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Work Package 7 – Non-destructive examination and materials health monitoring (RL4)

Deliverable D7.1 – D7.1.1. Research Line 4 contribution to the call preparation: scope, expectations, expected impact, KPIs

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List of abbreviations

NPP	nuclear power plants
NDT&E	non-destructive testing and evaluation
SHM	Structural Health Monitoring
INHM	intelligent materials health monitoring
n-MAPs	nuclear materials acceleration platforms
AQPs	accelerated qualification path

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Summary

This deliverable outlines the objectives and scope of Research Line 4 of the CONNECT-NM Open Call for Projects, focusing on non-destructive testing and materials health monitoring (NDT&E) for nuclear power plants (NPPs).
Continuous in-service inspection and NDT&E are vital for ensuring the safety, reliability, and longevity of materials and components throughout their lifecycle, from development to maintenance, repair, and recycling. This research aims to develop intelligent materials health monitoring (IMHM) systems, utilizing advanced sensors, AI, and multi-parameter approaches to monitor material degradation in real-time and predict component lifespan.
Key goals include enhancing monitoring techniques to track the condition of materials and components in situ, integrating sensors with digital twins, and improving predictive maintenance through data-driven models. Projects will focus on optimizing NDT&E technologies, developing adaptive sensors, and applying machine learning to predict material behavior. They must also consider reliability, uncertainty, and operational conditions such as temperature and pressure cycles, and radiation exposure.
Expected outcomes include reduced maintenance costs, improved safety, and better management of NPPs' operational lifespans.
Success will be measured through Key Performance Indicators (KPIs) such as the development of IMHM systems, accuracy of predictive models, reduction in maintenance costs, and the creation of scientific knowledge regarding material degradation under extreme conditions.

Introduction

Continuous in-service inspection for existing and future NPPs is a powerful tool in support of a high level of safety and reliable operation. Non-destructive testing and evaluation (NDT&E) can in fact contribute to all stages of the product lifecycle, starting with the development of materials and products, but covering also their maintenance, their repair, and finally their recycling where feasible. In this context, future NDT&E needs to include also sensors suitable to capture production-related microstructural patterns and to merge them in the sense of an individual fingerprint, a so-called 'product DNA', deposited in 'digital product files'.
Consistently, this research line shall define, develop and optimize multi-parameter approaches for the non-destructive characterization of the material degradation in materials and components for NPPs, thereby enabling the capture of (macro- and microscopic) material properties (material DNA) right from the start of its development, until its end-of-life.
This document outlines the scope, objectives and expectations that should be complied with by the proposals submitted in answer to the CONNECT-NM Open Call for Projects for what concerns Research Line 4, focused on Non-destructive examination and materials health monitoring. This description enters the work programme of the Open Call and can be used by potential proposers as a guideline to elaborate Project proposals. The document also specifies the KPI that will be used to evaluate the success of the Research Line, to which the Projects proposed should contribute.

Scope and objectives

Monitoring the degradation of nuclear materials is essential for managing component lifespan safely. Thus, it is crucial to monitor and assess the actual condition of products, components and materials, and to implement smart maintenance and repair functions, ideally at the level of individual products or components. Autonomous repair systems often use sensors to detect changes in the material's condition through physical principles or mechanical deformation. The unique feature of NDT&E methods is their ability to detect and evaluate continuously the progressive change of the material properties of the same specimen or component, in situ and/or in operando conditions. Advanced sensing techniques and the smart exploitation of this data, including distributed sensor networks and embedded microsensors, enable real-time monitoring of the material's condition. However, in the nuclear energy sector, NDT&E has traditionally focused on defect detection during periodic inspections, missing its full potential of being integrated into the design and manufacturing processes. Lessons learnt in the area of NDT&E reveal that:

- NDT&E can contribute to all stages of the product lifecycle, starting with the development of materials and products and then covering also their maintenance, their repair, and finally their recycling, where feasible.
- Continuous in-service inspection for existing and future NPPs is a powerful tool in support of high level safety and reliable operation.
- Structural Health Monitoring (SHM) using permanently installed sensors offers clear benefits as a complement to traditional NDT&E techniques, including easier and safer operations, reduced inspection time and costs, and the potential for more frequent or continuous monitoring, which facilitates predictive maintenance.
- Combining ageing models with physics-based and data-driven models (i.e. based on machine learning), thereby creating digital twins for materials and structural components, to be updated via sensor measurements, will enable enhanced diagnostics and prognostics.

- Digital twins based on the idea of accessing actual operating data, to continuously improve their capability of tracing the evolution over time of materials and components, are expected to improve NPP safety, providing support for selection process, reducing the costs and enhancing the lifetime of nuclear components.
- Inspection-oriented material and component design has to be considered from the beginning of the lifecycle, to enable replacement of components or retrofitting.

For this to be achieved, it is essential that materials and components must be easily characterised by using NDT&E techniques.

Systems that combine continuous and capillary SHM with digital twins, based on which suitable interventions of component repair or replacement can be timely planned to guarantee safety, are denoted as intelligent materials health monitoring systems (IMHM systems). These systems can improve performance of structural or functional components and products, combining longevity and efficiency.

In this context, this RL of CONNECT-NM aims to develop IMHM systems to evaluate parameters related to the micro- (defect location, density, size) and macro-structural state (mechanical properties) during service. It will also consider operational factors (such as temperature and pressure cycles, irradiation parameters, mechanical loading etc.) through continuous inspection. By using cognitive sensors, the RL seeks to improve estimations of the operational lifetime of nuclear power plants and support materials development and qualification.

Expected results

Projects in this research line are expected to contribute to develop IMHM systems, based on innovative AI-supported multi-parameter approaches for NDT&E of degradation in materials and components for NPPs. Proposals should focus on the operation phase of specific components or materials of future NPPs and provide a strategy towards the development of the corresponding IMHM. Since the development of robust technologies capable of determining in-service material performance will depend on model accuracy and data reliability, proposals shall consider collecting experimental reliable key data captured under realistic operation conditions. All Projects shall include reliability and uncertainty studies, considering initial non-degraded microstructure, material variability, and other influencing factors. Multidisciplinary proposed Projects shall address at least two of the following aspects, preferably addressing next generation nuclear systems for one of the materials classes of interest:

- Development and optimization of cognitive auto-adaptive sensor to understand the physical mechanisms affecting material properties in operation: thermomechanical fatigue, radiation-induced ageing, swelling, creep; corrosion and stress-corrosion cracking/dissolution/erosion in contact with heat-transferring fluids or due to solid-solid contact; creep; various concrete degradations; fuel assemblies degradation etc
- Development of multi-parameter/multi-NDT&E-method-monitoring technologies, which fulfil requirements of NPP operational conditions and support customised maintenance and repair plans, extending component lifetime economically and environmentally.
- Application of enhanced statistical analysis, machine learning algorithms, or artificial intelligence to select relevant data, instead of ‘blind’ big data

analysis, allowing sensors to decide which information is relevant and supporting monitoring tools for predictable materials degradation (mechanical and/or environmental).

- Advanced data fusion, interrelation of data generated by different NDT&E methods and machine learning-driven decision-making techniques can then be leveraged to enable the system to not only monitor the state of individual structures, but also to infer about their interdependencies and, thus, the evolution of the system as a whole.
- Analysis of the fault tolerance of the machine learning-driven decision-making techniques and development of embedded methods for indicating or even for qualifying the reliability of the outputs, as instrumental for human-free operation.
- Development of protocol(s) for training, testing and especially validating machine learning-driven decision making techniques that can increase the transparency of the machine learning applications in safety areas and can serve as a basis for future industrial standards and rules.

Expected outcome and impact

Projects in this RL are therefore expected to demonstrate their high added value in industrial nuclear applications, in terms of increased safety and cost reduction, in particular for better estimation and management of the operational lifetime of NPPs and their components, while providing a feedback/input to models and design rules, which can be in turn improved. NDT&E techniques are also expected to contribute to the development of n-MAPs (RL2) and AQPs (RL3).

While focused only on the operational phase, Projects should describe how the techniques developed for the operational phase of a specific component could be applied on other segments or even on the whole component lifecycle, thereby increasing safety and sustainability, including economic sustainability, of nuclear energy as a whole. Projects should describe pathways to:

- enable the capture of a variety of material properties right from the start of the component development, until its end-of-life.
- reducing maintenance costs, quantifying the reduction compared to the state-of-the-art.
- assess and validate the longevity of materials, components and products through accelerated testing.
- the traceability of materials information throughout the value chain to identify the possible origins of defects, thanks to the significant amount of *a priori* knowledge that becomes in this way available before each inspection measurement (including multi-scale modelling of structure, and structure vs. properties correlations).

Key Performance Indicators (KPIs)

The Research Line success and the progress towards of the final goals will be monitored using the following Key Performance Indicators (KPIs):

- one developed intelligent health monitoring systems for each of the four selected classes of materials in CONNECT-NM
- one developed intelligent health monitoring systems for each of the four selected classes of materials in CONNECT-NM, applicable for more than one section of the product life cycle
- 8 scientific publications about how the behaviour of the nuclear materials at high temperatures and in conditions of strong degradation (e.g. high irradiation doses, strong corrosive environment), typical in advanced nuclear systems can be non-destructively detected and/or monitored.

In addition, the accuracy of the predictive methodologies based on NDT&E for materials behaviour that should be applicable under an increasingly wide range of operational conditions, will be evaluated to be at least as high as for state-of the art methodologies.

Reference

Section 1.2.1.3. of the Annex I to the Grant Agreement.

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