ANNEX 3: NEA NUCLEAR INNOVATION 2050

R&D COOPERATIVE PROGRAMME PROPOSAL

Title/Subject: Lifetime management of Nuclear power plant:

Ageing monitoring and prediction

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1. Justification of the selection.

Recent years have seen major shocks to the nuclear power community, including those due to events at Fukushima and subsequent plant closures, such as those in Germany, and changes in economics in the USA due to the widespread availability of cheap natural gas following the introduction of hydraulic fracturing, which is causing some nuclear power plant closures too. The accelerated development of renewable energies in the frame of subsidized projects is also part of a structuring context for the future of the energy mix. The global energy situation is further complicated by the growing need for energy to support development and by political uncertainty.

In spite of these challenges, global interest persists in low-cost baseload electricity supply which is a critical enabler of economic and social development. Nuclear power has played a key role in delivering such supply for decades in many countries. Indeed, by the end of 2016, 448 reactors around the world were operating (up from 441 at the start of the year) and 61 were under construction.

The current global fleet was developed with plant design lives that were typically either 30 or 40 years. In the USA, which has many of the older plants, a process has been first developed to enable operators to seek a 20-year license extension, providing operation from 40–60 years. Now, a second license renewal process that may provide operation beyond 60 years of US NPP is ongoing. In looking to meet future energy demand, attention is also turning to consider any additional refurbishments or modifications that will be needed to ensure safe operation throughout the whole remaining lifetime of nuclear power plants, and also to manage new plant builds with a 60-year design life.

The economics of nuclear are characterised by low and stable operating costs, resulting from the low proportion of fuel cost in the total cost structure, which have enabled nuclear plants to supply reliable, competitive and low carbon baseload power. Once built and commissioned, and assuming a good operational performance, nuclear power plants should be able to carry out this indispensable role for the long term. With high fixed costs and low running costs, average electricity costs for nuclear plants fall substantially with increased output. It is therefore vital for nuclear operators to achieve high plant capacity factors.

In order to achieve these extended lifetime objectives in competitive economic conditions, new tools are now at our disposal. The technological revolution we have witnessed for some years now in the field of digital technology has led to the development of new capacities that can contribute to safer and more profitable long term operation of nuclear reactors. These developments relate to virtual reality, augmented reality, mobile devices, wireless systems, innovative instrumentation and the whole field of data science with big data technologies, the development of artificial intelligence... Digitization is a global trend for industries, from aeronautics to car manufacturing. Nuclear is no exception.

2. The issue to tackle and objectives to reach

To reduce O&M costs, the nuclear industry has taken advantage of computer technologies to automate much of its testing and maintenance activities. In particular, the industry has begun to transition from traditional time-directed, hands-on, and reactive maintenance procedures to condition-based, risk-informed, and automated maintenance strategies. This is partly because the current generation of nuclear power plants has passed its mid-life, and increased monitoring of plant health is critical to their continued safe operation. This is especially true now that license renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. Furthermore, many utilities are maximizing their power output through uprating projects and retrofits. This puts additional demand and more stress on the plant equipment such as the instrumentation and control (I&C) systems and the reactor internal components making them more vulnerable to the effects of aging, degradation, and failure.

To enable longer term operation a range of advanced diagnostics methods that are suitable for on-line, continuous, in-plant monitoring over extended time periods (months to years) are being considered. A related issue is then, based on a condition assessment or degradation trend, to have the ability to estimate the remaining useful life of components, structures and systems based on the available condition information. Such tools can rely on usual physical-based principals or more innovative artificial intelligence processes, these latter using mostly big data technologies. Integration of these diagnostics and prognostics technologies into the plant instrumentation and control system are necessary for safe longer term operations. The use of such diagnostics and prognostics technologies is a part of the philosophy of proactive management of component lifecycles that is becoming important for life management and extension.

Continuous plant assessment through on line monitoring (OLM) will enable plants to identify a degrading instrument or process in real time, rather than wait until the degradation causes a loss of function or proceeds to a failure. As a result, plants can focus maintenance activities where they are most needed, plant trips can be reduced, maintenance schedules can be optimized, and plant outages can be shortened.

Structural degradation, whether engendered by inherent material aging due to the environment and service loads (fatigue, corrosion, radiation etc) or by unpredictable external events (earthquakes, hurricanes, bird impact etc), is an inevitable part of life. Conventionally, the continued reliability of structural components has been ascertained through non-destructive inspections carried out at preset intervals. This approach is currently giving way to the concept of Integrated Structural Health Management to minimize the possibility of catastrophic failure of safety-critical structures. The ISHM approach includes initial assessment of a structure, followed by continual non-intrusive in-service assessment of the structure using on-board sensor systems, and intrusive off-line inspections and repairs as necessary when structures are close to failure. The ISHM approach requires integration of several emerging and some mature sub-fields of science and engineering: sensors, smart structures and materials, damage and failure mechanics, structural and reliability analysis, and non-destructive evaluation. ISHM represents a shift away from routine inspections, which are currently scheduled based on statistics obtained on similar structures, to inspections that are scheduled based on the actual state of the structural health of individual structures. This is expected to lead to improved safety and result in increased efficiencies in terms of reduced cost of inspections, and minimized disruption.

It is the management of materials issues that will ultimately determine the safe operating life limits for a nuclear power plant. Since the start of plant operation for the current light-water reactor (LWR) fleet, new degradation processes have appeared.

3. What is done/exist already, who is doing what, what are the means

To address these issues, various national and international programs have been initiated and major reports and databases developed by both regulators and industries. The international community has also focused on the issues with the IAEA's PLiM, OECD-NEA's Committee on the Safety of Nuclear Infrastructure (CSNI), European Groups through the NUGENIA association and EURATOM program, the Materials Aging Institute (MAI) in France, PMMD Programs in Japan and Korea, and related work in a number of other countries that are all recognizing the challenges faced in extended LTO for NPP.

The past collaborative projects (too many to be listed) have been structured along three main paths:

a- Projects aiming at providing laboratory tests results regarding various degradation mechanisms in order to construct empirical trend curves to support the engineering decisions.

b- Projects aiming at analysing in-service or surveillance programs from various decommissioned or operating reactors both to complemented and to verify the databases created in (a)

c- Recently, some projects have been initiated to use the existing experimental knowledge to formulate predictive models for a specific degradation mechanisms.

However, only very few projects are now on going to apply the existing knowledge to develop in-service monitoring strategies and/or to predict the residual life time of some safety related components.

Example: Recent European projects that are partially funded by the EC- Euratom programme (type according to the above definitions:

Acronym/type	Project title	Status
LONGLIFE/a,b	Long-term irradiation embrittlement effects in RPV safety assessment	finished
MULTIMETAL/a	Structural performance of multi-metallic components	finished
PERFORM60/c	Prediction of the Effects of Radiation For Pressure Vessel and in-core Materials using multi-scale Modelling – 60 years foreseen plant lifetime	finished
STYLE/a,b	Structural integrity for lifetime management – non-RPV components	finished
ADVANCE/a,b	Ageing diagnostics and prognostics of low-voltage I&C cables	finished
ACCEPPT/a	Ageing of concrete and civil structures in nuclear power plants	finished
MAPAID/a,b	Modelling and Application of Phased Array ultrasonic Inspection of Dissimilar metal welds	finished
McSCAMP/a	Minimising nuclear component Stress Corrosion Cracking	finished
ASATAR/a,b	Development and Analysis of the Suitability of Accelerated Testing methods for Assessing the long term Reliability of environmentally assisted cracking of nuclear components	finished
REDUCE/b	Justification of Risk Reduction through In-Service Inspection	finished
AGE60+/a,b	Applicability of ageing related data bases and methodologies for ensuring safe operation of LWRbeyond 60 years	finished
MICRIN+/a,b	MItigation of CRack Initiation +	finished

ADFAM/a	ADvanced FAtigue Methodologies to optimize fatigue assessment of critical components	finished
MICRIN/a,b	MIitigation of CRack INitiation	finished
COMRAD/a	Comprehensive investigation of performance of computed and digital radiography	finished
CIIDS/a,b	Crack Initiation by IASCC due to Dynamic Straining	ongoing
SOTERIA/a,c	Safe long term operation of light water reactors based on improved understanding of radiation effects in nuclear structural materials	ongoing
INCEFA+/a,c	INcreasing Safety in NPPs by Covering gaps in Environmental Fatigue Assessment	ongoing
MUREC/a,b	Pilot study on mutual recognition of inspection qualifications between countries	ongoing
ADVISE/a,c	Advanced Inspection of Complex Structures	ongoing
ATLASPlus /a,c	Advanced Structural Integrity Assessment Tools for Safe Long Term Operation	ongoing
GUSIP /b	Guidance on the USability of a Inspection Procedure	ongoing
T&M CABLES/a,b,c	European Tools and Methodologies for an efficient ageing management of nuclear power plant cables	ongoing
NOMAD/a,b	NDE System for the inspection of operation-induced material degradation	ongoing
CORTEX/a,c	Non-Intrusive Core Monitoring Techniques Relying on Inherent Reactor Dynamics	ongoing
MEACTOS/a	Mitigating EAC Through Optimization of Surface Condition	ongoing

4. What can be done to improve/accelerate, ia through cooperation:

The components, systems, and structures in NPPs are in general categorized in two classes: active or passive. Active components are managed under a maintenance rule, and this covers items such as pumps, motors, valves, and compressors. Passive components, which include the reactor pressure vessel, piping, core internal components, the containment structure, and cables, are managed using in-service inspections (ISI) performed in the context of an aging management plan (AMP). Degradation found under an ISI program is managed through mitigative actions, changes in designs, and repair or replacement of degraded components. This reactive, *find and fix*, approach has maintained the safety of operating reactors but it is becoming increasingly expensive as plants age. Attention is now moving to consider the potential for more proactive management of both active and passive components.

For passive component assessment, researchers have investigated NDE technologies that are sensitive to degradation precursors due to mechanical fatigue, thermal aging, and radiation effects. Most research to date has resulted in empirical relationships between precursor phenomena and NDE measurement parameters. More work is needed to fully understand the separate effects of multiple microstructural phenomena on NDE signals and to develop physical models correlating microstructural changes, induced by aging, to macroscopic NDE measurements.

Quantification of uncertainty through the measurement and prediction process is essential to bounding the confidence of diagnostic assessments and RUL predictions. Uncertainties are associated with the NDE measurements, interpretations of the degree of damage, stressor history, future stressors, and the models used to integrate factors and extrapolate and bound predictions moving forward in time.

The development of ruggedized sensors for NPP environments is key to the successful deployment of online surveillance technologies. Not only must sensors survive, but they must exhibit robust behaviour while exposed to stressors for periods of several years or decades. Excellent tolerance to thermal stress is required for sensors assigned to monitor pressure boundary components while sensors for internal component monitoring require an even higher tolerance to temperatures and radiation effects.

The what and how to measure questions remain only partially answered, as does the issue of the number and location of the sparse network of sensors to be used for monitoring degradation in passive components. Strategies are still needed to optimize placement of sensors. Such placement could be informed by expert opinion and/or the results of a risk-based analysis. As the number of sensors grows larger, data management and wireless implementation becomes important, particularly with regard to power needed for sensor operation and data transmission to a monitoring and analysis location.

Data fusion is also needed to form more holistic condition metrics at the system level from data obtained by multiple measurements. Components with complex architectures, such as cables, are most illustrative of this need. It is also likely that combined measurements can enable more complete condition indications for concrete and metal components as well. Methods to meaningfully combine stressor information with damage characterization are also needed to facilitate stressor-based prognostics.

In particular, artificial intelligence based prognostic tools should be developed and tested to assess their performance and complementarity with more traditional monitoring approaches. A prerequisite is the development of a comprehensive database gathering useful NPP online measurements as well as outage control results.

5. Plan of Actions and necessary means

An effective ageing management of systems, structures and components (SSCs) is a key element in plant life management (PLIM) for the safe and reliable long term operation (LTO) of NPPs. PLiM can be defined as the integration of ageing and economic planning for the purpose of maintaining a high level of safety and optimizing plant performance by dealing successfully with extended life ageing issues, maintenance prioritization, periodic safety reviews (PSRs), education and training,

- LTO 60 years and beyond

The LTO for 60 years and beyond necessitates a consistent PLiM programme that includes technical and economic assessment to:

- Maintain a high level of safety;
- Optimize the operation, maintenance and service life of SSCs;
- Maintain an acceptable level of performance;
- Maximize return on investment over the service life of the NPP;
- Provide NPP utilities/owners with the optimum preconditions for achieving the desired LTO.

Although each country and each reactor technology may have its particular needs and LTO justification methods, they can be classified in three main categories:

- The PSR method, which is typically used in Member States with unlimited or continuing licences;
- limited term licence and a licence renewal concept;
- A combination of the previous two approaches.

In all cases, the preparation for an LTO permit application, implies the conduction of a thorough ageing management review to establish the current state of critical SSCs and their usage factor for fatigue assessments, in order to determine their fitness for prolonged service to the end of the LTO permit duration.

The PLiM analyst needs to look into the past history of the SSCs, making use of all available records, including those generated by on-line monitoring and diagnosis systems, wherever available. On-line monitoring systems, if selected and set-up for the purpose, can provide a precise record of any deviations from the SSC technical specification by recording changes in parameters and variables, such as peak values, Fourier spectra, vibration residues, critical speeds and chemistry values, among other things. Monitoring can also provide information on the ageing assessment of SSCs, such as pressure boundary leak tightness, number and entity of pressure and thermal transients and functional anomalies in components. Monitoring systems can also provide information on unaccounted stressors and interference with the functionality of systems and components, including cases such as the inadvertent introduction of loose parts. Data, in the most advanced on-line monitoring systems, are post-processed, and recommendations are automatically issued to help operators optimize the planning of maintenance activities and, in special cases, design upgrades and system improvements can be suggested. On-line monitoring systems allow analysts to follow and trend the equipment behaviour and provide meaningful data for an LTO feasibility analysis.

Monitoring systems should be in place to reliably follow the SSC ageing process caused by known degradation mechanisms, including:

- Irradiation embrittlement (particularly reactor internals);
- Creep;
- Corrosion (water chemistry control);
- Wear;
- Flow accelerated corrosion and environmentally assisted corrosion, wall thinning of housings and piping (on-line detectors);
- Elasto-plastic thermal deformation phenomena.

Other parameters that need to be monitored include vibrations and thermal stratification (thermocouples and dilatometers).

Special attention should be paid to stress corrosion cracking of steam generator tubes from the safety and economic point of view for LTO. Critical components with perhaps difficult access, such as certain

RPV base metal sections, reactor supports and reactor structures and other components not included in normal ISI programmes, such as buried pipes and underground pipes, should also be included in ageing evaluation for LTO following best international practice and taking into account operations feedback, possible special design requirements and assumptions.

The main challenge is to develop multi-scale and multi_physics methodologies that take simultaneously into account the load history experienced by any and each critical component during its previous service lifetime and all known and properly assessed ageing induced degradation mechanisms to predict the reliability limits of any components under flexible operating conditions.

Ageing of materials of passive systems and structures

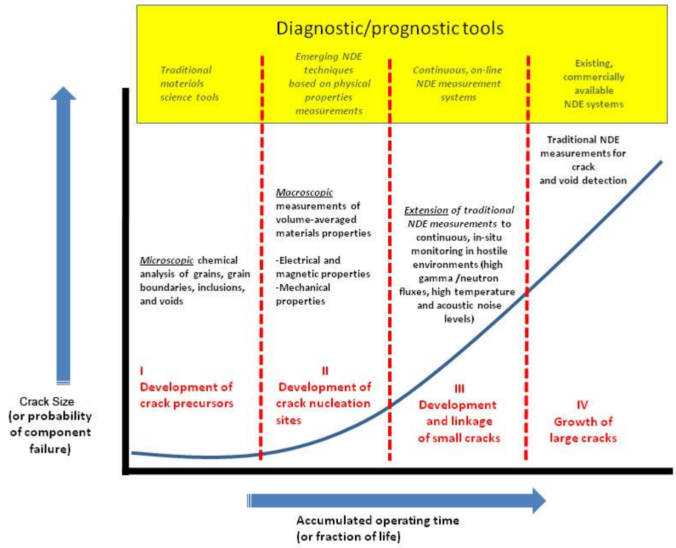
a) Monitoring early degradation in metals

Degradation in metal components in its early stage is characterized by development of crack nucleation sites and then small cracks, which are below the size for which current NDT is sensitive. Laboratory techniques, including optical methods and those using potential drop, can be used to study crack initiation. In deployed systems, inspection sensitivity to degradation in its early stages could lead to improved state awareness by increasing the probability that degradation phenomena are identified with sufficient time for planning and implementing corrective action. Earlier knowledge of degradation also has the potential to provide plant staff with greater flexibility in responding to degradation indications, and the opportunity to avoid a failure or leak rather than merely delaying or mitigating its negative effects.

The four stages in the evolution of aging degradation in passive components illustrated in Fig. 2, together with an assessment of the maturity of technologies suitable for their detection. Traditional NDE technologies are only sensitive to the most severe stages (stage IV) of degradation while the early degradation (stage I) is typically observable only using traditional tools of material science. The need is to investigate phenomena between these two extremes and provide field deployable technologies that are sensitive to “early” degradation (stages II-III).

The development of methods sensitive to the phenomena of degradation at early stages first requires the identification of suitable observables that correlate with changes in material condition. Such changes could be local changes in electrical, mechanical, or thermal properties that “localize” before initiation of a macro-defect, which could become metal loss or a crack. For example, gradual loss of fracture toughness may result from generation of dislocations and voids preceding failure due to mechanical-, thermal-, or irradiation-induced phenomena. To be useful from a plant aging management perspective, precursors should be detectable and quantifiable using non-invasive measurements. This may be achieved by understanding and linking the underlying microstructure property changes to measurable bulk material properties (elastic, magnetic, and electrical). Material aging can be manifest at the microstructural level in several ways. Examples include changes in dislocation density, grain size/orientation/shape, precipitation of second phases, and others. The influence of such microstructural phenomena on measurable bulk mechanical properties has to be assessed in details.

One of the challenges then becomes detecting and characterizing small local changes from among natural variability in a nominally homogeneous material using a modest number of sensors to interrogate critical regions. This challenge can be thought of in terms of determining what to measure, how to measure it, where to measure it, and how many measurements to make, all using sensors and instrumentation that will not be significantly impacted or degraded by the operating environment (temperatures, radiation, and chemistry) during extended periods. In addition progress has to be made regarding the on-time analysis of the huge amount of data yielding from the automatic and in-situ measurement of all implemented sensors.



Evolution of material degradation and correlation with damage measurement technologies

b) Primary containment structures

Typical safety-related concrete structures contained in LWR plants may be grouped into four general categories: primary containments, containment internal structures, secondary containments/reactor buildings, and other structures. Primary containment structures, in particular, have significant safety responsibilities including serving as a final barrier to the release of radionuclides, providing protection from severe external anomalies such as missile attacks or natural disasters, and also providing shielding for the external environment from radiation. As a consequence, primary containment structures must satisfy functional requirements for structural integrity and leak tightness. It is necessary to understand the relevant aging mechanisms, their impact on the lifetime of the NPPs, and the adequacy of aging management plans for discovering and mitigating the effects of primary containment degradation.

A variety of phenomena can compromise the functional integrity of concrete structures, including aging degradation, collapse of soils under the raft of the nuclear island which impacts load distribution, seismic activity, and long-term or transient fluctuations in pressures and temperatures during an incident. Leak tightness can be compromised by degradation of welds and seals at joints or through-thickness corrosion of liner plates. Structural integrity is impacted by many forms of degradation associated with both the cement-aggregate mixture and supplemental metallic hardware. The porosity and permeability of the concrete significantly influences susceptibility to degradation through impact on transport of moisture and chemical species through the interior of the member. Degradation of the cement-aggregate mixture can occur by chemical or physical attack, which is ultimately manifest as cracking and loss of strength. Some forms of chemical attack include alkali-silica reactions, carbonation, and sulphate attack. Examples of physical attack include freeze/thaw cycles, shrinkage, creep, and drying. Corrosion of metallic hardware embedded in the concrete can lead to cracking in the concrete. Loss of tension in the tendon system is a concern associated with prestressed containments and can occur by shrinkage or creep of the concrete, tendon relaxation, or corrosion of tendon cables and anchorage hardware.

Structural assessments of concrete containments are normally performed through NDE and destructive mechanical and chemical analysis of core samples. The heterogeneous nature of concrete containments and variety of degradation mechanisms requires the application of diverse techniques to obtain a holistic assessment of structural integrity. Some issues associated with concrete inspections are associated with access. Examples include sections that are below grade or thick concrete members such as the basemat, which is also heavily reinforced. The real-time information provided by the instrumentation gives operators a significantly greater state awareness.

For new plants, there is increased interest in the use of embedded optical fibers to continuously monitor the condition of concrete structures. Guided ultrasonic waves have been the focus of efforts to inspect embedded portions of concrete containment liners, and researchers are increasingly investigating GUW techniques and AE as a means to monitor strain in prestressed tendons, as well as reinforcing steel for signs of corrosion and delamination. Diffuse ultrasonic fields are under investigation for detection of damage in the heterogeneous cement – aggregate mixture.

c) Cable condition monitoring

Cables are a part of power, instrumentation, control, and communication circuits in NPPs and are essential to both normal and post-accident plant operations. Thousands of kilometers of cables, of a variety of classes, are routed throughout NPPs. Most cables were selected and tested to have a nominal 40-year life. However, LTO is now seeking operation to 60 and even 80 years. In many cases, cables are difficult and expensive to replace. It has even been suggested that it is the economics of cable replacement that could be the determining factor in the economic assessment for the feasibility of plant LTO.

The main components of an I&C or low-voltage power cable include the conductor(s), electrical insulation, shielding, and outer jacket. Typical cable architecture consists of one or several conductors individually wrapped with electrical insulation and bundled inside of a protective jacket. Single conductor cables will consist of the components listed above while multiple conductor cables will also include extra filler material between individual conductors to constrain the movement of individual conductors within the jacket. The cable insulation and jacket components are normally composed of polymeric materials. Common insulating materials include cross-linked polyethylene (XLPE), ethylene propylene rubber (EPR), ethylene propylene dimonomer (EPDM), and polyvinyl chloride (PVC). Common jacket materials include neoprene, hypalon (CSPE), and PVC. The polymeric materials will often contain protective additives (i.e., anti-oxidants, thermal stabilizers, fire retardants).

The aging degradation of a cable will be governed by the polymeric system, environmental conditions, and the time scale for which age-inducing stressors are applied. Exposure to high temperatures, moisture, and radiation are key aging stressors for cables. Polymeric insulation and jacket materials can become embrittled with sufficient exposure to high temperature and radiation while moisture intrusion can reduce the dielectric integrity of the cable. Exposure of cables to boric acid and mechanical vibration are also potential aging factors. In addition to the main cable body, splices and connectors can also be potential locations for degradation and failure.

Localized degradation (“hot spots”) can disrupt the function of the entire cable. Thus, consideration of cable architecture, connectors, potential environmental stressors, hot spot phenomena, and the desire to perform measurements in situ impose a complex set of requirements on cable condition monitoring systems. Condition assessment techniques are generally visual, mechanical, chemical, or electrical in nature. Visual, mechanical, and chemical techniques can provide detailed characterizations of damage but are often localized or destructive in nature. Further, in situ evaluations in extreme environments, such as within containment, are unlikely if sampling requires direct human interaction. Electrical techniques can sample larger sections of cable, they are nondestructive, and some techniques can be performed online. However, electrical techniques are most sensitive to damage in the conductor and are limited in their ability to characterize damage prior to a failure that impacts electrical function. The application of several condition monitoring techniques is often necessary to form a comprehensive assessment of cable condition. Thus, efforts should continue in the development of in situ online cable monitoring tools that are able to provide a more holistic assessment of cable condition.

- Inspection and on-line monitoring

Long term sustainability of SSCs in the existing fleet of operating reactors requires implementation of regular ISI and repair strategies. The purpose of periodic inspections, performed either during refueling outages or during unscheduled shutdowns, is to assess the health of critical SSC to ensure safe operation through the next cycle. This is commonly done by implementing appropriate non-destructive testing (NDT) procedures for inspection of passive components such as steam generator (SG) tubes, reactor pressure vessel, and reactor coolant system piping. A variety of conventional NDE methods are employed for ISI of plant SSC. Some prominent inspection techniques include remote visual/video testing, eddy current testing, magnetic flux leakage measurement, radiography, infrared thermography and acoustic/ultrasonic testing. In the nuclear industry, these and several other methods are employed on an application specific basis. Ultrasonic based NDE, for example, is routinely used for inspecting the structural integrity of the RPV, reactor coolant system piping, and welds. Eddy current testing on the other hand is more widely employed for ISI of SGs. A number of promising NDE technologies are emerging and may potentially be employed for in-situ inspection and ISI of NPP components. Modern NDE equipment has evolved significantly over the past two decades as a direct result of major advancements in microelectronics and computer technology. Some common features of modern NDE equipment include: *a*) higher degree of inspection automation (hardware and software); *b*) faster inspections through employment of linear and matrix array sensor configurations; *c*) increased accuracy and quantification capability; *d*) greater penetration depth and higher spatial resolution; *e*) more flexible and modular tools allowing incorporation of multiple sensors in the probe assembly; *f*) more compact systems (integrated inspection units for rapid deployment); *g*) rugged probes for operation in harsh environments (elevated temperature and pressure, radiation, moisture, and corrosive media); *h*)inspection techniques that are less affected by the surface condition of components.

In contrast to NDE, on-line monitoring (OLM) is the process of continuously monitoring or interrogating a system or component for degradation. It is worth noting that OLM is a more familiar terminology for the nuclear industry, whereas for aircraft, construction, automotive, and other industries the corresponding terminology is structural health monitoring (SHM).

The principal advantage of OLM compared to NDE is that the former is done in-situ and in a near-continuous or real time basis. A typical OLM system consists of networks of sensors which are permanently attached to a component or structure to monitor its condition over time. Because of this requirement, OLM/SHM techniques are often referred to as embedded NDE techniques. Both conventional OLM and NDE tools can only infer the state of the structure at any given instant of time. Whereas, the remaining life of the structure has to be estimated using a suitable predictive system. Merely identifying degradation through NDE or OLM does not necessarily imply that the part cannot survive the remainder of its design life. Additionally, economical constraints are always factored in when making decisions about repair and replacement.

Predicting the remaining life of a component in advance will minimize the probability of any major failure before suitable repair or replacement can be performed. The economy and safety of NPP components can be improved by accessing the remaining useful life of a component in real time and accordingly alerting the plant operator. This can be achieved using online prognostics (OLP) or a condition based life prediction system. OLP of structural components is an active area of research and development particularly for complex and expensive systems such as aircraft, spacecraft, and nuclear reactor SSC. For example, NASA has started an integrated vehicle health management program aimed at developing condition-based life prediction tools. Research on condition-based life prediction for NPP components is also becoming more prevalent.

An OLM-OLP system is used to estimate the current degradation in a structure and then predict its remaining useful life. The OLM system estimates the current degradation or state of the structure while the OLP system forecasts the remaining life of the structure.. The OLM system estimates the damage in real time using advanced signal processing algorithms and data management schemes whereas the OLP system predicts the future damage (or remaining life) using advanced mechanistic and probabilistic based forecasting models.

There are different attributes to address when designing an effective OLM system. Those are:

- *Sensor selection:* The first step is to match the OLM sensor to the component that is being monitored. For example, OLM sensors can be broadly divided in to two categories: active and passive. Active OLM sensors generally use a deterministic fixed input signal that is transmitted into a structure using an actuator. The corresponding sensor signals are analyzed to determine the presence of damage in the structure and estimate its type and severity. Piezoelectric ultrasonic transducers can be considered as an example of an active OLM sensor.
- Passive OLM sensors on the other hand do not require any actuators since they infer the state of the structure using the environmental or operating conditions of the structure to provide the input to the sensor from which the system response is then inferred. Vibration and dynamic strain sensors are some examples of passive OLM sensors.

In general active OLM sensors are more suitable for passive SSCs such as RPV and stiff RCS piping. Conversely, passive OLM techniques are more suitable for active SSCs including systems with moving or rotating components such as pressurizer, coolant pumps, and valves. When selecting a particular sensor type, it is further necessary to consider the requirements on the size of the defect to be detected. For detecting small cracks, it is almost always advantageous to select an OLM sensor with the highest possible frequency. Active OLM sensors (e.g., ultrasonic transducers) can be further divided based on the type of input signal such as narrow band or broadband inputs. In general, signal processing of a broadband input is more complex than the narrow band input because of the complex nonlinear mode mixing of signals. However, broadband OLM/SHM systems in general excite multiple smaller damage features (e.g. dislocations, vacancy, etc.) and hence are more helpful for detecting small changes associated with those features.

Thus, selecting the proper signal processing strategy is one of the principal challenges of the OLM system design. In particular, extracting information associated with a very small damage feature and that has been acquired in a real-life, noisy operating environment is a highly challenging task. Whether it is ultrasonic, electromagnetic, vibration or strain signal, a suitable technique is required to extract damage sensitive features from the time-series sensor signals. There are usually statistical features of the signal that are implicitly related to a change in physical behaviour of a structure. In fact, the SHM or OLM problem is fundamentally a statistical pattern recognition problem.

There are different functions that the OLM system should perform to assess SCC degradation such as damage detection, damage classification and damage quantification. The system must first detect when damage has initiated. This can be determined by statistically comparing the signal distribution from healthy structure with that from damaged structure. Once it is estimated that damage is present, the OLM system has to classify what type of damage it is. Finally, the OLM system is required to quantify damage. This can be achieved either by using supervised or unsupervised damage estimation techniques.

An OLM system may consist of a single or multiple sensor nodes. Each sensor node may consist of a single or multiple sensors. Also, individual sensor nodes may consist of identical or different types of sensors. Extracting useful information from multiple sensor nodes and heterogeneous sensors is always a challenging task. Information fusion and cognitive decision science tools can be used to extract information from multiple sensor nodes and heterogeneous sensors. These tools are becoming increasingly popular in structural health monitoring applications. In addition, OLM sensors typically generate large quantities of data which increases the cost of data transfer and storage. “big data” treatment strategy has presented itself as a candidate solution for directly collecting relevant information from sparse, high dimensional measurements. This type of technique can be used in OLM system design to alleviate the problem of large volume of sensor data.

In addition to assessing the current state of a structure through automated OLM, it is also necessary to estimate the remaining life of structural components in real time. Currently, the life of NPP components are estimated by using empirical trend curves or by integrating the damage growth rate obtained from simulated reactor condition tests. The remaining life of a component depends primarily on the microstructure, the loading environment (i.e., temperature, pressure, water chemistry, etc.) and the initial damage condition. The methods mentioned above are highly empirical and based on laboratory test data which may not always accurately simulate the field environmental loading conditions. In addition, the real SCC may not share the exact material alloy and processing as the laboratory specimen. Also, the initial condition for empirical or fitted models are commonly based on the design requirements and based on the field conditions estimated by NDE during periodic ISIs. As cracking may initiate in between the scheduled ISIs, the lack of information about the initiation time could result in inaccurate prediction of the remaining useful life of a component or system. Through the use of OLM systems, the possibility exists to overcome some intrinsic limitations associated with periodic ISIs. By assessing the real-time degradation state obtained with an OLM system with a predictive model, the remaining useful component life can be estimated in real-time.

These online prognostics (OLP) system have to work in conjugation with an OLM system. The OLP system can be also be coupled with real-time measurements of the process parameters (e.g., temperature, pressure, flow, level, vibration, leak, valve position and coolant chemistry) to reduce the uncertainty of forecasting remaining component life.

The OLM-OLP system essentially consists of an OLM system and a predictive model. The function of OLM model is to estimate the state of the structure in real-time based on the sensor measurements. Once the current state is estimated, the information is assessed using the predictive system. As such, the OLM-OLP system will predict a deterministic remaining life. However, due to micro structural material variability, loading and environmental variability, and other random factors, the damage trend curves have rather substantial uncertainty. Thus, “first principle” accurate models shall be developed to allow for interpolation and extrapolation to stringent conditions.

Although the initial OLM-OLP system implementation can be started with the most likely and critical SSC locations like dissimilar metal welds, their application could be expanded to other systems and ultimately for fleet-wide implementation. Nevertheless, rigorous performance demonstration programs need to be implemented and new codes and regulatory guidelines may need to be developed before this technology can be widely implemented by the nuclear power industry.

An extension of this approach is the so-called « Digital-Twinning » that consists on the clowning of a specific physical component by an appropriate numerical model that uses exactly the on-line gathered measurement results made on this component. This so-build model is used to perform in depth studies for predictive assessment of the residual life time of this component. The development of these digital twins is a technological challenge with high added value to reduce the costs of operation and maintenance of many critical components in the existing and future NPPs.