.

The disadvantages of this strategy include the following:

— IP issues may need to be addressed.
— This is not a low risk option. Reverse engineering with little original design documentation is not a guaranteed success.
— The process can be expensive and time consuming.

This strategy is covered in more detail in Section 6.5.

5.2.5. Partial and full replacement

Both partial (subsystem level) or full (system level) replacement are strategies that are characterized by the replacement of a large amount of equipment with significant complexity of interfaces to the existing plant. At this level of modernization, the detailed management of interfaces between existing and new equipment is vital to the success of the project.

A further distinction in this type of modernization is between system upgrade or replacement (either fully or partial). The distinction between the two lies in whether it is necessary to replace software. For example, a system upgrade whereby newer or faster processors are installed can, in many cases, mean that the software can be directly ported without the need for rewriting or extensive retesting. Conversely, if replacement uses different processor components (different family or significantly different generation), then the additional cost and complexity of software rewriting and testing become a factor.

The advantages of this strategy include the following:

— Remove a large amount of aged and obsolete equipment in one project;
— Correct inadequate design of the original plant;
— Take advantage of modern system diagnostics, the human–system interface (HSI) and fault tolerance designs;
— Can be used to manage any future obsolescence.

The disadvantages of this strategy include the following:

— High cost for the design development and testing of the new system;
— Risks of inadequately specified plant interfaces;
— Long project delivery time scales (resulting in the existing system requiring continued support).

Partial system replacements may also form part of an intermediate temporary or bridging strategy before a full system replacement can be undertaken. Even if the solution is seen as being temporary it is still necessary to ensure that a clear safety justification is produced to support plant operation during the lifetime of the bridging strategy. These strategies are covered in more detail in Sections 6.6.2 and 6.6.3, respectively.

5.2.6. Joint strategies

The reasons for a combination of strategies include the following:

- Replacement of part of a system or a specified number of components to release spares so that other systems can be supported in the future;
- Bridging strategies to allow support in the short term with alternatives, until such time that a full system replacement can be undertaken.

IAEA Nuclear Energy Series No. NP-T-1.4, Implementing Digital Instrumentation and Control Systems in the Modernization of Nuclear Power Plants [15], states that:

> "A common goal is to avoid the necessity to repeat an overall modernization during the remainder of the plant's operational lifetime by ensuring that a smooth migration/upgrade path for the system is possible and can be conducted in manageable steps. In such a way, the shorter life cycles of digital I&C can be addressed while the possibility to further implement advanced techniques or applications in the system remains feasible."

This is effectively a strategy of avoiding future 'big-bang' modernization versus a continual 'renewal/evolution' of the modernized I&C system.

When planning modernization strategies, holistic considerations for the entire NPP need to be included without just focusing on the system that is the subject of immediate concern. If this is not done, then successive 'independent' modernizations of systems will result in multiple solutions across the plant that are driven by when the modernization was implemented or the resources were available at the time. Ultimately, this will reduce the overall efficiency of managing the systems (e.g. holding more spares, introducing different skills/knowledge requirements, etc.). Instead, if a long term holistic approach is adopted, then a series of modernizations over many year affecting different parts of the plant can result in an overall unified and easier to manage set of I&C systems.

If modernizations are implemented over a long period of time due to their magnitude or complexity, it is likely to involve work over several outages. This will inevitably mean that the plant modification incorporates multiple intermediate steps, after which the plant is operated for a period of time. Care needs to be taken in planning the safety justification of each intermediate plant configuration to demonstrate that adequate safety margins are always maintained in the modification cycle.

5.3. DECISION MAKING PROCESS

It is possible that more than one of the obsolescence management strategies mentioned above may be required to achieve a successful technical outcome. Equally, it may be necessary to develop a 'bridging strategy' as part of a multistage obsolescence/modernization strategy. However, to understand the optimum option requires a wider view than the technical solution. Therefore, other factors may need to be considered. The following highlights some of the technical and organizational issues that require consideration.

5.3.1. Equipment availability judgements

When selecting the components/technologies for a modernization project, those products have to be selected which have an expected lifetime consistent with the needs of the project. Noting that, in some cases, the lifetime of the system means that future upgrades may be inevitable, there are several considerations that could be applied to product selection. These include the following:

- Avoid novel or niche technologies. Generally, products or technologies with a wide industry application will remain supported for longer than those that have a small demand.
- Avoid custom designs/components as these will most likely not be supported for long.
- Avoid products/technologies that are under development. While they may be popular and appear to have a longer life than established products, there are risks over the direction of the technological development, which could result in the selected product becoming ‘stranded’.

In the long term, products with market dominance are more likely to survive than those with technical superiority. Hence, as stated in Ref. [15]:

> “The use of I&C systems based on platforms that have a large installation base is generally preferred due to the greater likelihood of platform stability and future support options...For a qualified platform, it can usually be expected that many different tools can be used to support the requirement specification, the application programming, V&V, documentation and version management. It is important that the utility has a good understanding of these tools and is prepared to use them during the modernization project.”

Where there is the potential to choose ‘open systems’, i.e. products where the technological interfaces/means of using are licensed widely in the nuclear power industry, then this can be advantageous as such products are likely to be stable and support could be offered from a wide variety of sources. This subject is discussed in more detail in Section 6.2.

5.3.2. Operational judgements

When preparing for an I&C modernization project, it is necessary to consider life cycle/lifetime operating issues such as:

- The remaining life of the NPP. In relation to this, Ref. [15] states: “…the lifetime of digital systems is typically much shorter than that of the plant. This may initiate the need for more than one upgrade of the same system during the plant lifetime.”
- The long term role of the I&C system, including post-generation (i.e. defuelling and decommissioning) operating requirements.
- The identification of suitable NPP outage windows in which to complete the installation and commissioning work.
- Technologies used and their expected longevity.
- Training needs.
- Resource needs.
- Spares holding and availability.

5.4. SOLUTION JUSTIFICATION

5.4.1. Item equivalency evaluation

The IEE process is designed to take account of very minor modifications, where very clear fit, form and functionality criteria are specified. This process is described in an IAEA publication [16]. However, it is not an I&C specific concept; when applying this process to I&C modifications, the following need to be taken into consideration:

— Clear boundary conditions need to be defined for all critical parameters (e.g. accuracy, performance, reliability).
— There cannot be any change in functionality. This is particularly important for digital to digital replacements, where characterization of the functionality would need to be very clear.
— The potential to introduce additional failure modes into the design needs consideration. For analogue to digital replacements, this would be classed as a plant modification and would require the full engineering change process to be followed.

5.4.2. Non-identical component replacement/substitution

A non-identical component replacement (NICR) is used when no equivalent item can be found by the IEE process and a component replacement is required due to obsolescence or OPEX concerns. The first step in the NICR process is to perform an assessment to determine if use of the NICR process is justified. The key focus in the NICR justification assessment is to identify the critical design attributes and design intent, and confirm that the new component meets these attributes.

5.4.3. Engineering change process

Formal engineering change processes are well established in the nuclear power generation industry. For all other replacement modifications not covered by IEE or NICR processes, the full engineering change process will be required to be followed subject to the safety functions performed by the replacement I&C equipment/system.

5.4.4. Assessment of security arrangements

As technology changes, especially toward digital systems, the nature of the changes in potential cyber threats needs to be considered. This could be completed in the appropriate security protected documentation. Guidance regarding this is given in Refs [17, 18].

5.5. DEVELOPMENTS IN OBSOLESCENCE MANAGEMENT

A recent development in the area of obsolescence management is the application of advanced manufacturing methods to efficiently produce obsolete components in mature NPPs through reverse engineering 3-D printing. Annex IV contains an example of asset and maintenance management (AMM) at the Darlington Nuclear Station in Ontario, Canada. In this example, 3-D printed spare parts for the station's digital control computer (DCC) printers were used as a bridging strategy until permanent replacements were found.

The potential for the use of 3-D printing is clearly limited primarily to mechanical components, rather than complex electronic components. Similarly, the opportunities to use this technique for safety systems where, for example, understanding and qualification of material properties used in mechanical components such as gaskets or insulators may mean that 3-D printing is not an option. However, as illustrated by the example quoted, it can offer some advantages for extending the life of less safety critical equipment.

6. I&C SYSTEM/EQUIPMENT MODERNIZATION STRATEGIES AND ISSUES

6.1. STRATEGIES FOR MODERNIZATION

As they age, I&C systems will need to be modernized several times during an NPP's life, which could be in excess of 80 years for certain designs. Reference [15] states that:

> "A long term modernization strategy should also be created, which takes into account the remaining life of the plant as well as any future upgrades."

Therefore, it is important that NPP operators consider the 'end of life' date of their NPPs when deciding on a modernization strategy. In referring to their long term planning strategy to determine the most likely date when the NPP will shut down, the following also need to be taken into consideration:

— Periodic safety reviews (PSRs) will often highlight I&C systems that need modernization, either before the next review or before the end of the plant's life. PSRs are a valuable and objective source of guidance to reveal emerging modernization needs.
— Some I&C systems will have no functional requirements once the NPP has been shut down, while other systems may still be required to remain fully operational for many years after shutdown (e.g. fuel pond monitoring and radiation monitoring systems). Therefore, NPP operators need to note the future role that I&C systems will be required to fulfil during all life cycle stages of the NPP (including defuelling and decommissioning).
— Some I&C systems may be needed to fulfil an enhanced role or operate more frequently during the defuelling phase (e.g. fuelling machine control systems).
— End of life predictions can be difficult. Some reasons are technological (e.g. steam generator lifetime), whereas others may be economic. The latter are variable and tend to be the result of prevailing external factors (e.g. national policy, energy markets). Therefore, while end of life predictions need to consider economics, care is needed to avoid making decisions that prevent incremental plant life extension at some later date.

If the end of life date is:

— Nominally less than 10–15 years, future modernization of I&C systems can be assumed to not be necessary. Therefore, readily available items of equipment have to be selected, and lifetime purchases of spares made and/or contracts placed for equipment repair/maintenance.
— Nominally greater than 15 years, I&C systems will need to be modernized. It is therefore necessary to plan for this eventuality.

Once the NPP's end of life has been established, the following need to be considered:

— Which systems will need to be modernized and when they will need to be modernized.
— How much of the original functionality needs to be retained.
— The need to introduce additional functionality.
— The choice of modernization strategy to employ:
  - Replacement with similar equipment (i.e. FFF or like for like replacement). The level of 'granularity' also needs to be considered in relation to this strategy, for example:
    — Replacement of electronic circuit board components;
    — Replacement of a chassis or a rack;

  - Replacement of cabinets;
  - Replacement of subsystems.
- Remanufacture/reengineering.
- Reverse engineering.
- Partial replacement.
- Full replacement.

What will be done with the redundant equipment is another consideration. This needs to include:

- Whether the original equipment needs to be preserved to support/extend the life of other systems;
- The risks/costs associated with the physical removal of the original equipment (e.g. the potential to damage surrounding equipment, the need to employ specialist suppliers).

There are a number of ways in which each of the above-mentioned modernization strategies can be implemented. However, to determine the appropriate approach, thorough optioneering work is needed by a working group of personnel and all relevant stakeholders (e.g. operating, maintenance and engineering personnel, and suppliers).

Finally, as stated in Section 5.2.6, NPP operators need to take a holistic and coordinated approach to system modernization that takes the entire NPP into consideration and assesses the impact of undertaking multiple system modernizations over several years. Failure to do so is likely to lead to a combination of different I&C platforms and technologies being employed over time, which in turn is likely to lead to an overall increase in maintenance, spares holding and training costs.

6.2. CHOICE OF TECHNOLOGY

6.2.1. High level considerations

The choice of technology for modernization will be influenced by a number of factors, such as:

- Whether existing functionality needs to be improved;
- Whether new functionality needs to be introduced;
- The extent to which existing and new equipment will be supported by the OEM;
- The scale of the modernization;
- The need to migrate from analogue to digital technology;
- Whether the system is delivering a nuclear safety function, as this will determine the level of design rigour and the amount and depth of supporting evidence that is needed.

6.2.2. Use of the same technology

When developing the technical specification for a modernization programme that does not require additional functionality to be introduced, NPP operators need determine whether it is possible to implement the required functions, with the required integrity, with the same the technology used in the existing system. If this is the case, and the technology will remain readily available for the foreseeable future, then this may indeed be the appropriate technological route to follow, especially if a ‘replace with similar’ modernization strategy has been chosen where only circuit board components are to be replaced. Furthermore, changing the underlying technology of a system when there is no need to change or add functionality may not be economically justifiable, as a significant amount of work will likely be needed to demonstrate that the modernized system has the required level of integrity.

6.2.3. Scale of modernization

The need to change technology will typically increase with the scale of modernization. However, even where the scale of modernization is small, it may still be necessary to change the technology if the old technology is no longer manufactured or available. Under these circumstances the technology change is usually one of migration from analogue to digital technology or from one generation of digital technology to another. Even though many NPPs are already facing the challenge of modernizing outdated digital I&C systems, reverse migration from digital to analogue is not a general practice.

6.2.4. Benefits of digital migration

Where an existing I&C system is based on analogue technology, and there is no need to introduce new functions, it may be appropriate to retain this type of technology. However, the following factors have to be taken into consideration:

— Economic factors (currently, the average cost of digital solutions is usually lower than of analogue ones since the former is more common);
— The availability of spare parts and consumables;
— The availability of engineering support from the OEM or an equivalent supplier if transfer of IP from the original OEM can be agreed;
— The knowledge needed to support the technology into the future (see Section 4.6 for more information on I&C knowledge management).

It may also make sense to refrain from migrating to digital technologies where national regulators require systems important to safety to be implemented by diverse means. For example, if it is necessary to replace two redundant channels it may be appropriate to implement one with digital technology and another with analogue technology. An IAEA publication, Criteria for Diverse Actuation Systems for Nuclear Power Plants [19], identifies common criteria for the design of diverse actuation systems at NPPs.

When deciding to migrate from analogue to digital technologies, NPP operators also have to take into account the fact that analogue technologies tend to be extremely inflexible. However, they do have some notable advantages:

— Failure modes tend to be well understood;
— They provide a high degree of protection against cyberthreats.

6.2.5. Digital technology choices

The transition to digital technologies requires a decision to be made as to what type of digital equipment the modernized system has to be based on. Currently, there are two main types of digital technologies:

(1) Freely programmable devices;
(2) Devices with a limited set of functions.

Programmable logic controllers (PLCs) are the most common type of ‘freely programmable devices’ that are currently employed by NPP I&C systems. The following are the two most common main types of digital ‘devices with a limited set of functions’ that are currently employed by NPP I&C systems:

(1) FPGA: Integrated circuits that can be reprogrammed in the field using special tools;
(2) Application specific integrated circuits (ASIC): These devices are programmed (built) to perform a specific task (or set of tasks). However, they cannot be reprogramed.

A common advantage of these devices is that they can fulfil the functions assigned to them in real time. However, a common disadvantage of all these devices is that for the end user they are in essence ‘black boxes’ and that checking the correct implementation of functions and algorithms assigned to these devices is only possible by indirect methods. Therefore, testing such devices can be time consuming and expensive.

The advantages associated with the use of PLCs include:

— Relatively low cost;
— Widespread availability in the market;
— Wide availability and range of peripheral devices;
— Ability to vary their operating systems;
— High performance indicators;
— Availability of scaling (reconfiguration) of the system in the field;
— The presence of built in interfaces for interaction with networks and field devices according to standard protocols (including industrial ones);
— Relatively easy to reprogram in the field;
— Advanced features for self-diagnosis;
— Ability to implement direct high speed inputs.

The disadvantages associated with the use of PLCs include:

— Computer security vulnerability;
— They might not be qualified to withstand the operating EMI/RFI environment and may therefore need additional shielding.

The advantages associated with the use of FPGAs include:

— Lower power consumption than a PLC with a comparable performance;
— High speed;
— A large number of embedded input/output (I/O) ports;
— No operating systems (resistance to cyberthreats);
— High level of reliability;
— Independence from external memory;
— Availability from several lead suppliers, therefore more future proof.

The disadvantages associated with the use of FPGAs include:

— Complexity and high cost of programming;
— Floating point calculations are hard to implement;
— Limited field reprogramming capabilities.

Information regarding the use of FPGAs in NPPs is given IAEA Nuclear Energy Series No. NP-T-3.17, Application of Field Programmable Gate Arrays in Instrumentation and Control Systems of Nuclear Power Plants [20].

ASICs currently tend to be used in NPP I&C systems for limited applications (e.g. for a narrow range of intermediate signal processing tasks). However, although there are ASICs on the market with integrated processors and memory units, it is still too early to suggest them for use in NPP I&C systems as a base technology. Nevertheless, the use of ASICs within replacement products is not uncommon and care needs to be taken when using such products to identify if ASICs are used and to understand their role in fulfilling the safety functions of the product.

PLCs and FPGAs can be considered as equal candidates for modernization programmes, as neither have a significant advantage over each other in economic or technical terms. Currently, many NPPs have implemented, and successfully operate, I&C systems that are based on both technologies. However, it is advisable to use FPGA technology in I&C systems where:

— Relatively simple algorithms are implemented;
— The technological process does not require frequent changes in the algorithms during operation (or in the future);
— There is a large number of modules that have to solve similar problems simultaneously;
— There are requirements for the diversification of redundant systems;
— Reliability and performance have priority.

PLC technology can be used in I&C systems where:

— The implemented algorithms use mathematical calculations;
— There are no strict speed requirements;
— Where it is envisaged that functionality changes will be necessary in the future;
— There are no common cause failure (CCF) requirements that prevent several control loops being implemented in a single device.

6.2.6. Use of COTS equipment

The relatively high cost of specialized NPP I&C systems is increasingly forcing NPP operators to consider the use of COTS equipment. The main advantages of such equipment are:

— Low cost of products;
— Low operating costs (availability and low cost of spare parts, availability of personnel for maintenance);
— Reliable and relatively cheap engineering support from manufacturers;
— A wide range of peripheral modules;
— Flexibility and simplicity of configuration and reconfiguration;
— Extensive user base.

There tend to be no regulatory restrictions regarding the use of COTS equipment for I&C systems that are not important to safety. However, careful consideration is needed for the use of COTS equipment in I&C systems important to safety.

While it is generally straightforward to procure COTS equipment that has been qualified to operate within the climatic and mechanical conditions that I&C equipment are typically exposed to within NPPs, it can often be challenging to procure COTS equipment that has been qualified to operate in an ionizing radiation environment or under seismic conditions applicable to the location of the installation at the NPP. Unfortunately, due to the relatively small size of the nuclear I&C equipment market, COTS equipment vendors perceive that the benefits of making nuclear power generation industry sales do not outweigh the associated ionizing radiation qualification costs. However, where COTS equipment has been qualified to operate in an ionizing radiation environment, experience has shown that the costs of implementing I&C systems with such equipment is comparable to I&C systems that have been specifically designed and qualified for use in NPPs.

Another issue that inhibits the widespread use of COTS equipment in I&C systems important to safety is that COTS equipment vendors are often reluctant to share the equipment's software source code, which makes it very difficult for NPP operators to verify the integrity of the equipment.

The above considerations are covered an IAEA publication, Challenges and Approaches for Selecting, Assessing and Qualifying Commercial Industrial Digital Instrumentation and Control Equipment for Use in Nuclear Power Plant Applications [21].

6.2.7. Use of wireless network technology

Although the use of wireless network technology is increasing in commercial I&C systems, its use in NPP I&C systems important to safety is currently limited. Wireless network devices can offer significant savings through reduced cable use and can be placed in locations where there is limited space for cables. However, they have significant drawbacks, such as their sensitivity to, and generation of, EMI/RFI and their vulnerability to cyberthreats. Guidance on the use of wireless network technology in NPPs is provided in Refs [22–24].

6.3. INTERFACES WITH EXISTING SYSTEMS/PLANT

When employing a partial or full replacement modernization strategy, all system interfaces (internal and external) need to be identified and data exchanged through them are fully understood. All data requirements, such as transfer speeds and data accuracy, have to also be fully understood. Failure to do so will almost certainly lead to incorrect interface requirements being specified and signal/data transfer omissions/errors.

One of the benefits of following a replace with similar modernization strategy is that the original interfaces can be reused, which in turn avoids the need for connectors, cable lines and internal cabinet wiring having to be redesigned, the cost of which can be significant. The decision to modernize I&C equipment by replacing electronic circuit board components, modules and racks, or chassis in existing I&C system equipment will not normally necessitate interface changes. However, this is unlikely to be the case when modernization involves the replacement of I&C equipment, subsystems and cabinets.

Where the modernization strategy involves adding new functionality, new interfaces might be necessary. For example, replacing analogue equipment with digital equipment, which has additional diagnostic functions, will likely necessitate new communication channels.

Even if the chosen modernization strategy does not require interfaces to be changed, it may still be necessary to do so to meet modern computer security requirements. Guidance on this is provided in Refs [17–18]. Where new interfaces are introduced that enable communication between systems that have different safety classifications, many regulators will require the interface requirements for the highest class system to be applied.

Sufficient interfaces are needed to enable connections with other systems/subsystems to be made during future modernization programmes. Where there are no interface usage restrictions, NPP operators need to take the following into consideration:

— Optical communication channels normally have the greatest immunity to interference (mainly high frequency electromagnetic radiation).
— The communication lines through which protection and interlock commands are transmitted have to be implemented by individual lines without using a shared medium.
— Communication lines have to be implemented by field equipment using the ‘current loop’ interface (as diagnostics of sensors are provided). Modern sensors often can also transmit digital data through the highway addressable remote transducer (HART) protocol.
— Channels through which large volumes of non-critical data are transmitted have to be implemented by ethernet (or similar protocol) hardware.

6.4. REPLACEMENT WITH SIMILAR EQUIPMENT STRATEGY

Replacing obsolete analogue equipment with similar analogue equipment can be the most effective obsolescence management solution. One of the main aspects of this strategy is that there is generally less scope to introduce new functionality. However, as previously discussed, this may not necessarily be a disadvantage. Another aspect of this strategy is the need to maintain the external interfaces of the system to enable it to fully integrate with other I&C systems.

Such a strategy can be implemented in several ways; however, the following approaches are often taken:

(1) Replacement of old electronic components on existing boards with the preservation of the original chassis/blocks/racks in the original cabinets. This is the most cost effective approach. However, its use is subject to certain conditions:
   - Analysis demonstrates that there is no need to add new functionality to the system that is to be modernized.
   - There is no need to make significant design changes to fulfil the requirements of new standards.
   - Analysis demonstrates that existing structures (cabinets, frames, blocks), switching elements (terminals, connectors, plugs, sockets) and communication lines (signal and power cables) can perform their required functions over the planned life of the modernized system.
   - Inspections of electronic circuit boards reveals that their electrical circuits and interfaces are in satisfactory condition.
   - Analysis of equipment faults demonstrates that there is no increase in equipment failure rates.
   - The NPP operator has the design and construction documentation for electronic boards in which it is planned to replace electronic components. Alternatively, potential suppliers confirm that they have/can obtain the necessary documentation and are willing to utilize it.
   - Market research demonstrates that the electronic components are readily available. It is important to consider that the new electronic components will need to have electrical and dimensional characteristics that correspond to the original components.
   - Engagement with potential suppliers reveals that they are willing to carry out the work in the necessary volumes and on time. In some situations (e.g. low volumes, specific design of boards, limited production capabilities), the cost of this modernization strategy may be prohibitive.

(2) Replacement of old chassis/blocks/racks with the preservation of existing cabinets can be very effective from an economic and organizational point of view, although it is somewhat more expensive than the above approach. A positive aspect of this method is that it may allow improvements to be made to the existing equipment (e.g. reducing the overall energy consumption of cabinets due to the use of modern electronic components in modernized modules and units and, as a result, reducing the requirements for heat removal conditions). This approach can be used under the following conditions:
   - There is no need to add new functionality or to change the data characteristics of the system.
   - Analysis demonstrates that the existing cabinets and communication lines between cabinets are able to perform their required functions over the planned life of the modernized system.
   - Analysis demonstrates that there is no adverse trends of cabinet communication line or interface faults.
   - The NPP operator has the design and construction documentation for the cabinets (including their components) in which it is planned to replace chassis/blocks/racks. Alternatively, potential suppliers confirm that they have/can obtain the necessary documentation and are willing to utilize it.
   - Engagement with potential suppliers reveals that they are willing to carry out the work in the necessary volumes and on time.

(3) Replacement of cabinets, while maintaining the external and internal connections of existing systems is more expensive than the two previous approaches. However, it can allow some functional/performance/logistical improvements to be made to the existing system (e.g. adding built-in

diagnostics, reducing the energy consumption of cabinets and increasing ease of maintenance and repair). Such modernization also involves the replacement of field cables and cable communication lines between cabinets. A decision to do so is based on the results of a survey of the technical condition of the cables. The implementation of this approach needs to be under the following conditions:

- There is no need to make significant changes to the functionality of the system.
- There is a need to improve the quality characteristics of the system (e.g. increasing resistance to mechanical factors or environmental factors, such as RFI).
- Analysis of the cabinet's condition shows it will not sustain operations for much longer, or the trends of malfunctions indicate a critical level has or will be reached during the planned life of the NPP.
- Inspection of external cables connected to the system reveals that they are in a satisfactory condition and there are no negative trends in the malfunctions that can reach critical levels during the planned period of operation of the NPP.

(4) Replacement of part of the subsystems of the system while maintaining the external connections of the system is needed when there are financial constraints but there is a pressing need to modernize certain aspects of the system. Typically, this approach allows NPP operators to upgrade the system in stages, ensuring a significant 'flattening' of financial burdens on the NPP operator while maintaining a sufficient level of reliability and safety of I&C systems. Modernization can be performed with some improvements to the system or with the preservation of the functionality and characteristics of the system. An example of the implementation of such an approach is given in Annex III (replacing part of the cabinets for generating process protection signals and interlocks while maintaining the cabinets of the automatic control subsystem and the cabinets of the measurement subsystem of the safety I&C system). This approach is advisable under the following conditions:

- Analysis of malfunctions indicate the presence of 'weak links' in the system that require modernization in the near future.
- Examination of other subsystems demonstrates that their performance and condition is generally satisfactory and can be sustained for a required period.
- The funding at the present time is limited and insufficient to ensure a full system replacement.

6.5. REVERSE ENGINEERING STRATEGY

6.5.1. Introduction

Reverse engineering involves obtaining sufficient information about an item of equipment to be able to accurately specify its design and remanufacture it or design a fully functional replacement. The process may include examining the original equipment and reviewing associated design documentation.

In the absence of a complete set of original design drawings and manufacturing information, obtaining a like for like replacement can be very difficult. However, careful use of reverse engineering techniques can provide obsolescence solutions that are equivalent to the original equipment's FFF.

Application of reverse engineering techniques by itself is not a replacement for design control activities. Design control is required to avoid unintended design changes leading to unexpected failure modes. Reverse engineering activities need to be controlled carefully using a rigorous engineering change control process. All activities involving design control and configuration management of the replacement equipment need to be properly documented and issued prior to approval for use. A detailed valuation of risk and cost is required before adopting a reverse engineering solution.

6.5.2. Considerations for reverse engineering

Critical attributes

One of the key requirements of reverse engineering is the need to identify the critical attributes and design characteristics of the existing system/equipment. It is not appropriate to take this approach if this information cannot be obtained and it is therefore advisable that an alternative approach is taken instead.

Legal considerations

Before taking a reverse engineering approach, investigation is needed if there are any IP restrictions and if any IP controls need to be implemented.

Quality assurance requirements

Depending on the original design and applicable reverse engineering technique, various codes and standards may apply.

Risk assessment

Evaluation of risk and cost and preparation of a high level replacement schedule are needed prior to the selection of the reverse engineering solution for replacement of an obsolete item. These key elements, along with other requirements for procurement of the reverse engineered item, have to be documented in a procurement plan.

6.5.3. Conditions for reverse engineering

The following conditions have to be met when taking a reverse engineering approach:

— Full understanding of the original equipment’s design is needed. This includes a full understanding of the original equipment’s physical attributes, functional requirements, interfaces, performance and the environmental conditions in which it operates.
— A reverse engineered item needs to be subject to the same design and manufacturing process as the original item to be considered identical.
— All available and relevant design requirements of the original item, including OPEX, need to be shared with the supplier delivering the reverse engineering solution.
— All safety related design requirements have to be met either by testing or by analysis, or both if possible.

In relation to the first item in the list, there needs to be a distinction between understanding the design requirements and why these requirements are important versus its current operation or performance. The latter may be a product of technology available at the time or have changed over time as a result of ageing. Simply replicating current operation/performance can result in original design flaws being reintroduced or ageing related degraded performance being locked into a newly reverse engineered product.

6.5.4. Procurement, supply chain and material maintenance

6.5.4.1. Procurement plan

A procurement plan is needed to define the key reverse engineering requirements and activities prior to issuing a request for quotation. The production of this plan needs to involve all appropriate stakeholders to reduce the potential for technical shortfalls or errors during the procurement process. The procurement plan needs to include the following information:

— Rationale for selection of a reverse engineering solution;
— List of accountable stakeholders and their roles and responsibilities;
— Catalogue identification descriptions and quality requirements;
— Manufacturer quality assurance and documentation requirements;

— NPP operator and supplier interface requirements;
— Design, inspection and testing requirements;
— Project schedule and deliverables expectations;
— Project cost estimate;
— Risk identification and mitigation measures;
— Any design assumptions that require verification.

6.5.4.2. Procurement requirements

The supplier capabilities and competencies need to be reviewed prior to awarding a contract to undertake the specified work to ensure that the supplier is fully qualified to do so (e.g. to reverse engineer an electromechanical device, the supplier has to be appropriately qualified for both the electrical and mechanical elements of the work).

Prior to issuing the purchase order, the procurement team needs to ensure that the standards and procedures clauses contain sufficient information on the applicable technical requirements, jurisdictional requirements, and the inspection, test and acceptance requirements, including any special instructions. Depending on the complexity or safety significance of the item being reverse engineered, other procurement requirements include the following items:

— Manufacturer inspection and test plan;
— Manufacturer drawings and design, fabrication and manufacturing information;
— Bill of materials;
— Component level specification;
— Qualification test records and results;
— Manufacturer procurement documents and receiving inspection records;
— Record of supplier workmanship control;
— Qualification records of personnel undertaking key tasks;
— Supplier audit and evaluation results or reports;
— Prototype test procedure and results;
— Procurement documents for items furnished by sub-suppliers;
— Qualification records of design services provided by sub-suppliers;
— Certifications;
— Non-conformance or deviations and corrective actions.

Prototype testing may be considered as a hold point in the supplier’s inspection and test plan, at any point in the process, to close the gap associated with any unverified assumptions made by the supplier or the NPP operator. Prototype testing conditions have to be consistent with end use design conditions (see, for example, Annex I). The procurement plan also needs to clearly identify who is responsible for reviewing, approving and accepting the various types of documentation produced.

6.6. PARTIAL OR FULL REPLACEMENT STRATEGY

6.6.1. Preparation

The following need to be considered when deciding whether to take a partial or full system replacement approach:

— Is a full system replacement needed, or can the upgrade be done at a subsystem level?
— Does the new system/subsystem need to deliver the same functions as the existing system/subsystem or is there a need/requirement to add or modify functions?

— What interfaces does the existing system/subsystem have?
— How will the modernization be done (stepwise or at one time)?

Based on these decisions, the NPP operator needs to prepare a technical specification that will specify requirements for the replacement system/subsystem. At this stage the requirements have to be specified in such a way as to not assume any specific technological solutions. The focus of the specification needs to be on the task description and the functionality that the system/subsystem needs to deliver.

Once the candidate supplier is known, details regarding potential technology options include:

— System/subsystem upgrade with analogue technology. This option may require specifically tailored solutions and components, as there may be limited suppliers for the analogue technology.
— Digital system upgrade:
  - Full digital system with software that can be programmed.
  - System upgrade with equipment where software is configurable (e.g. FPGA, PLC).
  - Extension of a digital I&C system that is already in use.

The following issues need to be considered during the planning phase:

— Is a diverse backup system needed from a CCF perspective?
— Is suitable technology available?
— Are a system functional description and the technical specification for the existing system/subsystem available or do they need to be produced? Just providing wiring diagrams is not sufficient.
— The task description is ideally based on a process simulation analysis that involves the use of a full plant simulator.
— Interfaces to other systems and to other parts of the plant need to be identified as early as possible. The need for temporary interfaces also has to be checked, especially in the case of a stepwise upgrade.
— Allowance needs to be made for future system/subsystem expansion even if this is not planned at the time of the project. For example, additional spare I/O capacity, cabinets, chassis and cable trays may be provided.
— When the existing equipment is to be removed also needs to be planned. (Will it be decommissioned or dismantled at the same time when the new equipment is being installed?)
— Maintenance requirements for the new system/subsystem have to be identified.

6.6.2. Partial replacement modernization strategy

This section provides information in relation to partial replacement modernization strategies that involve significant functional changes. Information covering the partial replacement of the I&C systems where there is no need to change or add functionally (i.e. a ‘replace with similar equipment’ modernization strategy) is provided in Section 6.4.

6.6.2.1. General considerations

The adoption of a partial replacement modernization strategy needs to be considered when:

— New functionality is to be introduced.
— Performance changes (e.g. response time, accuracy, noise tolerance) are required.
— The physical condition of part of the system is degrading at such a rate that the system’s ability to deliver its required functionality is threatened within its specified design life.
— Certain subsystems cannot implement the new functionality that is required.
— Information is available that fully defines the original equipment’s operation and design (e.g. integrity, interface, functional, performance, and operating environment requirements).

6.6.2.2. Technical specification

As with any modification programme, a complete and accurate technical specification is needed to ensure that an appropriate technical solution is developed. The following are some of the main topics that the technical specification needs to cover:

— A detailed description of the functions that are required to be implemented by the new part of the system.
— Performance requirements (e.g. response time, accuracy, noise tolerance).
— Integrity and reliability requirements.
— Operating life requirements.
— Power consumption requirements.
— Interface requirements (i.e. internal and external).
— Input and output signal details and requirements, including:
    - Signal names;
    - Data transfer formats;
    - Communication protocols.
— Physical requirements (e.g. shape, size, weight, mountings, location).
— Operating environment requirements (e.g. temperature, humidity limits, ionizing radiation).
— Compatibility requirements with existing parts of the system and surrounding systems (e.g. electromagnetic compatibility, waste heat generation).
— HSI requirements.
— Computer security requirements.
— Verification and validation requirements (e.g. types of analysis, testing).
— Installation and commissioning requirements.
— Maintenance requirements (periodic overhaul and functional testing).
— Training requirements.
— Equipment support requirements.
— Design documentation requirements, which have to contain sufficient design detail to support a future modernization programme.
— Prototype production and testing.
— Key regulatory requirements and design standards.

All relevant stakeholders have to be involved in the production of the technical specification (e.g. procurement, engineering, operating personnel, maintenance personnel, safety case specialists, project management) to ensure that all key requirements are included. Further guidance regarding the contents of a technical specification is given in Ref. [16].

6.6.2.3. Manufacturer selection

Contracting the original OEM to implement a partial replacement modernization strategy may reduce the risk of the strategy being incorrectly delivered, as manufacturers are likely to have sufficient design information to ensure that full compatibility with the remaining parts of the system is achieved. This also helps avoid the scenario where parts of the system are supported by different organizations, which can lead to:

— Interface responsibility disputes;
— Disputes about the timing of system level support work (e.g. producing and implementing software updates) and who will pay for such work;
— Liability disputes if one part of the system adversely affects another part.

However, contracting the original OEM may not be desirable from an economic perspective, or be possible if the manufacturer has ceased trading, withdrawn from the market or no longer holds the IP rights to the original equipment.

6.6.2.4. Commissioning testing and original equipment retention/dismantling/disposal

Commissioning testing of the modernized system/subsystem needs to performed after the equipment has been installed at the NPP, which has to be carried out in accordance with a specially designed commissioning test programme. If the supplier develops this test programme, it needs to be reviewed and approved by the NPP operator. In addition to checking the functional characteristics of the system/subsystem, its response to typical and atypical input signals/data is also checked. During this testing, the performance of equipment which has not been modernized needs to be checked to ensure that it has not been degraded as a result of the introduction of the new equipment. Following successful completion of the testing programme, the modernized system/subsystem can be permitted to enter a period of trial operation.

Consideration needs to be given to retaining the old system/subsystem equipment and running it in parallel with the modernized equipment to build confidence in the correct operation and performance of the modernized system/subsystem. Retaining the old equipment will also provide the option of recommissioning it if unforeseen performance and reliability issues arise with the modernized equipment.

A risk assessment and planning are necessary for the dismantling and removal of the old equipment and associated cables to ensure that the correct equipment is removed and that adjacent equipment is not damaged in the process. In this regard, how equipment that holds security sensitive data will be securely disposed of needs to be studied. The old equipment may also contain toxic materials (such as mercury and cadmium) and how this equipment will be disposed of in a safe and environmentally friendly way needs to be considered.

The considerations discussed above are equally applicable in relation to complete system modernizations (see Section 6.6.3.4). Further issues in relation to the testing of modernized I&C systems are given in Section 6.8.7. Examples of implementing a modernization strategy by partially replacing I&C subsystems are given in Annex I and Annex III.

6.6.3. Full replacement modernization strategy

6.6.3.1. General considerations

From a technical point of view, replacing an entire system is likely to be the most straightforward modernization solution, as it enables issues associated with the existing system to be addressed and helps in the introduction of new functions. In addition, modern equipment can significantly reduce operating costs (e.g. reduced maintenance and energy consumption). The main drawback associated with such a strategy is its high cost, which may preclude it from being selected if other strategies are available.

Even if the operating organization has sufficient financial resources, this strategy is only employed if the remaining operating life of the NPP is at least ten years, or if it is planned to extend the life of the NPP by such a length of time or when it is essential to do so for nuclear safety reasons. It is likely that the costs associated with a full system replacement may not be offset by the increase in operational reliability or running costs in the event that an NPP has less than ten years of remaining operational life left.

The general approaches and stages of a full replacement modernization strategy are very similar to the approaches and stages of a partial replacement modernization strategy. The main difference is that with a full replacement modernization strategy, the system architecture tends to be more straightforward to design and specify.

6.6.3.2. *Technical specification*

As with a partial replacement modernization strategy, it is important that a complete and accurate technical specification is produced to ensure that an appropriate technical solution is developed. The following are some of the main topics that the technical specification needs to cover:

- A detailed description of the functions that are required to be implemented by the system.
- Integrity and reliability requirements.
- Operating life requirements.
- Operating environment requirements (e.g. temperature, humidity limits).
- Power consumption requirements.
- Specification of interfaces with other NPP I&C systems and systems that are external to the scope of systems being modernized. This needs to include:
  - Task description;
  - Lists of signals that the system has to exchange with other systems;
  - Data transfer formats;
  - Communication protocols;
  - Performance requirements (e.g. response time, accuracy, noise tolerance);
  - Definition of applicable codes and standards.
- HSI requirements. A decision is needed as to whether to change or leave HSI. Changes may be made based on existing OPEX and/or requests from operators. However, operating personnel may have developed certain skills and psychomotor habits through the use of the original HSI. Modernization experience indicates that significant changes in the HSI can induce operator errors, which in turn can affect the operation of the NPP. Further guidance is provided in Refs [25, 26].
- Cables, sensor and actuator requirements:
  - The technical specification also needs to identify the type and number of cables connected to the system and any unsatisfactory cables that need to be replaced. Therefore, the condition of the cables connected the original system need to be evaluated;
  - Replacing sensors with analogue outputs with sensors with digital outputs can significantly reduce the number of cables by combining channels in local switches and transmitting information using standard industrial computer protocols. However, the scope of this may be limited by CCF requirements. In such instances, signals from sensors will have to be input to the system via independent and physically separated channels;
  - Modern actuators are typically equipped with digital control and position indicators and there may be benefit in also replacing them when the modernized system is installed. However, it may not be economically possible to do this simultaneously. Therefore, the technical specification needs to make provisions for future actuator replacements.
- Computer security requirements.
- Verification and validation requirements (e.g. types of analysis, testing).
- Installation and commissioning requirements.
- Maintenance requirements (periodic overhaul and functional testing).
- Training requirements.
- Equipment support requirements.
- Design documentation requirements, which have to contain sufficient design detail to support a future modernization programmes.
- Key regulatory requirements and design standards.

6.6.3.3. *Equipment supplier selection*

When a full modernization replacement strategy is adopted, a single company needs to be selected to supply the entire system as this will offer the benefits of simplifying warranty obligations and future engineering support. It is also desirable to work with the supplier to define the installation and commissioning requirements.

However, a single supplier may not always be able to provide every part of the modernized system and products will need to be sourced from various suppliers. If this is the case, a lead or prime supplier needs to be selected to be the principal interface with the NPP operator. In some cases, the prime supplier may be considered as the ‘system integrator’, combining products from many suppliers to deliver the system that the NPP operator requires. This approach has the benefit of simplifying the relationship between the NPP operator and supplier and avoids the client having to micromanage the interactions between sub-suppliers.

6.6.3.4. Testing

The system testing approach in relation to a full replacement modernization strategy does not fundamentally differ from that needed for a partial replacement modernization strategy. The main difference is that it may not be possible to undertake a full end to end test of the system (sensor to actuator testing), given that it may not be practical to assemble the possibly several hundred sensors and actuators at an NPP. If this is the case, the inputs to the system are simulated. However, several representative sensors (e.g. pressure, flow rate, level, temperature, position) and actuators (e.g. gate valves, control valves, electric motors) still need to be connected to the system to check its operation.

Thus, a successful period of trial operation needs to be completed before the system enters full operation, though it may be possible to justify putting the system into full operation once commissioning testing has been completed. This may be possible if a similar modernized system has already been put into operation and has successfully passed trial operation earlier at a sister or similar NPP. Prior to the decision to exclude the trial operation phase, an assessment of the differences between the previously implemented system and the one that is being modernized needs to be undertaken. The results of this assessment need to confirm the absence of significant differences or the absence of a possible effect of differences on the functions of the system that is being modernized.

Further considerations related to the testing of modernized I&C systems are in Section 6.8.7. Annex I describes a major modernization project where an extensive and staged approach to testing, primarily in the factory, was a major contributor to the success of the project.

6.7. MODERNIZATION IMPLEMENTATION SCHEDULING

It is important to identify a suitable window to implement the selected modernization strategy and whether it will be implemented in a single step or in phases. The duration of the modernization process will depend on a large number of factors:

— The need to implement new functions of the system by a given deadline;
— The need to carry out modernization by a deadline specified by the national nuclear regulator (e.g.; the implementation of the so-called ‘post-Fukushima’ measures);
— The need to modernize the system before the condition/performance/reliability of the system degrades to an unsatisfactory level;
— The need to modernize systems to support the life extension of NPPs;
— The need to implement the system before the support contract for the original system expires;
— The need to implement the modernized system before spares for the existing system are exhausted and can no longer be sourced;
— The economic factor that determines the capabilities of the operating organization to finance the modernization.

A detailed modernization implementation schedule is needed with the technical specification, with all stakeholders (e.g. operating, maintenance, engineering, procurement, project management and financial personnel) are involved in the development of the schedule. The schedule needs to include:

— Details of the personnel who are responsible for implementing each phase of the project.
— The end date by which the system/subsystem needs to be manufactured.
— The dates of the supplier’s site tests.
— The end date by which the new system needs to be delivered to the NPP.
— The period of time during which the installation of equipment needs to be performed. This is typically confined to NPP outages. In cases where a replacement of old equipment is carried out, the time needed for its dismantling has to be taken into account. Furthermore, if the modernization involves nuclear safety systems, it will be necessary to take into account possible regulatory requirements on the number of safety systems that need to be operational under certain operating conditions. For example, at some NPPs there is a requirement that in any of the modes of the reactor, when nuclear fuel is in the reactor and/or spent fuel storage pool, at least two safety system channels (e.g. emergency heat removal systems) need to be in operation.
— The final date for commissioning of the equipment at the NPP and the production of necessary commissioning documents.
— The deadline for the documents necessary to support the entry of the system/subsystems into operational service.
— The deadline for delivering necessary training. Training of operating and maintenance personnel generally has to be completed well before the new system enters operational service.
— The deadline for implementing associated simulator modifications (where necessary). Early NPP operator involvement in the design/modernization of the simulator can also significantly reduce the risk of modernization projects by providing an opportunity for operational design flaws to be detected earlier in the modification life cycle.

The typical duration of an NPP outage will normally allow for part of the installation and commissioning work to be completed and may even allow for all of this work to be completed, especially where modernization work just involves the replacement of modules, racks or chassis.

International experience has shown that it is normally difficult to complete the modernization of complex I&C systems (for example, nuclear safety systems or the reactor island systems) in a short period of time. Given the time it takes to dismantle old equipment, install, configure and test new equipment, the implementation may take 40–60 days or more. If the modernization strategy allows for a piecemeal implementation, then this approach may be the most appropriate. Another advantage of this approach is the flattened financial burden on the NPP operator.

Exceptions include outages to enable major NPP repairs to be undertaken, which may have been planned for many months or even years. The duration of such outages can provide an opportunity to undertake and complete the necessary modernization work. In cases where the modernization is driven by new regulatory requirements, it is advisable to engage early with the regulatory body on the scheduling of such work.

6.8. MODERNIZATION PROJECT DELIVERY AND TECHNIQUES

6.8.1. Introduction

Project management is a well defined and understood process. There are numerous project management methodologies, tools, techniques and qualifications that can be employed to ensure the effective delivery of projects to time/quality and budget. General guidance on the delivery of projects can be found in Refs [7, 27].

However, there are specific issues relating to the delivery of NPP I&C equipment modernization projects that need to be highlighted. Examples of such modernization projects that some Member States have recently completed are given in the annexes to this publication. These examples contain key lessons learned from the projects.

This section covers several important areas of I&C equipment modernization projects and highlights good practice, as described in Annexes I–III.

6.8.2. Project scope and delivery method

Selection of the appropriate modernization strategy cannot be guaranteed unless the scope and goals of the project are fully understood. Even if modernization projects are to take place over many years, there needs to be an overarching schedule of work so that all stakeholders can clearly identify key project milestones and the end point.

Reference [7] provides useful guidance on determining the scope of modernization projects and the development of strategic plans. References [15, 28] also provides good practices for project execution, life cycle planning and the development of the technical specification. Guidance in the preparation of specifications is also given in Sections 6.6.2.2 and 6.6.3.2.

Once a clear understanding of the project scope has been established, delivery methods/strategies have to be considered. The scope/scale of the project will naturally direct the project to different delivery methods. For example, a simple modernization, consisting of the replacement of a single component, would not necessarily benefit from a phased delivery and could be considered as a single delivery phase consisting of the normal specification, design, implementation, testing, installation, commissioning and handover. For a more complex project, the division of the project into multiple phases, containing specific life cycle elements or pertaining to specific subareas of scope, may be more appropriate (see, for example, the modernization project in Annex I).

Large I&C system modernizations are typically complex projects which need to be managed around the operational and safety needs of the NPP. This often results in implementation methods that lead to the exchange of equipment in plant areas (by functionality) or in divisions (by segregation) at different times.

The advantages of this approach are:

— A smaller resource pool can move from phase to phase;
— Less disruption/less risk;
— Opportunity to learn/improve from phase to phase.

The disadvantages of this approach are:

— Projects tend to be longer in duration (from start to finish);
— Creates more ‘temporary’ or intermediate plant conditions;
— Operating and maintenance personnel may have an increased burden (e.g. due to having to operate and maintain old and new equipment in parallel);
— Delays delivery of final safety and operational benefits.

Project delivery also needs to consider the need to introduce temporary or bridging solutions to facilitate final project delivery. For example, a useful strategy can be to introduce plant field wiring ‘break-ins’ during scheduled plant outages, which allows field devices to be switched/driven in parallel between new and old systems. This allows modernization work to proceed in parallel with normal operation of the plant prior to an eventual change-over from old to new and decommissioning/lockout of the ‘break-ins’ and decommissioning/removal of the old equipment.

6.8.3. Pre-engineering phases

Due to complexity/novelty or other uncertainties, it is often difficult to accurately specify or select the appropriate modernization strategy and technology. Making such choices with limited or uncertain knowledge can lead to situations where projects proceed in inappropriate directions from the outset. This can result in the project failing to deliver on its objectives, or in expensive changes later in the project. Therefore, it is advisable that pre-engineering work is undertaken to evaluate project risks and uncertainties to ensure that all options are appropriately considered prior to the commencement of the main project delivery phase. It is not necessary to involve the supplier during this phase (although they can be asked to support this activity), or for this activity to be included in the final delivery contract (although it could be). Examples of pre-engineering activities include:

— Design studies/proposals from different suppliers.
— Prototyping of technologies/designs.
— Trials of methodologies/processes.
— Limited scope modernizations with post-implementation reviews.
— ‘Optioneering’ different design solutions. This involves identifying, analysing, scoring and ranking competing options to select the optimum solution.

It is important that pre-engineering phases:

— Are managed and specified with the same rigour devoted to any other project (i.e. there needs to be a clear understanding of the objective, duration, costs, inputs and outputs from the phase);
— Engage with all relevant stakeholders and involve them in the decision making process;
— Ensure clarity of pre-engineering phase project deliverables (e.g.; documents or prototypes) and associated responsibility for delivery;
— Allow sufficient time from the end of the pre-engineering phase to adequately inform the technical specification of the main project delivery.

Derivation of a comprehensive and clear technical specification is not a trivial exercise and is an essential pre-engineering activity. A team needs to be assembled which combines all relevant stakeholders and disciplines to collate, review and verify the specification. An extensive requirements capture phase also has to be part of pre-engineering, taking care to avoid vague or ambiguous requirements. Reference [28] provides detailed guidance on the process to develop suitable project specifications for digital modernization projects.

6.8.4. Contract strategies

Almost all I&C modernization projects of any complexity will involve the use of suppliers. Therefore, selection of an appropriate supplier and contract strategy will have a major influence on the success or failure of a modernization project.

There are various contract strategies that can be employed. These are not specifically discussed in this publication as adequate guidance is provided by a wide range of other publications. However, the following are some key points that need to be considered:

— Developing a close and continuous working relationship with the supplier aids overall efficiency.
— Risk has to be divided fairly between the supplier and the NPP operator.
— It is necessary to be realistic about the cost of modernization projects. An unrealistically low price inevitably results in poor relations with the supplier and increases chances of under-delivery later.
— Fixed price, target price or time and material contracts:
    - Fixed price may be appropriate where the degree of project execution risk is low;

- Target price contracts where delivery within the target price generates a bonus as a percentage of the savings, costs are shared where the delivery exceeds the target price;
- Time and material contracts (where charges are based solely on the time expended and materials used by the supplier) may be appropriate where there is considerable uncertainty. However, consideration needs to be given to bounding these (e.g. design/analysis contract to allow specification of a fixed price delivery contract).

— The use of bonus/penalty payments need to be considered to focus delivery against certain milestones. This can, however, have the disadvantage of harming the close working relationship with the supplier.

Most contracts for modernization projects will contain staged/phased payments against milestones. Early milestone or decision points may be based on the delivery of feasibility studies (e.g. demonstrating that a chosen solution is viable or providing sufficient data to enable a choice to be made between competing options). Later milestones may be based on delivery of prototypes, or high level or detailed design or completion of build or testing phases. While the proportion of the payment is a financial (rather than technological) consideration, it is important to ensure that there is a clear definition of the deliverables expected for each payment. It is also important to make best use of the leverage provided by stage payments and to define deliverables that are key to project success, rather than solely as a means of financial control. For example:

— Documents required to support licencing submissions;
— Documents or activities to 'de-risk' later stages of the project;
— Demonstration of full completion of project phases as a firm foundation for entering the next phase;
— Demonstration of elimination or mitigation of key specific risks.

6.8.5. Life cycle synchronization and hold points

In an I&C modernization process there may be several separate life cycles which may compete, with each other. Example include:

— Plant operational life cycle (scheduled evolutions, tests, outages);
— Contract life cycle (phases, payment milestones, hold points);
— Regulatory life cycles (safety case submissions, authorizations, regulatory hold points);
— Project delivery life cycle (conceptual design, detail design, implementation, installation, closeout);
— Security life cycle (assessments, mitigations);
— Design life cycle (specification, design, implementation, test, etc.).

All such life cycles have to be defined at the start of a project and there has to be a clear understanding of the ownership and purpose of each (illustrated in Annex I).

Various life cycles will interact at certain times during a modernization project which, unless properly planned and synchronized, can introduce project delays/costs or create barriers to further progress. For example, a specific safety submission may be required by the regulator at a certain time (regulatory life cycle), the submission of which may be dependent on the availability of documentation or evidence (design or security life cycle). This documentation or evidence may be tied to a contract delivery milestone or payment (contract life cycle). Unless this is recognized beforehand and interaction points lined up, the safety case delivery could be substantially delayed because a reference document has not been completed as per the contract schedule. Therefore, it is essential to recognize all life cycles and plan interactions accordingly.

6.8.6. Design and construction

The purchase of components and the construction of the modernized system will only commence once all stages of design have been completed and once the supplier has demonstrated that its design solution will achieve the design requirements. However, many components are likely to have long delivery times and such an approach could introduce significant delays between design and construction. Therefore, the completion of high level design work (sufficient to identify components and high level architecture) and detailed design (sufficient to configure components within an architecture) at different times has to be a priority.

6.8.7. Factory test and commissioning

Operational plant restrictions may prevent the same level of site testing of the modernized system/subsystem to be undertaken as for the existing system if it was installed during the NPP's construction. Thus, the modernized system needs to be designed to maximize off-plant testing; ideally, this would be undertaken in the supplier's factory. In this regard, the use of plant simulators and other test rigs may be of assistance (see Ref. [7]). Factory testing has the benefit of system designers and integrators being readily available to address any issue that arises during testing. It also has the benefit of providing confidence that the system/subsystem's design has been substantiated prior to being installed on-site.

The development of appropriate test procedures needs to be treated with the same degree of rigour as the design of the system/subsystem. These have to be sufficient to demonstrate that the system/subsystem will achieve its specified design requirements. It is important that detailed and traceable test procedures (i.e. that link to test requirements) are clearly defined. In this regard, NPP operators have to be involved in the development and approval of test procedures.

For a significant modernization project, several stages of testing will be necessary (see Ref. [7]). Where testing is completed in stages (e.g. unit test, subsystem integration test, installation test, commissioning), the testing strategy needs to explain how test stages overlap to avoid gaps in testing. In addition, NPP operators have to witness the various stages to identify any gaps and shortfalls and to provide timely feedback.

The resource requirements for the production of test documentation are not to be underestimated and need to be planned for in advance. Given that testing typically occurs at the end of a modernization project, failure to do so is likely to significantly delay the system/subsystem's entry into operational service. Similarly, failure to make adequate resource and time provisions for testing can lead to inadequately conceived or executed tests, which increases the risk that latent defects will go undetected. The planning of testing and commissioning, and the production of associated documentation, needs to therefore commence early in the modernization project. In this regard, the development of test procedures can often highlight requirement shortfalls and the early development of such procedures can have the benefit of such shortfalls being rectified in a timely manner (i.e. before their rectification would delay the system/subsystem's entry into operational service). Further dealing with the testing of modernized I&C systems are given in Sections 6.6.2.4 and 6.6.3.4.

6.8.8. Installation

It is important that installation planning considers operating routines at the NPP (e.g. outage cycles). Guidance on this can be found in Ref. [7]. As discussed earlier in this publication, the effective management of ageing and obsolescence management plays a significant role in delaying or obviating the need to modernize systems. Therefore, detailed inspections are needed, which have to be part of the design of modernized systems. Factors such as good lighting, ease of access, visibility of critical components/circuit boards or cables for inspection need to be taken into consideration.

Modernized I&C systems may involve the movement of large/heavy I&C panels throughout the plant to their final locations, and careful planning of access routes is therefore essential to confirm that there are no obstructions or that proposed routes do not have any load restrictions that may be violated. Several projects have found that plant walkdowns are necessary to achieve this. This may even involve the construction of simulated panels/equipment of anticipated size/shape to confirm that they can be manoeuvred into position. Other projects have found that the use of digital tools which allow comprehensive 360° 3-D imaging of installation locations can help vendors visualize such locations without lengthy and expensive visits to the plant.

Such early installation planning activities can reveal pre-installation work that may be necessary before the entire system can be commissioned, and it is therefore advisable that provisions are made for such planning. Pre-installation work could include the movement of existing equipment to make room for new equipment, the creation of ‘break-in’ points for easy connection of new equipment or the laying of network or power cables for the new equipment.

While early preparation/planning for installation is advisable, it is also suggested that walkdowns occur close to the time of installation since other works (especially during plant outages) may have introduced temporary obstructions or changes that were not there on the original walkdown or 3-D visualizations.

6.8.9. Long term support and spares

Experience suggests that entering into negotiations for product support at the end of a modernization project will leave the NPP operator in a weak negotiating position with the supplier. Therefore, such discussions need to take place before awarding modernization contracts. At this point, the nature of ownership of the modernized system needs to be determined. For example, if the approach taken is for the NPP operator to own the modernized system outright, then provision of long term maintenance contracts with spares holding/repair costs needs to be negotiated early. Alternatively, a strategy whereby the NPP operator merely leases the modernized system from a supplier would mean that responsibility for its continued operation (including maintenance and repair) needs to be covered by the leasing fee.

Long term support would ideally commence no later than the handover of the system to the NPP operator and, ideally, before that. Provisions of warranty may not fully align with the needs for long term support and so the warranty period is not to be relied on as a contingency for the late start of long term support (for example, warranty provisions may cover correction of defects at no cost but may not specify how quickly this is done, whereas a long term support agreement would specify service delivery levels such as response with 24/48 h). Also, warranty provisions may cover rectification of software defects, but would be unlikely to cover provision of support for elective modifications subsequently required by the utility.

Provisions for the NPP operator to maintain, fault find and repair the modernized system needs to be in place before it takes ownership of the system. This includes the provision of all appropriate maintenance and operating manuals and training material. The NPP operator also needs to have access to the necessary spare parts, which need to be considered in terms of the following categories:

— Commissioning spares (those required to rectify faults found during commissioning);
— Operational spares (those required in normal operation for repair of the equipment);
— Lifetime spares (those anticipated to be needed over the lifetime of the system).

Commissioning spares will typically be few in number, calculated by the supplier to able to complete commissioning and handover in the contracted period. There may be an opportunity to transfer the spares to the NPP operator at the end of the project.

Operational spares need to be calculated on the basis of the number installed combined with the expected failure rates and the design life of the equipment. During operation, failure rates have to be monitored and spares holding adjusted if failure rates are different from that predicted. A key decision affecting the spares holdings is also whether to repair failed components (in which case guaranteed repair time is significant), or discard and replace.

Lifetime spares need to be considered if the provisions of the long term support do not include provision of spares later in the life cycle of the system or if repair is not anticipated (i.e. components are discarded on failure rather than repaired). If this strategy is used, then a careful calculation of the number of lifetime spares is necessary as it could limit the life of the system.

Clearly, the spares held for an existing system are unlikely to be compatible with a new or upgraded system and so a thorough review of spares holding needs to be undertaken. Even spare parts purchased at different times can result in variations of version, which need to be managed. Ideally, all spares would be purchased at the same time as the component parts for the modernized system, thereby ensuring that spare parts are of the same version. If this is not possible, then an analysis of the adequacy of different versions or revisions needs to be included in the maintenance documentation. It is important to ensure that spares are stored securely both to ensure that they are available and in good condition when needed and also to ensure that no unexpected changes have been made to the versions held. This is particularly true for spares with programmable elements when unauthorized changes to software or firmware are a risk. Where failed components are sent for repair, the procedures need to ensure that items returned after repair are of the same revision (or acceptable revision within a previously validated range).

Various strategies can be considered for the long term management of the spares inventory for a modernized system. Examples and considerations are given below (see also Ref. [29]), and whichever approach is chosen the ageing mechanisms of spares held for the modernized system also need to be considered (see Section 3 for further information).

6.8.10. End stages, closeout and handover

The following issues have to be considered before the modernized system enters operational service:

- The NPP operator needs to ensure that an ageing and obsolescence management plan for the system and associated arrangements is put in place;
- A person (rather than a department) needs to be nominated as the system owner by the NPP operator;
- The NPP operator needs to ensure that adequate resources (e.g.; operating, maintenance and engineering personnel) are available to support the in-service operation of the system;
- The NPP operator needs to ensure that all planned installation and commissioning work has been satisfactorily completed and that all supporting evidence has been produced and received;
- The NPP operator needs to ensure that all design documentation necessary to support modernization of the system in the future has been obtained from the supplier;
- The NPP operator needs to ensure that all documentation necessary to support the entry of the system into operational services has been produced and received (e.g.; O&M procedures);
- The NPP operator needs to check that all training to support the entry of the system into operational service (e.g.; O&M training) has been delivered to the relevant stakeholders;
- The NPP operator needs to ensure that all necessary system support tools have been obtained from the supplier;
- The NPP operator needs to ensure that provisions have been made to record and store all supporting documentation (e.g.; design, operating, maintenance, training material);
- The NPP operator needs to ensure that adequate spares provision has been made;
- The NPP operator needs to establish the level of technical support that is required from the supplier once the system enters operational service and that this is agreed with them;
- The NPP operator has to ensure that there is a robust plan (with deadlines and owners) to close out any outstanding actions.

Appendix

CABLE AGEING MANAGEMENT THROUGH CONDITION MONITORING

A.1. INTRODUCTION

The ageing of NPP electrical cables has been the subject of several research and development (R&D) projects conducted by the nuclear power generation industry, national and international laboratories, universities and supplier organizations over the last few years [30]. These projects have been conducted to improve the ageing management of in-service cables in NPPs, research reactors, waste facilities and fuel fabrication plants. In recent years cable R&D has also sought to develop new cables for the next generation of reactors.

Over time, exposure to harsh environmental conditions such as elevated temperatures, radiation and humidity can result in age related degradation and failure of cables. There are thousands of kilometres of cabling in a typical NPP, many of which are exposed to harsh environmental conditions. Most of these cables are constructed from polymer insulation materials that can become brittle, crack, or degrade over time from exposure to harsh environmental conditions such as elevated temperature, moisture, vibration, mechanical shock and radiation. In general, wholesale replacement of these electrical cables is expensive, time consuming and impractical. To help minimize cable repair and/or replacement costs, a condition monitoring (CM) strategy can be implemented where results acquired from cable inspections, analysis and testing are used to identify and quantify degradation and estimate the remaining useful life of the cables.

A variety of cable CM methods have been developed and successfully used in NPPs around the world. These methods are used to identify ageing degradation and to assess the condition of cables to determine whether their insulation characteristics have changed with age. Some of the most commonly used cable CM methods are described in Section A.3. The methods listed include laboratory and field tests that, based on past work, have proven to be effective tools for trending age related degradation and assessing the condition of electrical cables. Each of these methods provides unique and important information on the overall health and performance of cables and insulation polymer. Moreover, a combination of some or all of these methods can be used to assess the condition of installed cables, depending on various factors such as cable configuration, insulation materials and the goal of the evaluation (e.g. ageing assessment or fault location). Though many of these methods have proven useful for identifying and trending cable and insulation degradation, currently there are limited objective criteria available for these methods that can be used to quantify the aged condition of cables. To fill this gap, ageing acceptance criteria are being developed for many of these methods through ongoing R&D efforts. This acceptance criteria will be useful for quantifying the condition of a wide range of cables and insulation polymers, thereby helping develop repair and replacement schedules. See Ref. [31] for further details.

A.2. BACKGROUND

In most Member States, approvals for long term operation or life extensions of NPPs have been predicated on plants implementing CM measures to ensure that ageing will not lead to the failure of components and structures important to safety. Through extensive R&D work undertaken by several international organizations, cable CM methods have been developed that can identify and trend age related degradation of cable polymers.

It is important that NPP operators are provided with up to date cable health and reliability information to help them prioritize and develop effective maintenance activities for in-service cables. For example, cables can be prioritized for maintenance or replacement prior to their failure if CM testing reveals that they have become significantly degraded and are nearing the end of their life. Conversely, NPP operators can avoid unnecessary cable maintenance and replacement if CM testing reveals that the cables have not experienced significant age related degradation.

Identifying and monitoring cables located in adverse areas plant is important to an ageing management programme. Areas where cables are exposed to elevated temperature, radiation, chemicals and moisture can accelerate the ageing process when compared with cables located in a benign environment.

Visual evaluations can provide a qualitative assessment of cable condition and are often the most common means of determining whether CM tests have to be performed [32]. For most cables installed in NPPs, the jacket material will age faster than the insulation. Discoloration or hardening of a jacket polymer is generally an indication that the underlying insulation may be degraded (Fig. 17). When ageing is detected during visual inspections, additional CM testing is generally performed for a more objective evaluation [9].

There are a variety of CM methods that trend degradation caused by cable ageing. However, each of these tests offer advantages and disadvantages such as being in situ, non-destructive, or only trending with certain polymers. For example, elongation at break (EAB) is a widely used method to trend the mechanical properties of insulation materials as they age. However, this is a destructive test that requires removing insulation samples from ‘sacrificial’ cables. Indenter modulus is a non-destructive measurement that can be performed in situ. However, this is a localized test that requires physical access to the degraded section of cable. Care needs to be taken when performing CM tests that require manipulation of the cable to perform the test as movement could cause additional damage to severely degraded cables (e.g. insulation cracking).

There are several CM tests that can provide a measurement of age related degradation of a cable. However, there is no single CM technique that can be used by itself to quantify the degradation of all varieties of insulation materials, cable configurations and installations that is non-destructive and can be performed both in situ and in the laboratory. As such, collectively applying multiple CM tests to evaluate the aged condition of cable insulation polymers is an important consideration.

FIG. 17. View of cables degraded from exposure to elevated temperatures.

Some traditional cable testing techniques, such as time domain reflectometry and insulation resistance, have proven to be useful for locating mechanical damage (e.g. cuts or sharp bends) and/or evaluating the operational status of a cable. However, research has shown that such techniques provide limited information on the age and condition of the insulation polymers. It is therefore important to consider the type of degradation that each CM test can identify. Future advancements in traditional cable testing technologies could make them more applicable for cable ageing evaluations.

A.3. TEST METHODS TO TREND AGE RELATED DEGRADATION

The following is a description of CM tests that have shown to correlate to age related degradation. Several of these tests can be sensitive to small changes in the test method and sample preparation. For example, when performing the EAB test, sample type and the rate at which the sample is pulled in tension can have significant effects on the results of the test. Following established standards, such as IEC 62582 Part 3 [33] for EAB testing and/or historical testing procedures, are important to help ensure a high level of accuracy and repeatability. Additional information regarding CM test methods for cable evaluations is given in Ref. [9].

(a) Elongation at break

The EAB test is an industry standard technique for determining a cable polymer’s condition. It is a mechanical test performed by pulling a sample in tension until failure and calculating the percentage elongation (Fig. 18). EAB measurements provide a quantitative assessment of the level of age related degradation that occurs to cable materials when exposed to the thermal, oxidative and radiation based environmental stressors present in NPPs. The EAB values of cable polymers decrease as the materials age due to degradation of their mechanical properties. This test is destructive with sacrificial samples of cable insulation polymers needed to perform the measurement.

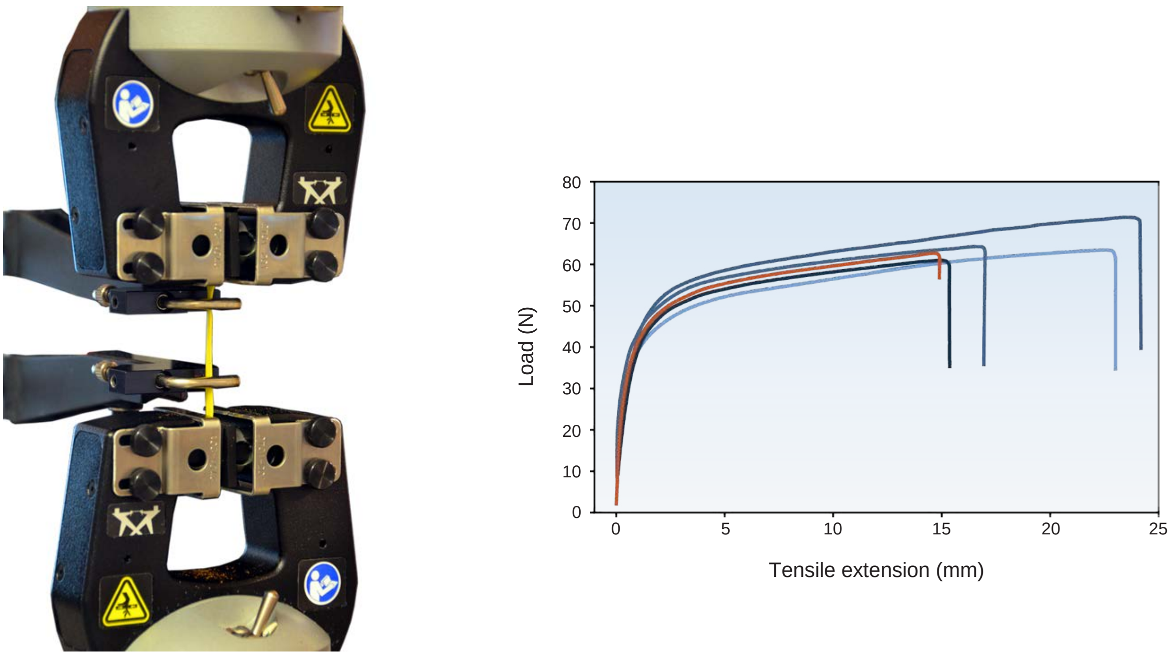


FIG. 18. EAB pulling sample (left) and data used for EAB calculation (right).

(b) Indenter modulus

Indenter modulus testing measures and monitors changes in the hardness of cable insulation and jacket polymers as they age. It is a localized, in situ, non-destructive mechanical test that is applied using a system that clamps around the cable under test and uses an instrumented probe that is pressed against a polymer to measure the localized hardness. The indenter modulus is calculated from the slope of the applied force versus deformation curve acquired during indentation (Fig. 19). The indenter modulus values of cable polymers typically increase as the materials age due to embrittlement.

(c) Oxidation induction time (OIT) and oxidation induction temperature (OITP)

OIT and OITP are thermal–chemical analysis tests used to assess the degree of oxidation and antioxidant loss that has occurred in polymer samples when exposed to environmental stressors during service. These tests are performed using a differential scanning calorimeter by exposing the material to oxygen at elevated temperatures.

The OIT test is a measurement of the time at which oxidation of a polymer occurs when exposed to a constant temperature and oxygen rich environment. The OITP test is a measurement of the temperature at which oxidation of a polymer occurs when exposed to a dynamic temperature profile at a constant heating rate and oxygen rich environment.

These tests provide information on the oxidative stability of polymers under isothermal and dynamic conditions. OIT and OITP values typically decrease as polymers age due to reductions in the thermo-oxidative stability of the materials. Figure 20 provides an example of OIT data with an oxidation time of 9 min.

(d) Thermo-gravimetric analysis

Thermo-gravimetric analysis is a technique that measures the mass changes that occur in industrial polymers during thermal decomposition. During testing, the amount and rate of mass loss of a material are measured as it decomposes at elevated temperatures. The data are used to evaluate the chemical composition and thermal stability of polymers and the additives used in the materials (e.g. antioxidants, thermal stabilizers and ultraviolet light screeners). This test is a useful CM technique for some cable materials where the weight loss of the polymer during the ageing process can be linked to cable insulation degradation from the loss of volatile organic compounds and oxidation. The test requires small amounts (less than 10 mg) of sacrificial cable polymer material.

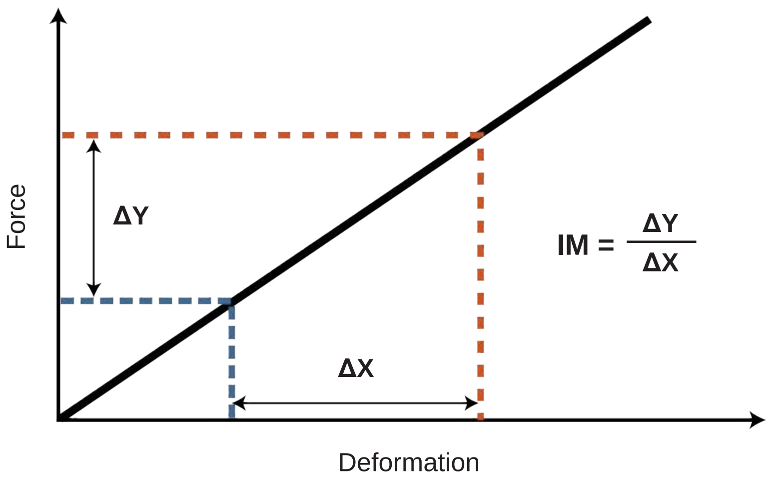


FIG. 19. Force versus deformation curve used to calculate indenter modulus.

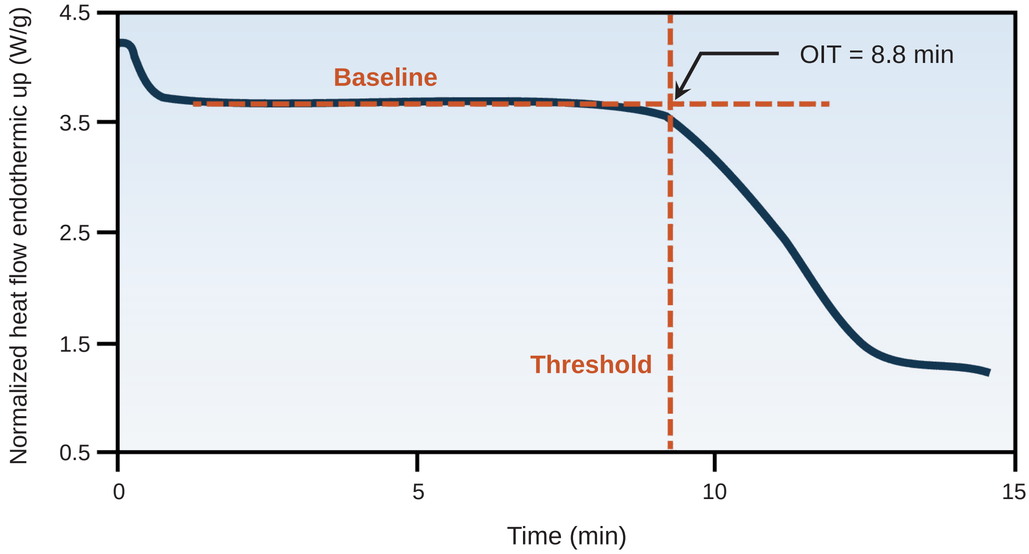


FIG. 20. OIT data showing polymer oxidizing at approximately 9 min.

(e) Relative density

Relative density measurements are performed based on the Archimedes approach and provide information on how the bulk properties of a cable polymer (e.g. mass loss, swelling or shrinkage) have changed due to degradation. As polymers age, oxidation typically occurs resulting in changes to the material structure, including increased cross-linking and chain scission, along with the generation of oxidation products. These processes can cause shrinkage and mass loss of the material, along with changes in the density of the polymer. During testing, the weight of a polymer is measured in both air and in a liquid such as water or isopropyl alcohol. The test requires small amounts (less than 30 mg) of sacrificial cable polymer material.

(f) Frequency domain reflectometry (FDR)

The FDR cable CM test is an in situ electrical testing technique used to remotely identify, locate and quantify the severity of insulation degradation. The test is performed by sending a swept-frequency signal through the cable circuit and analysing the circuit impedance changes that are reflected. During the ageing process, changes in the electrical permittivity of the cable insulation material will cause changes in the circuit impedance and therefore the FDR data. These changes in the FDR signal will gradually increase during the ageing process and are used to trend age related degradation of the material (Fig. 21). To perform the FDR measurement, the cable being tested needs to be a multi-conductor or have a metallic shield.

(g) Fourier transform infrared spectroscopy (FTIR)

The FTIR test is used to measure the infrared absorption characteristics of the chemical bonds in a cable polymer. It can be used to evaluate the chemical properties and composition of a polymer as well as monitor the aged condition of insulation materials. The test is performed by passing infrared radiation through a small sample (less than 1 cm^2) of cable insulation. During the test, a sample both absorbs and transmits parts of the infrared spectrum and the wavelength of light absorbed is characteristic of the chemical bond of the polymer. During the ageing process, changes in the chemical structures of cable polymers can cause changes in the characteristic FTIR peaks of the material, which can be used to trend age related degradation of the insulation.

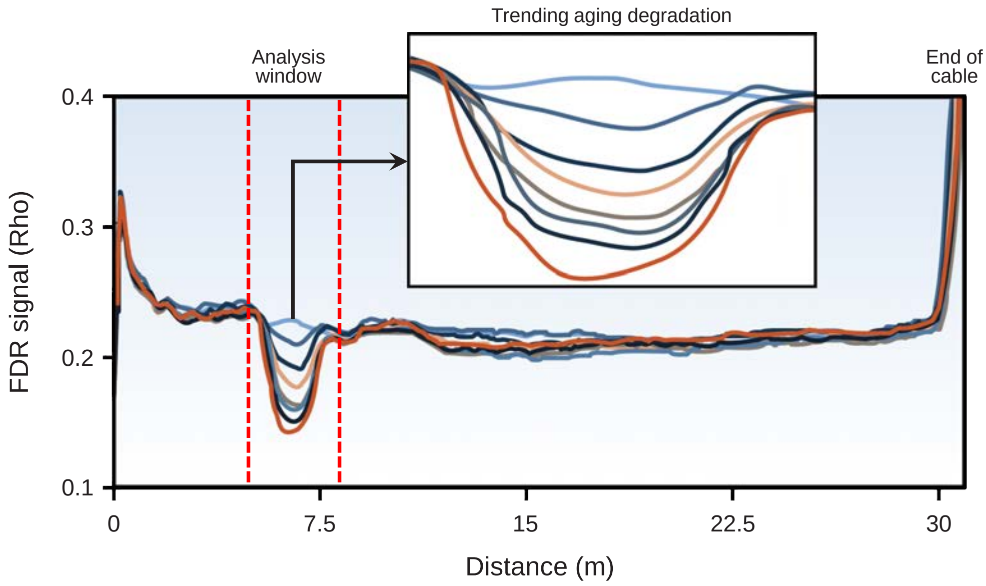


FIG. 21. FDR data showing trending ageing degradation (adapted from [31]).

Examples of the changes observed in the FTIR spectrums of an ethylene propylene rubber insulation polymer during the ageing process are shown in Fig. 22. In this plot, there is a clear increase in carbonyl infrared absorption peak intensities (i.e. peaks between 1600 cm^{-1} and 1800 cm^{-1}) of a material when comparing an aged polymer sample (red trace) that has undergone thermo-oxidative degradation to an unaged sample (blue trace). These carbonyl peaks appear in the data because of the polymer degradation process. The green shaded region of the plot corresponds to carbon–hydrogen bonds in the material and are commonly found in the FTIR spectrums of polymeric materials.

(h) Near infrared

This test measures the near infrared absorption characteristics of the chemical bonds within cable polymers. Like the FTIR test, it can be used to evaluate the chemical properties and composition of a polymer as well as monitor the condition of insulation materials. In the test, a sample both absorbs and transmits parts of the near infrared spectrum. The wavelength of light absorbed is characteristic of the chemical bond. During the ageing process, changes in the chemical structures of cable polymers can cause changes in the characteristic near infrared peaks of the material. These changes can be used to trend age related degradation of the insulation.

(i) Electrical permittivity (Ɛr)

The electrical permittivity CM technique is used to measure the dielectric properties of a material. It involves measuring the real and imaginary permittivity of an insulation sample at different frequencies and can be used to monitor changes in the electrical properties of the insulation material due to age related degradation. The electrical permittivity test requires a small amount (less than 25 mg) of sacrificial sample.

(j) Tan delta

Tan delta, or the dissipation factor, tests the integrity of the cable insulation by measuring the tangent (loss) angle between the resistive current and the capacitive current with a low AC voltage applied across several frequencies. Impurities in a cable polymer increase the resistive current in the insulation, which causes the current and voltage angle to shift from a nominal 90° value (Fig. 23). During the ageing process, tan delta test results acquired at certain frequencies can be used to trend changes in the electrical properties of insulation material caused by age related degradation.

A.4. CASE STUDIES

The following two case studies show examples of how in situ and laboratory CM tests have been used in the nuclear power generation industry to perform cable ageing evaluations. The results of these tests were used by NPP operators to determine whether cable replacements were needed and to develop a strategy for future replacements.

The FDR technique has been used as an in situ electrical test to identify and locate cable insulation degradation in NPPs (see Ref. [9]). For example, cables were tested at a BWR in the USA to help determine if a group of cables that were installed during original construction of the plant and in service for over 40 years needed to be replaced.

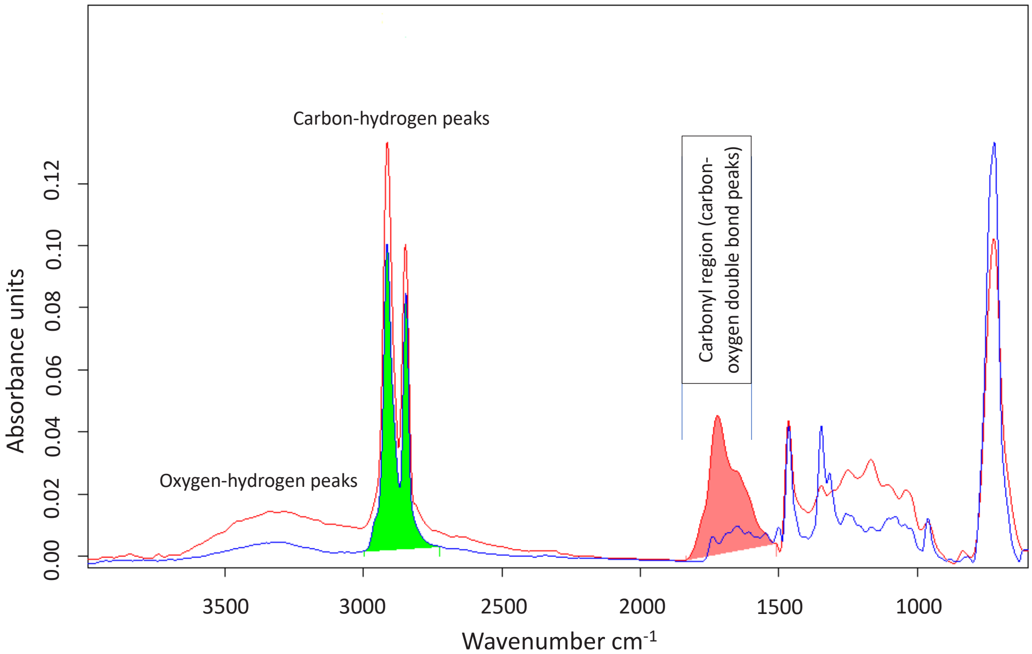


FIG. 22. FTIR data of aged (red trace) and unaged (blue trace) EPR polymer.

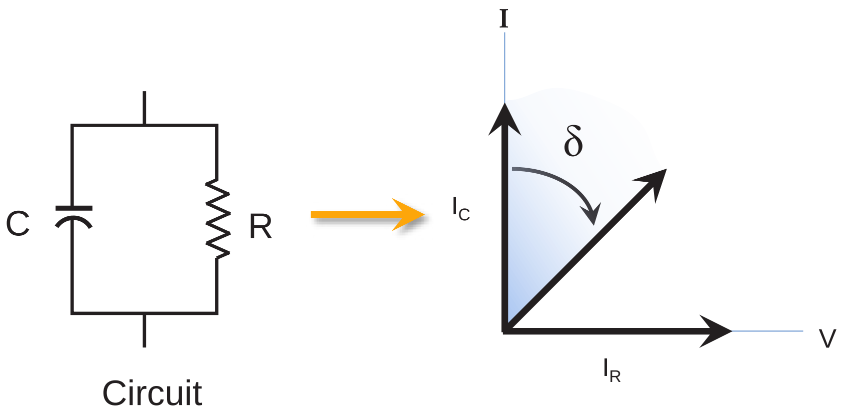


FIG. 23. Conceptual diagram of the tan delta test technique.

Prior to testing, NPP operators conducted visual inspections of the cables and identified signs of age related degradation, including jacket discoloration and cracking. These visual inspections were limited to areas of the plant where the cables were accessible, and the results did not provide a good indication of the condition of the insulation polymers of the cables. Thus, FDR testing was performed following the visual inspections to assess the condition of the insulation materials along the entire length of the cables, from the plant control room to the terminations.

To quantify age related degradation of electrical cables using FDR, research has been conducted to develop ageing categories for a wide range of cables and insulation polymers. Four categories have been developed for field application that provide a method to quantify age related degradation (Table 1). As with many CM tests used to identify age related degradation, there is often no method to quantify the level of degradation as it relates to the cable's end of life.

Using these criteria, cables assigned a Category 1 ranking have experienced little to no age related degradation during service, Category 2 cables exhibit some signs of degradation, Category 3 cables have aged significantly, and Category 4 cables have reached their end of life condition. These FDR ageing acceptance criteria were established based on the results of laboratory research, where FDR test results acquired during thermal accelerated ageing for common types of NPP cables were correlated with the industry standard EAB test. This test was performed on the cable insulation materials periodically during the ageing process. Based on the results of past research, the EAB test exhibits a strong trend with age related insulation polymer degradation for a wide range of materials and can be used to determine their condition. The results provided here demonstrate how ageing acceptance criteria can be established for CM techniques and used to assess the condition of installed plant cables.

Overall, the FDR test results revealed that 10% of cables exhibited a noticeable degree of degradation, 30% were only slightly degraded and the remaining 60% were essentially unaffected by ageing. The results of these tests provided information that was used to make important maintenance decisions that ultimately saved the utility the cost of cable replacements.

The second case study demonstrates how laboratory ageing assessments have been performed using a variety of CM techniques on cables removed from service at operating NPPs. For example, a series of measurements were conducted to determine the aged condition of three cables removed from the steam tunnel of a BWR in the USA [34]. Prior to their removal, two of the cables had been in service for over 40 years, and one cable had been in service for approximately 15 years. During plant operation, these cables were exposed to a service temperature of approximately 65°C, and the 40 year old cables received a total gamma radiation dose of approximately 140 kGy. These cables were manufactured with types of cross-linked polyethylene/polyolefin (XLPE/O) insulations, some of the most common types of insulation polymers used in the nuclear power generation industry.

As shown in Table 2, CM data acquired during this evaluation revealed significant differences in the condition of the cable insulation, primarily due to the number of years the cables had been in service and the in-service environmental temperature. These differences are observed in the visual inspection, EAB and OIT results. For the EAB and OIT CM tests, research has shown that an XLPE/O insulation

TABLE 1. FDR CABLE AGEING CATEGORIES (ADAPTED FROM Ref. [31])

FDR category	% aged	Comments
1	0–33	Little to no indication of age related degradation
2	33–66	Initial indication that age related degradation has occurred
3	66–99	Cable insulation has significant ageing but is expected to function normally
4	>99	Cable insulation is at or near its end of life condition

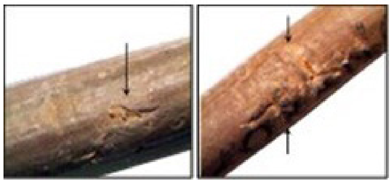
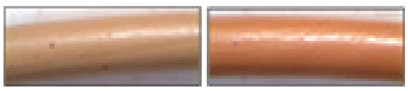
polymer that has not experienced significant age related degradation will have an EAB greater than 150% and an OIT greater than 40 min. In general, a cable insulation polymer that has a low EAB (near 50%) and a low OIT (less than 5 min) will experience a significant decrease in mechanical properties and thermo-oxidative stability due to age related degradation.

Table 2 also shows cable Type I XLPE insulation exhibiting signs of age related degradation, including cracking, an EAB value of 74% and an OIT value of 5.5 min. Cable Type II XLPO insulation also revealed signs of age related degradation, including cracking along the outer layers of the insulation and moderately low OIT values of approximately 15 min. Cable Type III XLPE insulation exhibited no significant signs of age related degradation. The data provided here demonstrate the strong correlation between these CM techniques and the condition of the cables.

A.5. PATH FORWARD

Many NPPs around the world have implemented cable ageing management programmes which feature periodic CM testing to support regulatory requirements for subsequent licence renewals to extend operating life. Initially, cables are categorized based on the ambient environmental conditions of their installed locations and their intended function. Cables installed in harsh environments as well as those that are important to safety and plant operation are normally monitored or evaluated more frequently than those installed in less harsh conditions or are used in non-safety and critical applications. Any identified cables of concern based on environmental conditions and function are typically included in the list and periodically tested during the extended operating period. The programme of CM testing provides

TABLE 2. AGE ASSESSMENT OF COOPER NPP STEAM TUNNEL CABLES (ADAPTED FROM Ref. [31])

Cable type	Year installed	Elongation at break (%)	Oxidation induction time (min)	Visual inspections
Type I	1974	74	5.5	Insulation surface cracks 
Type II	1974	181	14.5	Outer layer insulation cracks 
Type III	2001	199	23.5	No discoloration, cracks or other signs of age related degradation 

reasonable assurance that the insulation for electrical cables and connections will perform its intended function for the subsequent period of extended operation.

Various research projects related to cable ageing are currently being undertaken to provide additional ageing cable management guidance for NPP operators. These projects include the following.

(a) US Nuclear Regulatory Commission (NRC) cable research project

This is a research effort under the direction of the NRC and is being performed at the National Institute of Standards and Technology to evaluate the effectiveness of commonly used cable CM techniques for specific insulation materials. The cables in this study are exposed to simultaneous thermal and radiation accelerated ageing and aged to an equivalent of 50 years, 60 years and 80 years of service life as defined by the Arrhenius method, including exposure to various levels of relative humidity and temperature. Following the accelerated ageing, the cables are subjected to a loss of coolant accident (LOCA) simulation including an accident radiation dose. The results of the CM data collected during the ageing will be used to assess qualified life predictions of the various years of service and provide better understanding of qualification methodology to support decisions for subsequent licence renewal.

(b) Analysis and Measurement Services Corporation cable research project

This project is being led by the Analysis and Measurement Services Corporation, in collaboration with the Oak Ridge National Laboratory and the Pacific Northwest National Laboratory in the USA. It is being conducted to develop acceptance criteria for CM tests that trend with age related degradation in insulation polymers used for low voltage cable insulations commonly used in NPPs. These criteria can be used to provide a quantitative or condition based assessment of the condition of cables installed in NPPs as well as other industrial applications.

The work performed under this project includes using NPP cables with common insulation polymers and subjecting them to typical environmental qualification gamma radiation exposure followed by thermal accelerated ageing. During the ageing, the cables are periodically tested using various CM techniques to trend changes in the insulation polymer properties as they age. After the sequential radiation and thermal ageing, the cable samples are subjected to a LOCA simulation [35]. These LOCA exposures and test results will be used to determine when the cable insulations have reached their end of life, and the data will be used in conjunction with the CM data collected during the ageing process to develop acceptance criteria that directly correlate with the end of life condition of a cable polymer.

(c) TeaM Cables research project

TeaM Cables (‘European Tools and Methodologies for an efficient ageing management of NPP Cables’) is a research project related to nuclear safety and long term operation. The project is coordinated by Électricité de France (EDF) and is scheduled to be completed by 2022.

TeaM Cables aims at providing NPP operators with a methodology for efficient and reliable cable ageing management by developing:

- Cable ageing models and algorithms, which are based on multi-scale studies and can be tailored to cover variations in fillers, additives and degrees of cross-linking;
- Methodologies for non-destructive testing techniques and their associated criteria identified from multiscale relations;
- An ‘open access’ tool, referred to as the ‘TeaM Cables tool’, integrating all the models developed and providing the residual lifetime of cables by combining non-destructive measurements with predictive models and knowledge of cable exposure conditions.

Reference [36] contains details on the TeaM Cables research project.

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Annex I

UNITED KINGDOM SIZEWELL B WISCO-2 DATA PROCESSING AND CONTROL SYSTEM REPLACEMENT PROJECT

I–1. INTRODUCTION

The Sizewell B NPP in the United Kingdom is a four loop PWR owned and operated by Électricité de France (EDF). It was constructed in the early 1990s, entering commercial operation in 1995. The data processing and control system, known as the Westinghouse Integrated System for Centralised Operation (WISCO) was supplied by Westinghouse Electric Corporation (WEC) and has been in continuous operation since the mid-1990s. The vast majority of closed loop and sequence controls are provided by WISCO, together with manual actuation of plant, data acquisition, alarm management and nuclear safety calculations to support plant operations.

WISCO comprises three separate subsystems: (1) the process control system (PCS); (2) the distributed computer system (DCS); and (3) the high integrity control system (HICS). The PCS and HICS execute control algorithms and provide the direct interfaces to plant and control room devices, whereas the DCS provides graphical displays, data processing, alarm management and logging functions. The PCS/DCS was based on the WEC WDPF-II product line, whereas the HICS was based on the WEC Eagle-21 product line. All systems have performed reliably since original commissioning and have been in continuous operation 24 × 7 with less than 4 h down time in the last 25 years. However, all systems in WISCO have been obsolete for many years. Therefore, the decision was taken in 2012 to modernize the PCS/DCS subsystems of WISCO, but retain HICS for the foreseeable future. This decision would also involve replacement of the off-line maintenance and test systems for the PCS/DCS as well as a significant upgrade to the full scope training simulator to accurately represent the behaviour of the new system.

The partial modernization project, hereafter referred to as WISCO-2, is discussed in this annex. It describes the key decisions for the replacement project, the challenges and how they were solved, highlighting lessons, both positive and negative, which other similar projects would need to consider.

I–2. PROJECT SCOPE, FUNDAMENTAL REQUIREMENTS AND PROJECT PHASING

Replacement projects for systems similar to WISCO had been undertaken before by EDF, notably at the advanced gas cooled reactors at Hinkley Point and the Dungeness B NPP. Both projects delivered effective replacements and provided a great deal of information to the WISCO-2 project team while determining the scope and requirements of the replacement project. Learning from earlier projects and, where possible, utilizing the skills and experience of team members who had delivered similar projects in the past is a major success factor informing future projects. The WISCO-2 team benefitted from experience with previous replacement projects and also from the availability of team members who were part of the original WISCO installation. Earlier projects had also demonstrated the need to ensure appropriate resource levels from the start and the need to be proactive to respond to additional resource needs as they emerged through project phases.

The WISCO-2 project was framed by three overarching decisions:

(1) Retain existing field cabling and input/output (I/O) terminations;
(2) Replicate functionality with minimal changes/enhancements;
(3) Retain, as far as possible, the architecture of existing systems.

Previous projects had demonstrated the difficulties associated with changing computing architectures and therefore introducing new or different failure modes to those assumed in the original safety justifications. A consequence of such changes is a need to revisit field I/O termination and cabling, which carries with it significant overheads in terms of proving I/O circuits after restoration. Also, the installation of temporary break-in facilities to allow connection of the new system in parallel with the old to permit working outside plant outages adds significant costs to project delivery — although parallel installation also has benefits in confidence building in the new system. There is also strong evidence from earlier projects that the addition of new functionality and enhancements carries significant project risks in terms of determining the scope, specification and impact as the definition of robust requirements is often difficult to achieve for new or enhanced functionality.

When selecting a supplier/product line, it is better for the user if there are competing products available to ensure that quotations are competitive and offer value for money. The above overarching decisions significantly limited the number of potential platforms available for WISCO-2. However, there was more than one supplier choice available and so a competitive tender process was possible. After evaluation, a contract was awarded to WEC in 2014 to replace the PCS/DCS subsystems using the Ovation product line manufactured by Emerson. The contract to upgrade the training simulator was awarded to the supplier who had delivered the existing training simulator. Upgrading to the simulator was needed significantly earlier than the installation of the replacement PCS/DCS to allow sufficient time to train plant operating personnel in the new system before it was installed and so close cooperation between suppliers was essential for the overall success of the project.

Although the Ovation product line was a direct descendent of the original WDPF-II product, it still represented a complete replacement of the PCS/DCS rather than a small evolutionary step, partly because the PCS/DCS had not followed WDPF-II product developments and upgrades since originally commissioned. However, the product line could be installed without disturbing the original field I/O and (for the PCS) replicate functionality and footprint, on a cabinet by cabinet basis.

Although changes to field I/O termination had added considerably to project costs in previous EDF data processing and control system replacements, this approach did convey an advantage: by engineering break-ins to existing field cabling it was possible to run old and new data processing and control systems in parallel for extended periods prior to eventual changeover from old to new. This was achieved successfully in all cases with the reactor on load with the only ‘lost’ generation being to introduce load changes to demonstrate control loop performance. In the case of WISCO-2, a consequence of the requirement to retain existing field I/O coupled with replication of the system architecture was that the entire system would have to be installed and changed over during a scheduled refuelling outage. Therefore, any emergent issues or delays arising during the final installation and changeover would immediately result in delays in returning the plant to service, with significant financial penalties. So, the baseline project position was assumed to be that all equipment would be installed in a refuelling outage with only limited enabling works (e.g. network cabling) completed prior to this. As the project progressed, some optimizations were possible, but the key lesson here was to assume/plan for the worst case, avoiding unrealistic optimism. After analysing the project requirements and scope, the refuelling outage in 2019 was selected for installation and changeover to WISCO-2.

Experience with earlier projects of this magnitude showed the necessity of maintaining strong control over design development, building and testing — so that project work did not proceed at undue risk of rework due to activities being completed out of sequence. Prior experience had also demonstrated the need for strong quality control arrangements supported by a robust audit and surveillance schedule throughout the project. Therefore, the contract was phased with defined hold points and explicit expectations that phases proceed serially rather than in parallel. For WISCO-2, these principal project phases (with approximate correlation to calendar year) were:

— Requirements definition and tendering (2013);
— Prototyping and contract finalization (2014);
— High level design (2015);

— Detailed design (2016);
— Hardware and software build (2017);
— Factory testing (2018);
— Shipping, installation and commissioning (2019).

The early phases of the project have to have sufficient time to acquire strong quality foundations for the contract and establish team relationships from the start. Prior to 2013, a period of pre-contract/expressions of interest and options was considered which enhanced the early foundations of the project. As part of this extensive operational experience from past projects, a detailed project risk log was established and regularly reviewed during the course of the project to ensure that risks and mitigations were being effectively managed.

Once in contract, strong quality arrangements built into the contract ensured that the supplier was not permitted to proceed beyond each phase until EDF was satisfied that all necessary work for the phase was complete and all the requirements for the phase satisfactorily validated. Coupled with strong quality arrangements was a strong design and change control process ensuring clarity of design basis at any time with clear linkage to documented requirements. It was also recognized as good practice to conduct a lessons learned review of the preceding phase before commencing the next so that continual improvement could be encouraged throughout the project cycle.

A further key success factor for the project was the early analysis and identification of the impacts on station documentation. Clearly, a new installation introduces many new documents and drawings associated with the new systems, but it also impacts many existing station documents and procedures. Several thousand documents were identified early in the project that would need either deletion, replacement or amendment prior to the new system entering service. Early analysis allowed for prioritization of effort to ensure that the right documents were available for station maintenance and operations engineers at the right time in the project cycle — essential for smooth installation and changeover between the old and new systems.

I–3. REQUIREMENTS, STANDARDS AND GUIDANCE

Although Sizewell B is a relatively modern plant and the youngest in EDF’s fleet of NPPs in the United Kingdom, international standards and best practice had developed and changed since the plant was constructed. Therefore, a safety justification for the replacement system was necessary against current standards adopted by EDF for modification and replacement.

EDF incorporated relevant international standards and guidance in internal company technical standards (CTS) to ensure a consistent level of interpretation and application across projects and the fleet. Demonstration of compliance of the project with these standards is fundamental in the safety justification. This involved delivering the project in a way that demonstrated compliance with five fundamental and mandatory requirements of the company’s policy for instrumentation and control (I&C) modifications:

— Following a defined safety life cycle as set out in the standards.
— Application of the detailed guidance contained in the CTS throughout the safety life cycle.
— Categorization and classification of safety functions and systems/equipment.
— Production of a clear requirements specification with traceable requirements.
— Production of a design substantiation that demonstrates compliance with requirements.

Since WISCO-2 was a computer based system important to safety, EDF standards for computer security were also applicable, necessitating the integration of a security life cycle and security justification alongside the safety life cycle and safety justification. EDF experience is that computer security requirements are best considered and designed from project inception, and not at or near the end of a project.

From the outset, there were multiple competing and potentially conflicting requirements arising from the need to translate multiple standards and guides covering the needs of project management, safety case justification, contract management, security cases and project phases. To plan and optimize the project, these were consolidated in a single project life cycle plan (PLP). This document provided the initial and central point of reference for planning whereby the key safety case submissions, security case submissions, contract and project hold points or investment decisions could be articulated, and any contradictions or dependencies analysed and assessed. It also provided a sound basis to define key project deliverables and an identification of which deliverables were in the scope of the supplier or the client. Production of the PLP document was key to minimizing the risks associated with misunderstanding the scope division and responsibility, and to understanding the significance of deliverables in the safety or security justification. It allowed a clear articulation of contract hold points and payment milestones and provided the framework to manage stakeholder expectations during the project execution.

The safety life cycle mandated by the CTS was a typical V model moving from high to low level requirements decomposition, through design specification, implementation, unit testing, integration testing and finally commissioning. Verification and validation steps along the way were clearly defined.

The WISCO-2 requirements specification contained over 2500 individually traceable requirements which were independent of the product. These included functional requirements to replicate the existing subsystems, the design and safety life cycle requirements from detailed company guidance, and a small number of judicious enhancements to the functionality of the original subsystems. Once the project became supplier/product specific, the initial requirements developed into over 3500 individually traceable requirements covering design specification documents (comprising nearly 6000 pages).

Learning from earlier projects had demonstrated the need for clear requirements capture and tracking. Earlier projects had made use of bespoke spreadsheets/databases for tracking requirements using standard tools such as Microsoft Access or Excel. However, consistent use of these for tracking large numbers of requirements throughout a long project had proved problematic. This was not only because of the large number of initial requirements but the recognition that high level client requirements create multiple product or design requirements, each of which later needs to be linked to test and validation activities, so the eventual number of requirements needing to be tracked is several times the initial number. Therefore, an early project decision was to adopt the IBM-DOORS (Dynamic Object Oriented Requirements Systems) tool for requirements capture and tracking — both by the supplier (WEC) and the client (EDF). Since both supplier and client were using the same tool, it was anticipated that exchange of data throughout the project would be enhanced. The tool provided the capability to track several thousand requirements and was later to prove invaluable in providing the platform to demonstrate and substantiate the design. For example, the production of reports showing where each requirement was mapped into detail design documents or test documents was relatively easy to produce. In addition, individual design substantiation statements were easy to associate with requirements and then to produce a final design substantiation report. Without this tool and the robust requirements tracking/traceability it offered, design substantiation and demonstration of test coverage later in the project would have been very difficult and time consuming, representing significant back end project risks.

Perhaps the most significant developments in international standards since the commissioning of WISCO was the adoption of categorization and classification of safety functions. EDF CTSs implement a process of safety function categorization and system classification to the I&C systems/equipment that are broadly aligned with those defined in international standards IEC 61226 [I–1] and IEC 61513 [I–2]. Consequently, safety functions are assigned safety categories A, B and C and equipment to safety classes 1, 2 and 3. Although, for Sizewell B, safety categorization was not a new concept, the categorization applied during the design and construction of Sizewell B preceded current standards. Equipment that formed a principal means of ensuring nuclear safety was assigned as Category 1, that making a significant contribution to ensuring nuclear safety was assigned to Category 2 and the remaining equipment was assigned to Category 3. In relation to these criteria, the PCS/DCS subsystems of WISCO were assigned to Category 2. It is important to note that these categories (i.e. Categories 1, 2 and 3) are EDF criteria and do not correlate with IEC 61226 [I–1] safety categories or classes.

Therefore, an early stage of the project was to assess the safety duty of each of function in the DCS and PCS (either individually or by group), assign an IEC 61226 [I–1] safety category to them and from that propose and justify a safety class for the corresponding equipment used in delivery of the function. With such a large system providing many diverse functions such as indication, control, data logging and nuclear applications calculations, this was not a trivial exercise although it was possible to group some functions for ease of analysis. The outcome of the categorization and classification exercise demonstrated that the PCS contained safety functions of Category B or lower whereas the DCS contained safety functions only of Category C or lower. There were no Category A safety functions. Consequently, PCS components would be engineered and justified as a safety Class 2 system whereas the DCS components would be a safety Class 3 or unclassified. As discussed later, this had significant implications for architecture design and qualification.

I–4. PROTOTYPING AND HIGH LEVEL DESIGN

After contract placement there followed a period of project ‘de-risking’ characterized by a period of initial analysis/decomposition of the WISCO-2 project requirements and physical prototyping of key interfaces. Because the scope of WISCO-2 was the replacement of only the PCS and DCS from the original WISCO, this created the need to develop and demonstrate the feasibility and performance of interfaces from the new Ovation technology to the legacy WISCO equipment—particularly that part based on WEC HICS Eagle-21 technology. Legacy interfaces were seen as key risk areas and so a great deal of attention was given to developing and demonstrating solutions early in the project to de-risk later stages.

With successful demonstrations from the prototyping and de-risking phases, the project entered into the high level design phase. Experience from earlier projects had indicated that splitting the design phase into high level and detailed design phases would be a significant de-risking strategy, allowing key design decisions to be made and their implications understood. It also facilitated the delivery of a safety justification laying out the main issues, principles and proposed solutions to build stakeholder confidence (particularly regulatory confidence) and endorsement early in the project. Experience from other projects where all design issues (high level or detailed) were not captured in the safety justification until late in the project had shown that this risked significant delays or challenges late in the project and could result in lengthy and complex safety case submissions.

Key features of the high level design were that the DCS would deliver safety Category C or lower functions and the PCS would deliver safety Category B or lower functions. Consequently, the platform and engineering processes for the DCS would be justified according to Class 3 expectations and the PCS would be engineered and justified to Class 2. As the two systems would be integrated together, further justifications and arguments were presented to justify the electrical and logical segregation of the lower class from the higher.

The Ovation product line integrates third party and bespoke technologies to create computing cabinets that communicate over a network utilizing fast ethernet communications with fibre/copper media and third party network switches. DCS computing hardware was primarily third party in origin. By contrast, the PCS controllers were a proprietary product. Electrical segregation of the Class 2 and Class 3 elements of the design was relatively easy to demonstrate since communications between subsystems was by fibre cable with inherent electrical segregation. More detailed justification was needed to demonstrate that faults in the Class 3 system could not propagate into the Class 2 system and adversely affect Category B safety functions.

The physical architecture of the PCS and DCS was kept close to the architecture of the original subsystems, although opportunities were taken to increase availability of some functions by introducing additional redundancy. Advances in computing power meant that the Ovation DCS servers now needed considerably smaller footprints than their WDPF-II counterparts. As a consequence, there was sufficient space available in the equipment rooms to install the Ovation DCS alongside the old WDPF-II DCS (which would later present opportunities for parallel running of parts of the old and new systems).

The logical architecture remained similar, with similar division of functions between servers, but the opportunity was taken to combine several servers into single cabinets—subject to the requirements of maintaining segregation between Class 3 and unclassified components.

The WDPF-II PCS cabinet architecture was effectively a ‘back to back’ design whereby field cables were landed on terminal rails in a rear cabinet with internal cables from these to a front cabinet where WDPF-II I/O boards and processing units were housed. Since a principal project de-risking goal was to avoid disturbance to field cabling, the project focused on the means to replace the WDPF-II I/O boards and processing units in the front cabinet. Competing options were evaluated, ranging from in situ replacement of boards and chassis within the existing front cabinets to complete replacement of the front cabinet.

Ultimately, the project chose to develop a replacement design whereby the old front cabinets containing processing and I/O would be entirely removed and replaced with completely new, factory built and tested, Ovation cabinets with new processor and I/O modules. Although, chassis replacement within the old cabinets would probably have been less expensive, the approach adopted was seen to have considerable de-risking advantages in allowing better factory integration and demonstration of the replacement system as well as being less labour intensive during the time critical installation window. Consequently, installation involved disconnecting the old internal cables from the I/O boards, removing the old WDPF-II processing cabinet, replacing it with a new Ovation processing cabinet and reconnecting the cables. In this way, the PCS architecture would be retained, I/O and processing functionality in the new Ovation cabinet could be identical to the old, and field I/O terminations would be untouched. An area of potential risk was that this strategy resulted in retention of the old internal cabling and connectors and there was concern that these may be damaged during the exchange process or that the cables themselves may be degrading due to age. This was investigated by sample examination of the cables themselves, examination of similar unused cables from original commissioning and searching for positive or negative evidence from other upgrade projects that WEC had been involved in, the conclusion being that the risk was low and tolerable.

The final key elements of the high level architectural design were how to handle legacy interfaces that were left unchanged as part of the project. Field connections consisted mainly of 4–20 mA current loops inputs and outputs, low level voltage inputs for thermocouples or 48 V digital inputs/outputs or relay contacts. The Ovation product line had modern equivalents to the WDPF-II I/O cards both in terms of I/O electrical characteristics and numbers of channels on a module; so, subject to qualification, it was a relatively straightforward exercise to select appropriate modules from the available product range.

However, the legacy interfaces to the HICS subsystem and control room desk devices (lamps, switches, meters, etc.) were via the Eagle-21 product line. Since the HICS delivers the highest integrity functions of WISCO and would need to be engineered to safety Class 1 standards, it had been a key project constraint that there would be no change to HICS as the additional costs associated with Class 1 engineering and safety justification would have greatly added to the project cost/timescale. Therefore, development of a new Eagle–Ovation interface was needed as part of the project. This was recognized as a key project risk area and its feasibility demonstrated by early prototyping prior to the high level design phase.

In addition to the legacy Eagle-21 interfaces, there were also several datalink interfaces to remote systems that used legacy high level data link control (HDLC) communication protocols. In this case, rather than develop an interface to the existing datalink protocol it was considered better to adopt a more modern protocol for the remote systems as this would ease maintenance of those systems in the future. This was one of the few prudent enhancements (rather than direct replication) endorsed by the project. It was a practical project decision since the remote systems had been confirmed to be only delivering safety Category C or lower functions and therefore the engineering and safety justification at Class 3 were not anticipated to be onerous. Clearly, this necessitated some change to the remote systems and engagement of the original equipment suppliers for these systems as subcontractors to WEC. However, as it was recognized early and planned accordingly, the development proceeded smoothly.

I–5. PLATFORM QUALIFICATION

Following the PLP and EDF CTSs was sufficient to demonstrate that engineering activities associated with designing, building and installing the PCS and DCS were to the appropriate rigour to substantiate claims of safety Class 2 and 3, respectively.

A consequence of the desire to avoid affecting field cabling and follow the existing system architecture was that there were relatively few commercial platforms available for the project and none had prior nuclear sector qualification within the United Kingdom's regulatory environment. The Ovation product chosen for WISCO-2 was widely used in electrical power generation around the world, including in the nuclear sector, although qualification and licensing had been performed to satisfy applicable standards in conjunction with project specific design principles. Therefore, the project was faced with the same challenge facing many modernization projects: How to substantiate the integrity/quality of commercial off the shelf (COTS) components not developed to a nuclear sector recognized safety life cycle? This was most challenging for the Class 2 components and had been recognized from the outset as a considerable risk to the project. Consequently, as part of contract negotiations, essential assurances and guarantees were obtained that, where necessary, additional testing, documentation or analysis of product line design records would be undertaken and that EDF would be able to see the background intellectual property associated with the product line to substantiate subsequent safety justification claims. Without this agreement the contract/project could not have proceeded.

Some of the high level design activities helped constrain this task. In particular, the demonstration that the DCS was Class 3 or unclassified removed much of the WISCO-2 platform from the more onerous Class 2 qualification requirements.

The PCS architecture consists of proprietary Ovation controllers communicating over a fast Ethernet fibre mesh. Third party switches form part of the network and hence the requirement to qualify the PCS to Class 2 initially implied the need to qualify third party COTS switches to Class 2, which was anticipated to be difficult due to lack of access to intellectual property owned by third parties. Various project options were considered to address this problem, including development of a separate safety Class 2 network in addition to the standard Ovation network, thereby eliminating third party switches for safety class data. Although feasible, this had the considerable disadvantages of deviating from the proven Ovation standard design as well as introducing architectural and future maintenance complexity that would be at odds with the desire to closely follow the original architecture. The option was discounted in the high level design phase in favour of a product line development known as a high integrity 'safety shell'. This aimed at detecting and mitigating potential data transmission errors not otherwise covered by standard Ethernet protocol and Ovation diagnostics — by adding such additional checks the integrity of the data transmitted over the highway was justified without the need to qualify the switches to Class 2.

The above considerations were necessary to limit the amount of hardware and software that would be subjected to qualification activities, thereby avoiding unnecessary project risk and expense. Consequently, qualification of the platform was justified on the basis of three work streams that proceeded through detailed design phases:

— Electromagnetic compatibility (EMC) and environmental qualification of Class 2 hardware;
— Class 2 enhanced development processes for new product features;
— Audit of legacy design against nuclear standards followed by complementary testing.

The subset of product line components for use in Class 2 applications was subjected to EMC and environmental testing according to the project requirements. This could have been avoided if complete test records aligning with current EMC/environmental requirements had been available. As an established industrial product, much of this was available but it was recognized that gaps in records or to current standards and associated mitigating arguments would still be necessary and this would not be without cost or risk. Therefore, it was decided to repeat a full set of tests to generate the necessary documentation to prove that the hardware conformed. This was a good pragmatic decision. Projects often are tempted to spend time justifying products on the basis of incomplete information, which both clouds the visibility of safety justification and may hide project risk. Often, the lower cost option is (as in this case) to conduct sufficient tests to generate documentation to support the design.

There were three product developments that WEC specified and Emerson undertook to an enhanced development process (consistent with the expectations of Class 2 software), which became part of the standard product available to any user. These were:

— Development of the high integrity safety shell;
— Development of the Eagle-21 Ovation interface;
— Development of steam tables.

The requirement for the high integrity safety shell and Eagle-21 Ovation interface has already been explained. The steam table development was to support specific secondary calorimetric calculations required by WISCO-2. Since an enhanced production process was used, closely supervised by WEC and EDF through all stages of the life cycle, there was confidence that these developments met the necessary Class 2 standards. Consequently, only pre-existing product developments needed to be considered as part of the audit of legacy design against nuclear standards.

EDF and WEC jointly audited product line production records in a clause by clause review of the product life cycle against relevant nuclear standards [I–2 to I–4] As would be expected, this yielded many areas of compliance and also gaps in compliance where the necessary evidence was not clearly visible. Subsequently, gaps in compliance were categorized according to significance and, where necessary, recommendations or additional actions taken. In some cases, gaps could be addressed by the project. For example, additional checks/records made on the hardware/firmware revisions of purchased components installed in WISCO-2, complementary testing of functions to demonstrate expected behaviour, or documentation of application restrictions. In other cases, it was possible to provide additional evidence, for example using static analysis tools. These activities, although lengthy, allowed the project to put forward a sound justification for the use of the Ovation product line in the Class 2 and 3 architectures.

I–6. DETAILED DESIGN, BUILD AND FACTORY TESTING

With completion of the prototyping, high level design phase and the confidence arising from the platform qualification activities, the detailed design phase proceeded on all the WISCO-2 cabinets. Confirmation of correct interpretation (and in some cases extrapolation) of EDF requirements was achieved by the end of the high level design phase and these were translated into multiple detail design specifications — in all cases being captured and tracked in the requirements tracking tool DOORS, selected by EDF. Since this tool was the same product as used in-house by WEC, this facilitated frequent exchange of DOORS data sets between WEC and EDF. Coupled with review of design documents by EDF, the detailed design was completed with confidence by being able to show full traceability of requirements demonstrated with agreed validation statements appropriate for the phase.

Not until all detail design activities were complete, reported through the DOORS tool and endorsed by EDF, was permission granted to commence the build phase. This was a fundamental constraint that allowed engineers to focus on design issues, rather than issues that may emerge from build. It was also fundamental in managing the risk associated with any late design changes occurring after build had commenced and the associated increased costs that would be incurred. However, some pragmatism was also necessary when following this principle. It followed that no hardware needed to be purchased until the design was completed but, as much of the hardware had long delivery lead times (three–four months), such an approach would have introduced an unacceptable delay between completion of the detailed design and commencement of build. However, an advantage of splitting the design phases into high and detailed levels was that there was good confidence in the hardware procurement requirements to support the architecture at the end of the high level design phase — so release of the supplier to purchase hardware before the end of the detailed design phase carried much reduced risk.

The same functional design documents that were used by WEC in the build of the replacement PCS/DCS were also used to engineer the configuration of the full scope training simulator upgrade by the simulator supplier. It was essential for the training simulator to be available ahead of the installation of the replacement PCS/DCS systems so that operating personnel would already be trained in the new system before it was installed. A positive consequence of the parallel working of two teams and necessary faster life cycle of the simulator upgrade was that a small number of design issues (not detected in the original review of design documents) were raised by the simulator supplier in the build phase (as a consequence of simulating the functions) rather than being revealed only in the test phases.

The international nature of the project and the need to transfer data (and later hardware) between countries was a particular concern in relation to the project security case. To comply with computer security requirements, the security case not only had to recognize and manage security of the final installed system but also had to recognize and manage security during every phase of the project cycle, including design, build and test. In particular, although the security arrangements at supplier locations were generally good by modern standards, additional inner security fences/access control was needed to limit access into test areas. This emphasized the need to consider the security life cycle from the beginning of the project as there was significant lead time involved in establishing and demonstrating the necessary project security provisions. If not considered early, this could have resulted in project delays or even violation of national legislation and subsequent legal penalties.

Another key lesson from earlier projects was the need to avoid shipping equipment to the plant for installation before completion of all testing and resolution of all issues, as testing in the plant environment is much more difficult than in the factory environment. For this reason, a hold point was placed at the conclusion of testing, which needed to be cleared before shipping of equipment. Once again, the traceability of requirements through DOORS to specific test procedures was used to demonstrate that test coverage was complete — aligning this with records of test completion and results provided the necessary justification to permit shipping of the WISCO-2 equipment to Sizewell B.

It is often the case in major I&C replacement projects that insufficient time is allowed for testing, which can lead to pressure to deliver equipment to the site with factory testing incomplete. Test documentation production was part of the build and test phase of the project and was not produced until the detailed design phase was completed. As the project intended factory acceptance testing to be as extensive as possible (thereby minimizing testing at site), this meant that test documentation was very detailed and took longer to produce that the software build itself. Consequently, there were delays in testing due to procedures being unavailable. On reflection, a better strategy would have been to link the production of test documentation to the detailed design phase rather than the build and test phase. Similarly, the project encountered some time pressure associated with the installation design late in the project and so would suggest that installation design is also included as part of the design phase of future projects.

I–7. INSTALLATION, SITE TESTING, COMMISSIONING AND HANDOVER

At the commencement of the project, the conservative view was that it would not be possible to install equipment and energize it before the planned installation outage in 2019, the initial assumption being that only enabling works such as network cabling for WISCO-2 would be installed prior to the outage. This was a consequence of the highly integrated nature of the system, particularly the controls in the control room and interfaces to HICS. It was also a consequence of the project desires to avoid changes to field cabling and follow the same architecture as the original WISCO.

However, as the design progressed it became apparent that the DCS components could be installed early, energized and attached to the network cabling, which was installed in parallel with factory testing. Furthermore, the novel design of the Eagle–Ovation interface meant that HICS originated data could be made available on the new DCS in parallel with the old DCS. This considerably de-risked outage installation activities both by reducing the volume of work during the outage and by creating opportunities for station maintenance and operations staff to increase their familiarity with the new system ahead of operational service. So, the DCS was installed, energized and testing during the first quarter of 2019 while the plant was operating at power. A period of parallel operation followed where the new DCS was fully operational and additional, confidence building, testing was possible prior to the main installation outage.

The PCS was installed in the second quarter of 2019 during Sizewell B's refuelling outage. Although installation was in a scheduled outage, the outage duration had been extended several years earlier in recognition of the one-off activities that would be needed to achieve the installation and handover of WISCO-2. The extended outage had been built into EDF's business planning. Detailed planning leading up to the outage resulted in progressive release of PCS cabinets from the operations team to the project team as the outage progressed. As WISCO is claimed in many plant surveillance and compliance activities, both at power and during outage, it was clearly going to be an extraordinary situation for operations staff not to have WISCO available continuously during the outage. Therefore, much work was done assessing routine operational procedures and plant evolutions entering and exiting the outage to identify where reliance on WISCO was assumed and the consequences/alternatives that would need to be enacted during the installation. These processes where checked in detail at the preceding outage in 2017. As a consequence of this and the detailed outage planning, the time that WISCO was unavailable to operating personnel was kept to a minimum and the project was able to commence installation of WISCO-2 while parts of the old WISCO were still in operational service.

Installation, site test and commissioning were successfully completed within the allotted outage in 2019 with no loss to generation beyond that already accounted for in business plans as a result of the changeover. WISCO-2 has now entered operational service and has performed reliably since installation.

I–8. REGULATORY ENGAGEMENT

Throughout the project the team established and maintained a strong relationship with the United Kingdom's regulatory body — the Office for Nuclear Regulation (ONR). This was essential as, based on experience from earlier projects, ONR had stipulated certain hold points and permissions that would be necessary to allow the project to proceed to installation. From this the project was able to agree, early on, to a progressive sequence of interactions with the regulators and hence ensure that sufficient time was allowed in the project schedule for governance and oversight. This was particularly important when agreement was required to progress between phases so as to ensure that sufficient information was provided when approaching a hold point, avoiding project delays that might arise from waiting for information to be assessed or analysed.

The decomposition of the project into the phases described earlier, coupled with the early identification of multiple 'stage submissions' justifying the safety of various aspects of the project was key to ensuring a 'no surprises' approach. Developing and maintaining regulatory confidence was essential to the success of the project and this was further facilitated by frequent meetings and presentations. At these meetings, EDF would present details of progress, key decisions being taken and justifications in advance of formal justification through safety case documentation and also discuss any areas of concern raised by the regulator.

I–9. CONCLUSIONS

The ageing and obsolescence threat posed by the original WISCO has been eliminated for the PCS and DCS by this modernization work. The project was delivered on time and cost and is considered one of the most effective major I&C modernization projects delivered by EDF in the United Kingdom. This has been recognized both internally within the sector and externally by the ONR. Practices and experiences from the project have been shared more widely within EDF for the benefit of other projects and through external publications.

ONR has also recognized the success of the project and has recognized many best practice activities that shape its expectations going forward. Recognizing the need to manage the future obsolescence of WISCO-2, a multi-decade support arrangement has been put in place with WEC, which will provide software and hardware support and maintenance services going forward.

REFERENCES TO ANNEX I

[I–1] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Nuclear Power Plants — Instrumentation and Control Systems Important to Safety — Classification of Instrumentation and Control Functions, IEC Standard 61226, IEC, Geneva (2020).

[I–2] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Nuclear Power Plants — Instrumentation and Control Important to Safety — General Requirements for Systems, IEC Standard 61513, IEC, Geneva (2011).

[I–3] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Nuclear Power Plants — Instrumentation and Control Systems Important to Safety — Software Aspects for Computer Based Systems Performing Category B or C Functions, IEC Standard 62138, IEC, Geneva (2018).

[I–4] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Nuclear Power Plants — Instrumentation and Control Important to Safety — Hardware Design Requirements for Computer-Based Systems, IEC Standard 60987:2007, IEC, Geneva (2007).

Annex II

LOVIISA ELSA PROJECT IN FINLAND

II–1. BASIS FOR THE MODERNIZATION

The Loviisa nuclear power plant units (Fig. II–1) were commissioned in 1977 and 1980. The baseline operational statistics for 2020 are shown in Fig. II–2.

FIG. II–1. The Loviisa nuclear power plant, Finland.

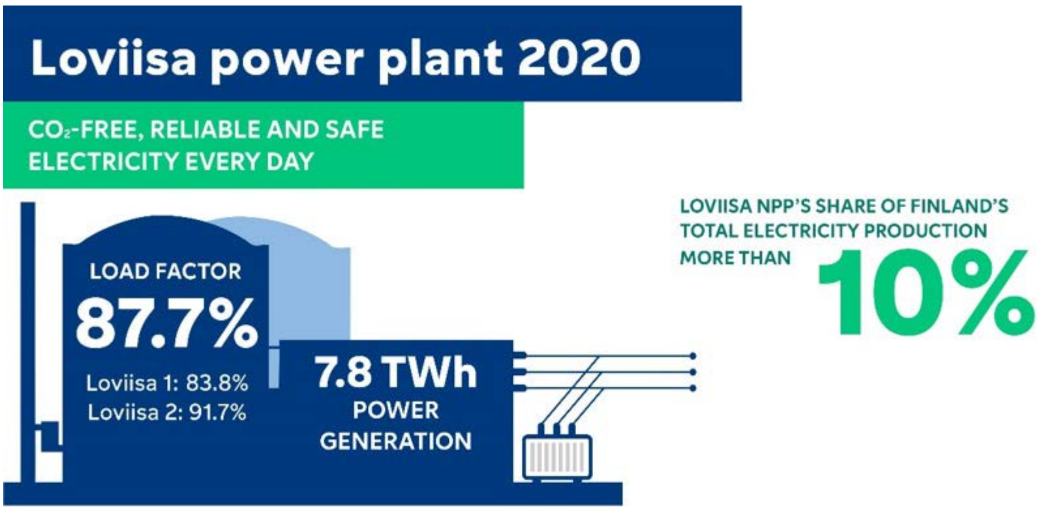


FIG. II–2. Main statistics of the Loviisa nuclear power plant in 2020.

Despite continuous improvements since commissioning, the instrumentation and control (I&C) systems needed renewal after 30 years of operation due to the unavailability of spare parts. Also, the goal of the modernization was to enable high levels of availability, licensability, maintainability and safe energy production until the end of the power plant's life cycle.

The planning of I&C modernization started in 1999 and led to an extensive plantwide modernization project called 'Loviisa automation renewal project' (LARA). The LARA project started in 2004. The renewal scope contained the majority of the power plant's I&C systems, including I&C systems important to safety and I&C systems for normal operation. As the project progressed, there was extensive scope creep due to many safety and usability improvements. After ten years and only one successful commissioning phase, the LARA project was terminated in 2014 due to the ever-changing scope, increasing complexity and unpredictable adverse impact on outage, which would have prolonged the required installation outage significantly and unpredictably.

As the need for I&C modernization did not disappear during the LARA project, the ELSA-R modernization programme and the ELSA I&C modernization project were established in 2014 to enable the continuation of work. Figure II–3 shows the timeline of the Loviisa ELSA I&C modernization project.

II–2. PROGRAMME MANAGEMENT

The LARA project was an extensive plantwide automation renewal project that was not successful due to its large scope and complexity. Based on lessons learned from the LARA project, the scope of the ELSA project was restricted to only renewal of essential safety functions and systems. All other important and related projects were managed by the ELSA-R programme.

This centralized management ensured the follow-up and proper management of related projects, but also made sure that the individual project scopes remained manageable. Despite the different suppliers in the projects, their overall management remained under Fortum. Interfaces between the projects was also managed by Fortum's interface managers. All ELSA-R projects are shown in Fig. II–4.

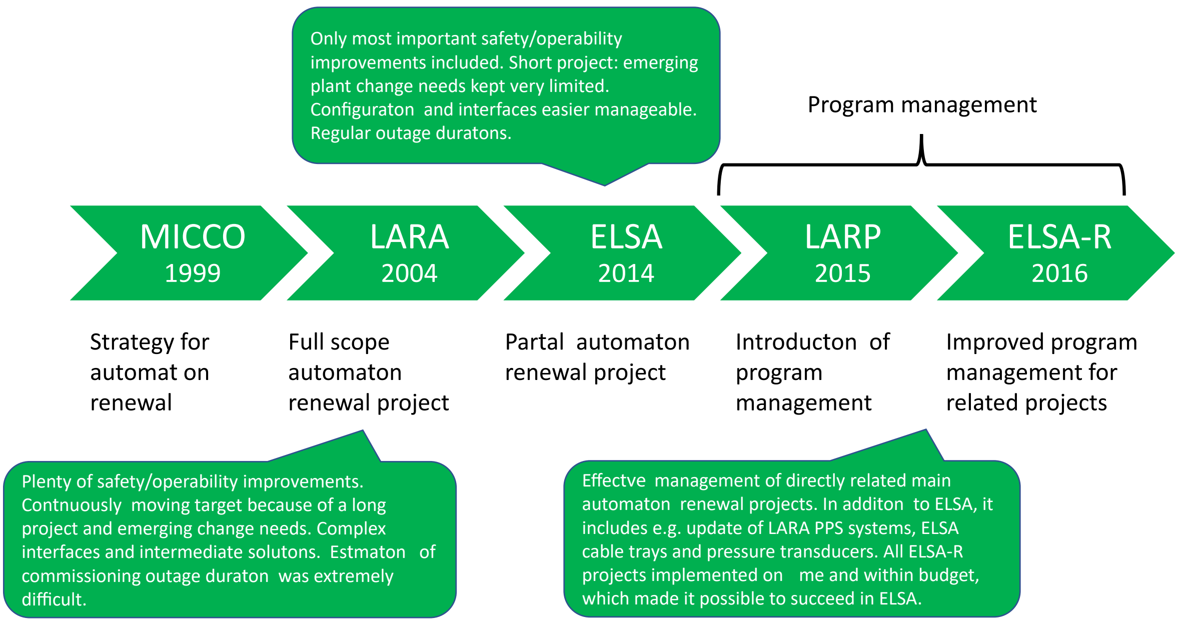


FIG. II–3. Timeline of Loviisa ELSA I&C modernization. MICCO: Modernization of Loviisa I&C, conceptual design phase; LARA: Loviisa automation renewal project (2005–2014); ELSA: Loviisa automation renewal project (2014–2019); LARP: Loviisa automation renewal programme; ELSA-R: Programme of ELSA related projects.

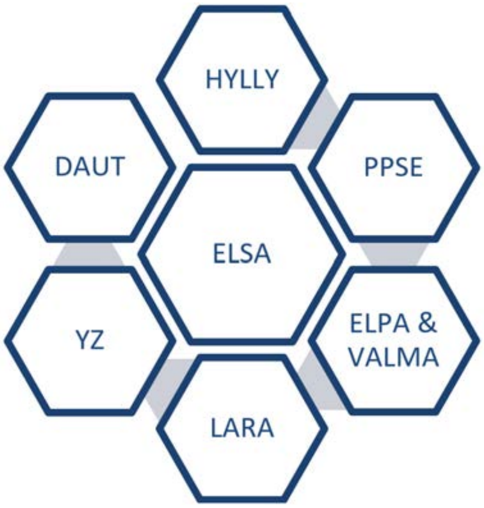


FIG. II–4. Projects of the ELSA-R programme. HYLLY: Implementation project for new cable trails; PPSE: Modernization project for the preventive protection system; ELPA: Installation project for new pressure transmitters; VALMA: Control room preparation project of Loviisa automation renewal; LARA: Loviisa automation renewal project (2005–2014); YZ: YZ automation renewal project; ELSA: Loviisa automation renewal project (2014–2019); DAUT – Diesel automation renewal project.

II–3. PROJECT MANAGEMENT

The ELSA project started with new people in leading roles compared with the previous project. The project organization was also fully reorganized.

For effective project management and control, in the beginning the ELSA project was divided into four subprojects such as engineering, qualification, plant operation and site management. All subprojects had their own subproject managers, project plans and clear areas of responsibility. Responsibilities were shared with technical leaders such as subproject managers, system responsible persons and site leaders. Sharing of responsibility was essential for the ownership and commitment of people in their areas of responsibility. Leading roles were shared throughout the project organization. Having several subprojects increased bureaucracy, but ensured that sufficient progress was made.

When the project evolved from planning and design to installation and commissioning activities, the project's organizational structure was adapted, and the number of subprojects was reduced from four to two, and finally only one. At the beginning of the project, there were several parallel active areas such as licensing, engineering and other activities, which were easier to control as work packages. When the project proceeded to the realization phase, these parallel packages were not needed any more and they were combined. This ensured the change of focus and made oversight of the relevant subprojects easier.

II–4. MANAGEMENT OF INTEREST GROUPS

Management of interest groups and communication with them, especially with the Finnish Radiation and Nuclear Safety Authority (STUK), was recognized as an important success factor. In the beginning of the project, pre-approval of technology and solutions was sought from STUK with an extensive conceptual plan that contained preliminary quality and qualification plans, I&C architecture descriptions, system specifications, component and platform descriptions and preliminary designer's and licensee's safety assessments. These materials were prepared in close cooperation with the suppliers. The work breakdown was based on ways to manage elaboration of licensing documents by natural entities, so-called 'licensing packages'. The intention was to provide the authority beforehand with a clear visibility of the documentation to be delivered in the near future for authority review (or oversight).

A preliminary set of project materials enabled the authority to start the inspections and be prepared for the large amount of documentation that was coming from the project. Follow-up during the project was ensured by the licensing documentation schedule that was communicated in a timely manner and managed by the project coordinators in STUK and at Fortum. Through this efficient communication channel, document approvals were achieved on time. This also ensured STUK’s commitment to support the project schedule.

Other interest groups, like plant operating personnel and plant maintenance personnel, were handled by the subprojects. Power plant operating personnel were involved in the design from the project start, which ensured that their opinions and experience were taken into account. The available operator experience was used extensively also during the testing and commissioning phases of the project. This ensured the high quality of the design from start to end. Maintenance personnel were also trained during the project and, due to this arrangement, they were ready to take the new systems directly under their responsibility after commissioning.

FIG II–5. SUPPLIER CONTROL AND DIVISION OF RESPONSIBILITIES

One of the most remarkable success factors of the project was the clear division of responsibilities between supplier and purchaser, which was carefully prepared in the pre-engineering phase of the project. The sharing of responsibilities was based on the areas of expertise of each party. Responsibilities were also changed and agreed again during the project when a more feasible solution was found. It was important that there were only common problems and problem solving was always to be a common objective before finding a responsible party.

Common (schedule) risk recognition and management between the purchaser and the supplier were the most essential factors behind the success of the project. The division of responsibilities remained clear, despite the extensive changes made in the supply chain during the project. The decision was based on comprehensive schedule follow-up and analysis of different scenarios.

II–6. MANAGEMENT OF TECHNICAL IMPLEMENTATION

II–6.1. Project phasing

The project was divided into three main phases commissioned in consecutive annual outages in 2016, 2017 and 2018. These project phases contained everything from basic design to installation and commissioning. The overall project scope was divided for these phases in a way that installation scope and level of difficulty increased correspondingly. Also, the division took into account the needs of preliminary partial installations (pre-installations).

The first phase was a trial round where the organizational capabilities and working methods from every aspect was tested. The second phase was smaller from the scope perspective, but on the other hand it ensured proper resource allocation for preparation and testing of third phase. The third phase contained the most critical systems and successful implementation of it was the ultimate goal of the project.

Figure II–5 describes the I&C architecture and systems together with the I&C platforms used in the ELSA project:

II–6.2. Licensing and engineering

The project’s licensing approach was based on the ADLAS method developed at Fortum. The method was used to define the plant and functional level requirements for the new automation systems. The requirements were defined hierarchically, based on the plant's accident management concept.

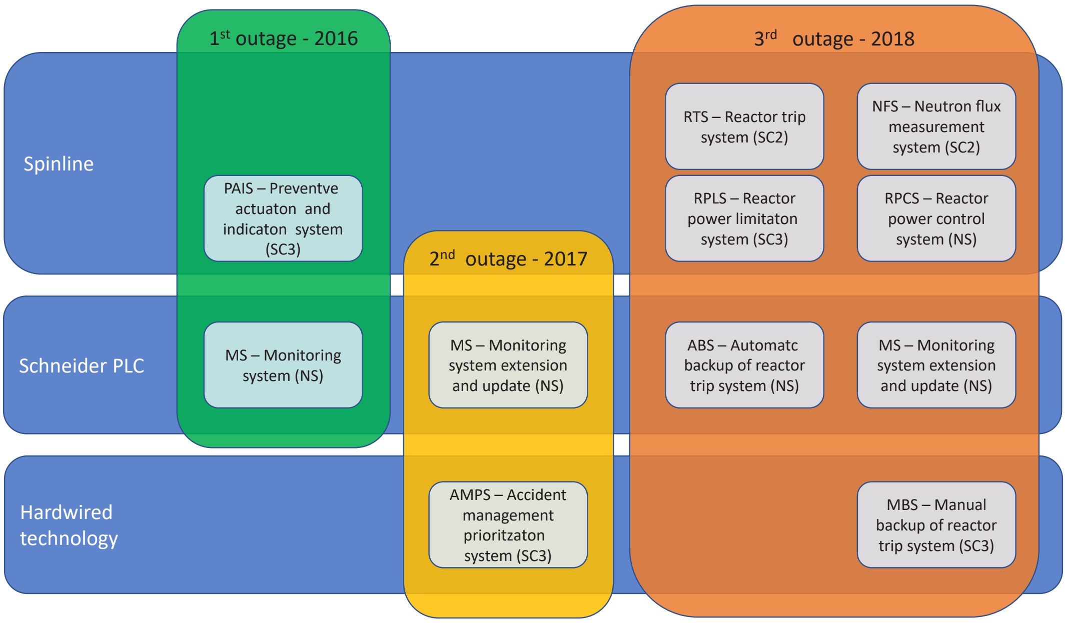


FIG. II–5. Architecture and I&C systems of the ELSA project.

The plant level functional architecture that was developed contains all safety functions, old and new, of the plant. Functional architecture then made it possible to define diversity, redundancy and separation requirements for the safety functions, which were then allocated to new automation systems in the automation architecture. The first version of automation architecture was included in the conceptual plan at the beginning of the project, and it was further developed and extended during the project. This approach also ensured that the system design was performed in a systematic way and there was no need to go back to plant level issues in the system level design. This way of working made it possible to trace all requirements from the regulatory requirement to the design solutions. This information was used extensively in the designer's and licensee's safety assessment reports of the project.

II–6.3. Testing

Due to the tight project schedule, effective testing methods were also a necessity. With around 30 000 monitored signals and over 2000 field and control room connections, conventional, manually performed signal by signal testing was not possible. Also, the project had to ensure that new systems were able to function properly with existing systems. Due to these constraints and existing expertise at Fortum, an APROS simulator was utilized extensively.

Simulator based testing started early in the basic design phase, immediately after first versions of software logics were sketched. The existing plant model of automation logics made it possible to dynamically test the new automation software logics in the early phase. Test coverage was extended to cover all plant states and different possible transients. The new reactor power controller was also successfully tuned only with these dynamic simulator tests. Even fine-tuning of the controller was not needed after the commissioning.

Interfaces between the new and existing automation systems were also ensured by type circuit testing of all interfaces. These tests were carried out with real spare components.

The project's supplier estimated that the time savings gained with the APROS simulator based testing was around seven months. In addition to automation testing, the simulator was utilized in the validation of control room concepts, operating instructions and operator training.

II–6.4. Decommissioning and dismantling

Fortum's experts planned and performed most of the preparation and dismantling works at the site in every phase of the project. Recognition of the work needed and its timely management ensured that installations of new systems were performed according to schedule.

Old and renewed I&C systems were only decommissioned during the commissioning of new systems during the outages. This arrangement reduced the risk with the new systems and in theory it was possible to return back to old systems if some major issue would have been found from the new systems.

Dismantling of decommissioned systems was started after one year of successful operation with the new systems. The experience gained from the performance of the partial dismantling also led to a plan to combine ELSA dismantling works with the dismantling works of other projects. This decreased the overall costs as the dismantling was done under the same rules and in a coordinated manner.

To enable continuous improvement of the project, feedback was collected regularly and in specific sessions through the project. The feedback was analysed and any changes or improvements were completed.

II–7. LESSONS LEARNED: IMPROVEMENTS FOR PROJECT EXECUTION

The project as a whole was a success, taking into account previous experience with Loviisa I&C modernizations. However, there are always issues that can be improved for future projects and activities. The main improvements that have been identified are:

— Termination work and final documentation of the previous project. When the ELSA project started, the entire project organization was focused on the new project. Termination work of the previous LARA project was not done properly.
— Stagewise management of resources and organization. The challenge is to keep all resources effective during the project when stages are in different life cycle phases. In the ELSA project, this was especially challenging at the start of the project when the first stage was ahead while the remaining stages were just in the beginning.
— Preparation of final documentation of ELSA I&C systems. This activity was started after implementation. This caused the as-built documentation to not be fully available for the end users when the I&C systems were already in operation. This could be avoided if preparation of final documentation was started during the detailed design phase.

Annex III

UKRAINIAN NPP I&C MODERNIZATION PROJECTS

III–1. CONCEPTUAL DOCUMENT FOR SAFETY CONTROL SYSTEM MODERNIZATION AND UKTS REPLACEMENT

Ukrainian nuclear power plant (NPP) instrumentation and control (I&C) modernization projects were greatly facilitated by comprehensive ‘concept documents’ prepared by a working group at the outset of the modernization project. These documents addressed three principal considerations:

— Reasons to implement the modernization (e.g. norms, regulations, functional performance).
— Detailed description of the modernization (e.g. key features and objectives of the modernization).
— Available experience, and existing solutions for the implementation of the modernization (e.g. analyses, similar projects and experience, market capability).

III–2. EXAMPLE OF CHOOSING THE STRATEGY FOR UPGRADING THE CHANNELS OF A CONTROL SAFETY SYSTEM FOR WWER-1000 POWER UNITS

The Zaporizhzhia Unit 3 NPP (Z-3) was commissioned in 1986. Unit 3 of the South Ukrainian NPP (SU-3) was commissioned in 1989. The I&C systems of both units were based on the same analogue devices developed in the former Soviet Union in the 1970s and 1980s. The systems comprised about 130 cabinets per channel and each unit had three channels. The systems performed their functions effectively, but had low reliability due to the large number of wired connections and laborious diagnosis of faults as well as the high energy consumption (1 kW per cabinet) requiring ten fans per cabinet, with overheating causing many faults.

By the end of the 1990s, I&C failures reached critical levels, exacerbated by the lack of spare parts due to the collapse of the Soviet Union in 1991. Consequently, a working group was established in the operating organization to develop solutions. The working group concluded that the most effective strategy was the replacement of blocks and boards, since: (a) the condition of the cabinets and cable communication lines was satisfactory; (b) good design documentation was available (including circuit board diagrams); (c) electrical components were still available; and (d) manufacturers for new equipment were available.

III–2.1. Modules and boards developed using the fit, form and function (FFF) strategy

At least three suppliers developed the necessary boards and modules, which were fully compatible in physical and electrical specifications with the existing equipment. Figure III-1 shows the ‘old’ and ‘new’ valve control module.

Retraining of operating personnel was unnecessary since the boards were FFF replacements. The new components had lower energy consumption, reducing the cabinet thermal emissions. Also, the new components had higher efficiency and had more reliable cooling fans installed. Additional benefits included: the least expensive and relatively fast solution; spare parts availability; minimal changes to the NPP documentation; and absolutely no changes in the main control rooms (MCRs).

There were some drawbacks. It was a temporary solution to extend the operation by about 5–10 years (together with the impossibility of introducing new functions). A large number of cabinets, communication lines and electrical contacts were preserved and the flexibility of the systems remained extremely low.

a) b)

FIG. III–1. An example of modernization of an electronic valve control module compatible with an existing control system cabinet. (a) The upgraded control module; (b) the original control module.

The implementation of the FFF strategy for the modules and boards allowed NPPs to gain some time to develop a concept for further modernization. However, by the mid-2000s, the condition of the cabinets at the Z-3 units was at critical level even with the new modules and boards due to ageing of switching elements, cables, loops and wires, which were located directly in the cabinets.

III–2.2. FFF strategy for cabinets

Complete replacement of the control systems was not economically justified and so it was decided that the only upgrade was the replacement of the cabinets with the following features:

- The design of new cabinets allowed for installation of the previously upgraded modules and boards.
- There was the possibility of placing advanced diagnostics devices in the new cabinets, which could, in the future, be combined using a local area network (LAN) for the centralized collection, storage and presentation of information on a special workstation.
- New cabinets had to have the same dimensions, power supply, electrical and physical interfaces as those of the replaceable ones.
- The presence of digital interfaces that would ensure the connection of cabinets with subsystems, the replacement of which is possible in the process of subsequent stages of modernization.

The NPP working groups considered the available malfunctions and failure statistics, and identified the critical subsystems that most influenced the safety and efficiency of the power units. At least two suppliers offered products that fully met the requirements of the plants. Figure III–2 shows the front panels of the ‘old’ and ‘new’ control cabinets.

In the mid-2000s, a step by step replacement of cabinets at Z-3 began, followed by similar upgrades at Z-4 and Z-5. A staged integration of cabinets through a LAN significantly improved diagnostic capabilities and similar systems were installed at Khmelnitsky-2 and Rivne-4 (commissioned in 2004).

The most significant aspect of this modernization was the upgrading of the control systems. The technical characteristics of the control systems had to be improved. The strategy chosen was to modernize the existing system by partial replacement, thereby compensating for the inadequacies:

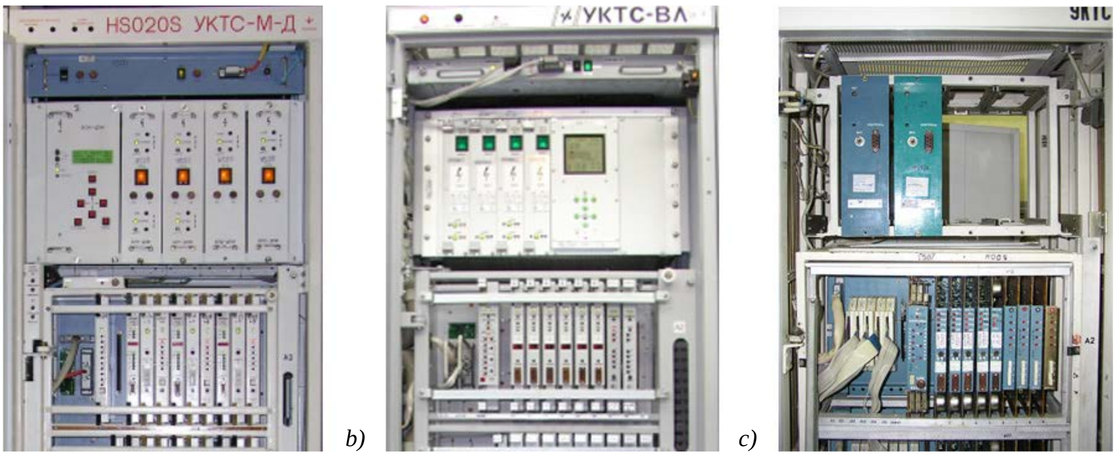
— Technical protections, interlocks and alarms (modernized in the mid-2000s) remained unchanged, but the integration of cabinets via the LAN had to be completed.
— Actuator power and control subsystems remained unchanged.
— Sensors and modules with digital signal processing were installed to replace the existing measurement system.
— Analogue regulators were replaced with redundant digital instruments.

The advantages achieved were as follows:

— The global system architecture remained the same (reducing the likelihood of errors by experienced personnel);
— Spare parts availability;
— Implementation of extended diagnostics;
— Reduced energy consumption;
— Reliability of the most vulnerable parts of control systems increasing significantly;
— Absolutely no changes in the main control rooms;
— Potential for subsequent modernization of associated subsystems.

The disadvantages were as follows:

— More expensive than the boards and components FFF strategy;
— The original communication lines, controls and actuators remained;



a) b) c)

FIG. III–2. An example of the modernization of cabinets for the formation of technological protection, interlocks and alarms, compatible with each other in terms of internal components and external communications. (a) Modernized cabinet manufactured by Radiy; (b) modernized cabinet manufactured by Impulse; (c) the original cabinet.

— The reliability and functionality of the systems still needed to be addressed;
— A large number of cabinets, communication lines and electrical contacts were preserved;
— The ability to reconfigure the systems remained insufficient.

The most important aspect in this modernization was to ensure the compatibility of the ‘new’ and existing subsystems. After a tendering process, the necessary modernization was carried out at the safety system of the Z-3 power units (and later at Z-4 and two channels of Z-5). This form of partial modernization carried a total cost of about €3 million per safety system channel. Permits have now been given to extend the life of Z-3 (in 2017) and Z-4 (in 2018). At the Z-5 power unit, the extension of the plant life was competed in 2021.

III–3. EXAMPLE OF MODERNIZING A CONTROL SYSTEM BY REPLACING ONE OF THE SUBSYSTEMS

III–3.1. Replacement of the automatic regulation subsystems in selected channels of Ukrainian units

General approaches to the selection, planning and implementation of such a strategy, as well as the advantages and disadvantages, are described in Section 5.2.5 of this publication. The Zaporizhzhia-2 (Z-2) unit in Ukraine was commissioned in July 1985. The control systems equipment was developed and manufactured in the late 1970s and early 1980s. The I&C equipment was analogue. Computer and digital equipment was used only as part of the main plant computer and in its communication systems with other NPP automated systems. By the beginning of the 2000s, the Z-2 malfunctions of the control systems had reached a critical level. Particularly alarming was the condition of the automatic control subsystems of the control safety systems. Based on analysis, the NPP operator decided on the urgent modernization of the automatic regulation subsystems of redundant safety channels No. 1 and No. 3 of Z-2.

Automatic subsystems of the safety control system channels were installed based on analogue equipment (Kaskad-2 set). The regulator panels and modules are shown in Fig. III–3.

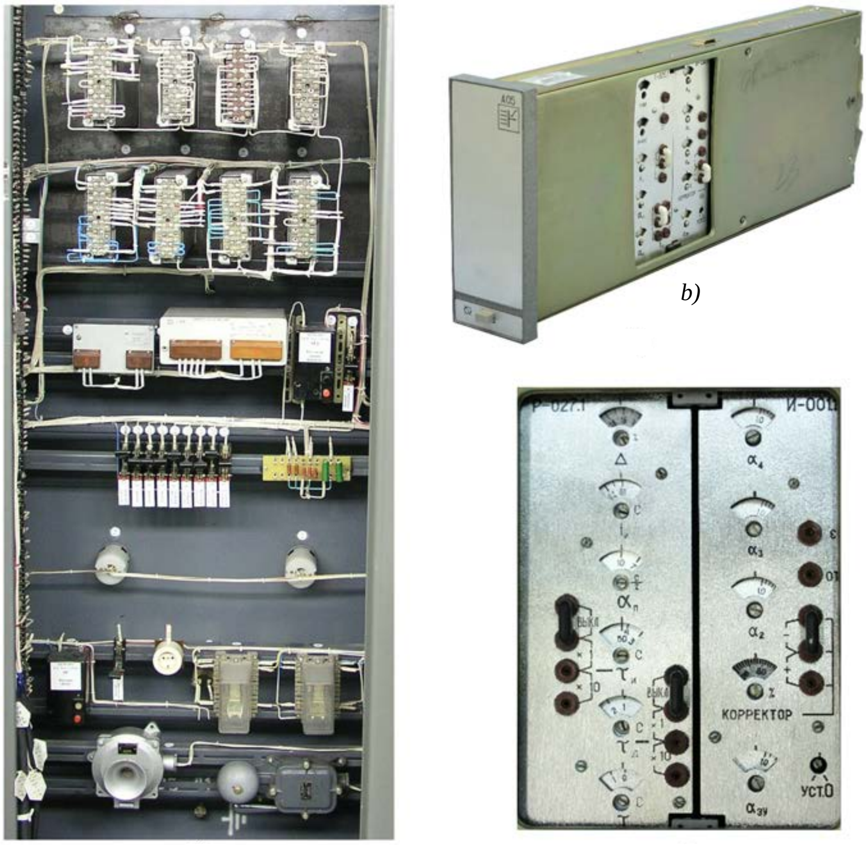
The operating organization developed a technical specification, including the following:

— The subsystem has to be based on digital technology.
— The subsystem needs to be redundant (at least two redundant channels).
— The subsystem has to be capable of receiving signals from existing analogue sensors;
— The subsystem needs to be able to transmit control commands to the existing subsystem for actuators.
— The subsystem design has to provide spare capacity of digital communication channels with other subsystems that can be replaced in the future.

After selecting a Ukrainian equipment supplier, the first modernization was carried out on safety control system No. 3 during the 2006 outage period. The upgraded automatic control subsystem was based on the M2002 software and hardware platform. The equipment that was introduced in the modernization process already had some positive operational history. Namely, it was originally installed at the Rovno-4 power unit (Ukraine), which was commissioned in 2004. In this regard, the pilot operation was greatly simplified.

The results of the pilot operation of the upgraded equipment were found to be satisfactory and, during the 2007 outage period, a similar modernization of the automatic regulation subsystem of safety channel No. 1 was carried out. Figure III–4 shows the appearance of the upgraded safety system automatic control subsystem.

The reliability problems of the Kaskad-2 based regulating subsystems installed at Ukrainian NPPs were systemic. Therefore, at about the same time as the modernization process was ongoing at Z-2, a similar problem was solved at the Rovno NPP and the South Ukrainian NPP. The approaches to modernization were the same.



a) *c)*

FIG. III–3. External views of the panels and modules of the automatic regulating subsystem before modernization. (a) The regulator panel (rear view); (b) the summation and limiter module; (c) the control module settings panel.

III–3.2. Automatic regulation subsystems for channels No. 1 and No. 2 of the Rovno-3 unit

Positive results from modernization of the Z-2 power unit made it possible to carry out the same modernization of the automatic regulation subsystems for channels No. 1 and No. 2 of the Rovno-3 unit in 2007 and 2008.

Another Ukrainian supplier (Westron) was selected for the South Ukrainian NPP, which implemented a subsystem based on its own Vulcan-M hardware and software platform. The sequential modernization of the automatic regulation subsystems of the three channels of the safety system of the SU-1 power unit (commissioned in December 1982) was carried out between 2005 and 2007. The equipment installed in the SU-1 power unit now is shown in Fig. III–5.

The advantages were as follows:

- — Cheaper than complete replacement;
- — Availability of spare parts;
- — Implementation of extended diagnostics;
- — Reduced energy consumption;
- — Significant increase in subsystem reliability;
- — Significant reduction in (cabinets and subsystem components, etc.);
- — Human–system interface (HSI) improvement, etc.

FIG. III–4. External views of the automatic control subsystem of the safety control system after modernization. Left: Regulator cabinet; right: adjusting, diagnostics and historian workstation.

The disadvantages were as follows:

— It was more expensive than the ‘boards and components’ FFF strategy;
— Associated subsystem communication lines, controls and actuators remained as the original;
— Problems with the reliability and functionality of the systems remained unsolved.

The requirement of the operating organization for the availability of spare capacity for modifying the channels of external information exchange made it possible to organize the replacement of the regulation subsystem with the new subsystems without any major problems. In 2010, at the Z-2 power unit, the subsystem for the protection and interlocks formation, the instrumentation subsystem and the actuators control subsystem of the safety control system channel No. 3 were modernized. The old equipment was replaced with programmable logic controller based digital equipment. The supplier of the new equipment was not the one that manufactured the automatic regulation subsystem. However, because the requirements in the specification were complete and accurate at one time, there were no problems with pairing the subsystems and setting them up to work together. In 2014, the modernization of channel No. 1 was also carried out.

FIG. III–5. General view and internal layout of the cabinet of the safety control system automatic regulation subsystem after the modernization of the SU-1 power unit.

FIG III–4. EXAMPLE OF THE FULL REPLACEMENT OF AN I&C SAFETY SYSTEM

The objectives of the Rivne NPP digital safety upgrade included the following:

— Perform a safety level upgrade that enables the NPP to meet modern national safety standards;
— Implement IAEA recommendations;
— Implement corrective measures for preventing accidents and spurious actuations.

The Rovno NPP’s team determined that full I&C system replacement was needed. New equipment was procured according to all current Ukrainian legislation. The RadICS platform (developed by RPC Radiy) was chosen as being functionally similar to currently installed I&C systems, which allowed the Rovno NPP to streamline the installation, reengineering and upgrade process.

As stated in Section 5.2.5, the full I&C modernization is characterized by the replacement of a large amount of equipment with significantly complex interfaces to the existing plant. The scope of the I&C modernization project included the system core logic, switchgear assemblies, manual control elements at the MCR, primary sensors and actuators. A significant point was that the NPP’s operator decided to remove the old I&C cabinets. The full I&C replacement scope is shown in Fig. III–6.

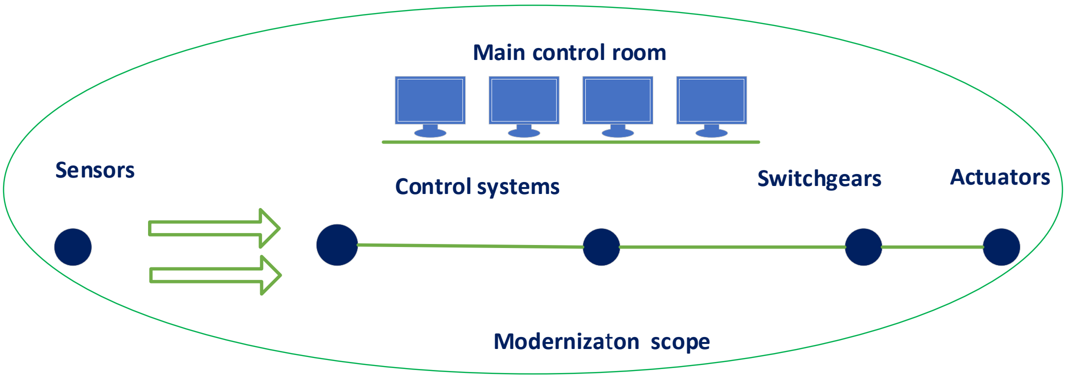


FIG. III–6. Diagram of the full I&C replacement scope of system core logic, switchgear assemblies, manual control elements at the MCR, primary sensors and actuators.

III–3.3. I&C development cycle with a new digital platform for the Rovno NPP

The full I&C replacement scope allowed the project to optimize the scope of work at the project's preliminary stage. In this case the new system was designed as a 'black box'.

Since the old cabinets and cables were dismantled, there was no need to spend time gathering information about internal interfaces within the system (between logic core cabinets). Such an approach decreased the risks to an inadequately specified set of internal interfaces between cabinets.

FIG. III–7. I&C system installation in process.

The scope of the on-site work shown in Fig. III–7 was optimized due to:

- Advance preparation of all cables at the supplier's site, including their production and testing.
- Complete testing of cabinets at the supplier's site (including electromagnetic compatibility and seismic stability).
- Complete functional check of the assembled system at the supplier's site. The system's functionality was tested using simulators of sensor signals and connecting simulators of actuators in accordance with the requirements of external interfaces received from the Rovno NPP.

As a result, the NPP received a completely new logical core with switchgears. The new diagnostic covered the entire system core, switchgears and any actuators. The Rovno NPP now relies on the new RadICS digital platform as the basis for several new digital safety systems such as:

- The conventional island control system, operational since February 2017.
- The nuclear island instrumentation system (see Fig. III–8), operational since July 2018. The new system requires fewer equipment racks, reducing the system's total footprint.
- In addition, the Rovno NPP has installed three new engineered safety feature actuation systems, one of which has been operational since 2018, the second since 2019, and the third since 2021.

The new digital I&C equipment has a smaller equipment footprint than the analogue equipment it has replaced while adding significantly more diagnostic and monitoring capabilities.

In addition, the new modular digital I&C system is much simpler since there are only ten platform module types, as opposed to 34 for the old safety system. The convenience has increased, human errors have been virtually eliminated, the labour force spends less time on technical maintenance, and the modern software has allowed for greater automation of key processes and procedures.

FIG. III–8. The new digital safety system.

III–3.4. Flawless operation, outstanding results

Section 5.2.5 of this publication lists diagnostics, HSI and fault tolerance as advantages of a full I&C replacement. The Rovno NPP depends on the new digital platform to continuously monitor system status through signals that are received from field sensors.

Routine work, such as testing and preventive maintenance, is easier, faster and more informative, thereby reducing labour, thanks to the expanded monitoring and diagnostic information available through the new interface. As part of the upgrade, the team replaced old copper cable runs with fibre optic communication links, reducing the cabling footprint ten-fold. This has also served to improve the plant's overall safety posture, since less copper reduces the fire load in the power unit cable structures. Furthermore, fibre optic links improve performance, are immune to signal noise, and are more reliable.

New single turn electric actuators were equipped with reliable position indication modules which gave more information to the operating personnel about actuator position. Replacement of obsolete sensors by new ones allowed the use of remote diagnostics.

The full I&C replacement option was used by the NPP to add the advanced functionality to the plant, address obsolescence in multiple systems, upgrade technology for the workforce of tomorrow, and expand the use of digital technology to improve plant monitoring and diagnostic capabilities.

Annex IV

USE OF 3-D PRINTER TECHNOLOGY TO ADDRESS AN AGEING AND OBSOLESCENCE ISSUE AT THE DARLINGTON NPP

The Darlington Nuclear Generating Station is located in Clarington, Ontario, Canada. Design and construction began in the 1980s. It was commissioned and has been in operation since the early 1990s. The NPP's digital control computers (DCCs) use Xerox 8812 printers. These printers have been in use since the mid-1990s. The spare parts for these printers are obsolete since the original equipment manufacturer stopped producing spares many years ago. The printers have a specialized interface to the DCCs, so replacing the printers is a significant undertaking that involves replacing the entire display subsystem of the DCCs. A project was under way to replace the display subsystem to make it easier to connect modern, universal serial bus interfaced printers. However, the replacement project was going to take about three to five years to completely replace all the DCC display subsystems, including the printers. Before the printers could be completely replaced, the team turned to 3-D printed spares as a bridging strategy.

One of the spare components that was 3-D printed was an aged and obsolete printer drive belt (see Fig. IV–1). The belt was a particular component in the printer that required replacement due to ageing. However, no replacement was available since Xerox discontinued production many years ago. After many years of service, these original rubber belts are subject to stress and high temperature within the printers and therefore they deteriorate and break.

In 2011, 100 replacement belts were purchased from the surplus market to support nine printers across the NPP. By 2018, the replacement belts were all used up. Therefore, the team decided to use 3-D printing technology to create the belts in-house. Since the shape of the belt was simple, one belt was 3-D scanned and a computer generated, 3-D computer aided design file was created. The replacement belts were printed using the NinjaFlex filament. The new 3-D printer belts were installed in all nine printers in 2018 and so far, as of 2021, the component has been highly reliable with no failures. 3-D printing technology is currently being considered for in-house fabrication of other DCC printer components, such as the gears and exit rollers.

FIG. IV–1. A 3-D printed roller belt by itself and inside the DCC printer.

Annex V

USE OF ACCELERATED AGEING ON EQUIPEMENT IN A MILD ENVIRONMENT

A lifespan extension project towards 2040+ was implemented on equipment located in a mild environment at the Ringhals NPP in Sweden. The equipment was of 1970s design and was installed in the early 1980s. Some parts were exchanged during the 2010s.

The cabinets were screened for high temperatures with thermography. This was done to establish the real ambient temperature and to look for hot spots that would expose electronics outside their maximum specification. None were found to be outside the specification of the electronic components. A conservative ambient temperature was established as 30°C.

All electronic components and construction details (guide rails, sockets, connections, pins, etc.) on different electronic cards were screened for:

— Susceptibility to ageing degradation;
— Consequence at failure.

The next step was to perform a degradation analysis to set a degradation factor. This was partly based on internal and external knowledge (from other NPPs) of fault statistics. Large parts of the installation had been ageing for 30+ years. A consequence analysis was made to determine how important the individual electronic component was for the total function. A consequence factor was set from this analysis. A risk factor was then calculated on all components from the degradation factor and consequence factor. From the risk factor analysis, one could then determine the worst risk on each individual electronic card and detail the effects depending on application.

A statistical number of different electronic cards and construction details of equipment were then subjected to accelerated ageing based on an Arrhenius value for 35 years. Functional testing against acceptance criteria was performed at different times:

— Before accelerated ageing started;
— Four times during accelerated ageing;
— After completed accelerated ageing.

Seismic testing in accordance with KBE EP-147 [V-1] seismic environmental classes SL3 and SL5 was then carried out after the accelerated ageing. Some equipment in the installation were delivered in different ‘eras’ (1980s and 2010s); this resulted in a variety in materials being used. Special consideration was necessary to put these in different categories for evaluation.

The results from the accelerated ageing presented Ringhals with a trend for possible faults in the equipment and how they could develop over time. Some types of electrolytic capacitors and polymers were very susceptible to degradation over time. Through this project, Ringhals obtained knowledge on how the equipment would behave during ageing. Different types of preventive maintenance were then set up to mitigate future failures.

REFERENCE TO ANNEX V

[V–1] OKG, VATTENFALL, SKB, Quality and Inspection Requirements for Electrical Equipment (KBE) — Examination Procedure — Seismic Qualification, Rep. KBE EP-147, OKG, Vattenfall (2017), https://tbekbe.se/home/kbe-ep/kbe-ep-147

Annex VI

DARLINGTON NPP LIQUID ZONE CONTROL POSITIONER REPLACEMENT

In a Canada deuterium–uranium (CANDU) reactor, the liquid zone control (LZC) valves are the primary method of controlling reactor power during normal operation. The LZC valves control the individual water levels in each of the reactor’s 14 zones. At the Darlington Nuclear Generating Station (located in Ontario, Canada), the existing analogue positioners of the LZC valves were becoming a maintenance burden and the decision was made in 2018 to replace the positioners with highway addressable remote transducer (HART)-enabled digital valve positioners to improve system reliability.

The LZC valve positioners are controlled by the plant digital control computers (DCCs) and the new digital positioners also provide health diagnostic information. The positioners are capable of recording and storing system diagnostics to assist in maintenance troubleshooting activities (not available in the previous analogue positioners).

Although other existing CANDU plants have previously upgraded their LZC valve positioners to digital versions, the requirements for Darlington were more challenging than previous digital implementation. Prior to the start of design activities, a test rig was developed, and performance testing was performed to successfully demonstrate that the new digital positioners could meet the LZC system functional and performance requirements. The software within the digital positioners and maintenance tools (e.g. laptop and handheld devices) were categorized based on their safety significance, and the software was qualified in accordance with the applicable standards. Since some of the diagnostic functions performed by the maintenance tools needed to be performed while the digital positioner was in service, as part of software qualification activities, additional testing was performed on the LZC valve test rig to demonstrate that these diagnostic functions did not interfere with the ability of the digital positioners to meet the LZC performance and functional requirements.

Also unique to this project was the use of SNC-Lavalin’s advanced portable polymer tester (APPT) tool to assess the remaining life of existing cables in the LZC system. The APPT is a lightweight and portable cable indenter tool that can accurately determine the condition of low voltage power and control cables through in situ non-destructive examination. The APPT can measure recovery time in addition to indenter modulus. Recovery time measurements can be more sensitive to degradation than indenter modulus alone for irradiated polyvinylchloride, thermally aged chlorosulphonated polyethylene and irradiated and thermally aged XLPE cables. The APPT successfully demonstrated that the existing multi-conductor trunk cables would last for the remaining life of the station, thus eliminating the need for cable replacement as part of plant refurbishment activities.

ABBREVIATIONS

AMS	asset management system
APPT	advanced portable polymer tester
ASIC	application specific integrated circuits
CCF	common cause failure
CM	condition monitoring
COTS	commercial off the shelf
CSPE	chlorosulphonated polyethylene
CTS	company technical standards
DCC	digital control computer
DCS	distributed computer system
EAB	elongation at break
EDF	Électricité de France
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPRI	Electric Power Research Institute
ESD	electrostatic discharge
FDR	frequency domain reflectometry
FFF	fit, form and function
FPGA	field programmable gate array
FTIR	Fourier transform infrared spectroscopy
HART	highway addressable remote transducer
HICS	high integrity control system
HSI	human–system interface
HVAC	heating, ventilation and air-conditioning
I&C	instrumentation and control
I/O	input/output
IEC	International Electrotechnical Commission
IEE	item equivalency evaluation
IGALL	international generic ageing lessons learned
IP	intellectual property
LAN	local area network
LOCA	loss of coolant accident
LZC	liquid zone control
MCR	main control room
NICR	non-identical component replacement
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (USA)
O&M	operation and maintenance
OEM	original equipment manufacturer
OIT	oxidation induction time
OITP	oxidation induction temperature
ONR	Office for Nuclear Regulation (United Kingdom)
OPEX	operating experience
PCS	process control system
PLC	programmable logic controller
PLP	project life cycle plan
PSR	periodic safety review

R&D	research and development
RFI	radiofrequency interference
SSC	structures, systems and components
STUK	Finnish Radiation and Nuclear Safety Authority
V&V	verification and validation
WEC	Westinghouse Electric Corporation
WISCO	Westinghouse Integrated System for Centralised Operation
XLPE	polyethylene
XLPO	polyolefin

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Technical Meeting

Vienna, Austria: 2–5 March 2021

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NR-T-5.4: Nuclear Reactors (**NR**), Technical Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6: Nuclear Fuel (**NF**), Technical Report (**T**), Spent Fuel Management (topic **3**), **#6**
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