

Coordination of the European Research Community on Nuclear Materials for Energy Innovation: the research agenda of the CONNECT-NM co-funded European partnership

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Abstract. CONNECT-NM is a recently launched co-funded European partnership that deals specifically with boosting innovation in the field of nuclear materials. It pursues five research lines, dedicated to: (1) knowledge and data management; (2) advanced materials development and manufacturing; (3) materials and component qualification (testing, standardization and design rules); (4) non-destructive examination and materials health monitoring; (5) advanced materials modelling and characterization. The present paper details the methodology and the scientific and technical expected results for each of these research lines, in pursuit of the corresponding five nuclear materials-dedicated end-products, respectively: knowledge organisation system, materials acceleration platforms and advanced manufacturing processes, qualification test-beds and accelerated qualification paths, intelligent materials health monitoring and advanced predictive methodologies. The work to be performed in connection with prioritization of research activities, education and training, access to infrastructures, communication, dissemination and results exploitation is also discussed, together with the expected impact.

1 Introduction

Nuclear power plants (NPPs) play a key role, alongside renewables, in building a resilient and sustainable Energy Union. They help Europe reduce fossil fuel use, achieve lower geopolitical dependence and support the goal of becoming climate-neutral by 2050. According to OECD/NEA¹ projections, global nuclear capacity must at least double, possibly triple, by 2050, to reach net-zero targets [1]. Many countries, including European ones, are actively working toward this goal [2]. Like all technologies, nuclear energy must continue evolving toward greater sustainability. It is in this context that CONNECT-NM (Coordination of the European Research Community on Nuclear Materials for Energy Innovation)

was launched on 1 October 2024. A co-funded European partnership, CONNECT-NM builds on the Joint Programme on Nuclear Materials (JPNM) of the European Energy Research Alliance (EERA) [3,4], the Sustainable Nuclear Energy Technology Platform (SNETP) [4,5] and the preparatory project ORIENT-NM (Organisation of the European Research Community on Nuclear Materials) [6], which developed the relevant Strategic Research Agenda (SRA) [7,8].

CONNECT-NM aims to provide the materials science tools, knowledge and expertise for European countries to:

- maintain current nuclear capacity;
- develop advanced nuclear systems aligned with national priorities;
- enhance sustainability in nuclear energy.

Materials research is central to this mission, as it supports:

- safe and cost-effective long-term operation of existing Gen II and III light water reactors (LWRs);

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¹ Nuclear Energy Agency (NEA) of the Organisation for the Economic Cooperation and Development (OECD).

- design and construction of Gen III+ new builds;
- deployment of small and medium-sized modular reactors (SMRs), of light water technology within the next decade;
- faster, more cost-efficient development of advanced reactors, including advanced SMRs, by 2040.

For instance, intelligent materials monitoring combined with advanced manufacturing help detect damage early and safely and affordably extend component lifetimes. High-performance materials resistant to heat, radiation and corrosion can improve both efficiency and safety, with positive economic outcomes.

However, realizing this potential requires strong innovation in materials science. CONNECT-NM's core goal is to drive innovation in nuclear materials, accelerating the development and qualification of advanced materials and manufacturing processes, while also integrating principles of circularity and sustainability in materials and component management. Improving the ability to predict material and component behaviour in operation, through continuous monitoring and digital tools, is also critical for safe plant management and design. Achieving these advances demands close and effective collaboration between academia, research institutions, industry and regulators across Europe. As a goal-oriented co-funded partnership, CONNECT-NM is the crucible for the creation of a network between all these actors and the tool to produce the required shift of paradigm in nuclear materials, from 'observe and qualify' to 'design and control'. This vision is particularly timely, given that a wave of European nuclear start-ups—backed by both public and private funding—is developing innovative reactor concepts. Most of these designs require either new materials or new ways of producing them, along with integrated health monitoring and digital inspection technologies, while the time available for start-ups to achieve this goal is short. CONNECT-NM can support these innovators by providing access to expertise, infrastructure and standards, helping them accelerate their proof of concept. Similar efforts are in fact underway in the U.S., as well (for instance, the Advanced Materials and Manufacturing Technologies programme [9]).

In this paper, we outline and discuss the objectives of CONNECT-NM and the methodological paths to be followed for their achievements, stressing aspects of scientific and technical novelty, as well as its expected impact.

2 Objectives

2.1 Specific objectives and final products of CONNECT-NM

The ambition of CONNECT-NM is to strengthen safety and sustainability of nuclear energy by promoting innovation in the field of materials. The purpose is to contribute to high safety standards in power generation, while accelerating the process of materials development, improvement and qualification, thereby reducing time-to-market. Its general objective is therefore to nurture

the joint and coordinated exploitation of national competences, facilities and infrastructures in Europe dedicated to research, development and innovation, in the field of nuclear materials, in pursuance of the above-mentioned shift of paradigm. The enablers of this paradigm shift are modern digital technologies, such as machine learning, data analytics, semantic approaches, high-performance computing, block-chain, digital twins and robotics, which are at the core of data-driven modelling, along with high throughput calculations and experiments, advanced manufacturing techniques, as well as (when available) lifecycle sustainability assessment tools. Table 1 shows the specific objectives of CONNECT-NM, organized according to its research lines. The same table also shows the final products targeted in CONNECT-NM, which are better defined below. Importantly, except in rare cases, none of these exist yet for nuclear materials, and often not for nuclear technologies in general. They will be progressively developed in CONNECT-NM, so actual examples cannot be provided. Their impact can therefore only be surmised from applications in other technologies.

Nuclear materials acceleration platforms (nMAPs)

A materials acceleration platform (MAP) [10] is an integrated system that leverages automation, artificial intelligence and high-throughput experimentation and calculation to accelerate discovery, development and deployment of new materials. MAPs enable materials to be designed for fitness, safety and sustainability. Advanced manufacturing processes are part of the platform and benefit from it. MAPs are being developed and seeing their first applications for instance in materials for batteries [11,12].

Nuclear materials' test-beds for accelerated qualification

A Test-Bed (TB) is a collaborative, accessible, integrated platform that enables new materials to be tested and validated using shared resources and standardized protocols for accelerated qualification (exposure, characterisation and testing protocols), denoted as accelerated qualification paths, AQP's. An example of a first construction of this type in the nuclear field does exist, on fuel materials [13].

Intelligent materials health monitoring

This is the combination of non-destructive examination and testing (NDE&T) with suitable diagnostics and simulation tools (both physics-based and data-driven), to monitor materials and components, thus enabling the use of digital twins for the optimization of safe component and plant life management along the whole materials lifecycle. An example of a system of this type applied to an out-of-core nuclear component (water pumps) is presented in [14]. The challenge is to extend systematically this approach to in-core components.

Advanced predictive methodologies

These are defined in CONNECT-NM as the blend of physical and data-driven (e.g., machine learning-based) multiscale models, in combination, and possibly dialogue, with advanced microstructural characterisation. The idea behind this definition is that purely data-driven approaches remain largely empirical and do not improve knowledge, while purely physics-based approaches are often limited in their application to real systems, for

Table 1. Specific objectives and final products of each research line in CONNECT-NM.

Research lines	Specific objectives	Final products
Advanced materials development and manufacturing	SO1: To reduce drastically the time required to Improve, develop, and even discover new or advanced nuclear materials and elaborate advanced manufacturing processes	Nuclear materials acceleration platforms and advanced manufacturing processes
Materials and component qualification: testing, standardization and design rules	SO2: To accelerate the qualification of nuclear materials for safe operation.	Nuclear materials qualification test-beds and accelerated qualification paths
Non-destructive examination and materials health monitoring	SO3: To enable safer and more efficient management of the lifetime of nuclear components	Intelligent materials health monitoring systems
Advanced materials modelling and characterization	SO4: To improve the capability of prediction of the behaviour of nuclear materials in operation	Advanced predictive methodologies
Knowledge and Data Management	SO5: To create the conditions for nuclear materials data to be correctly collected and stored, so as to be fruitfully analysed and used	Nuclear materials knowledge organisation systems

instance because they are hampered by the chemical complexity of real materials. The combination of these approaches are expected to improve significantly the possibility of models to be applied to materials of industrial interest. The goal is to enable increasingly efficient and reliable prediction of component behaviour in operation. Physics-based and data-driven methodologies are described for instance in [15,16]. An example of multi-physics model corrected using data-driven techniques applied to the coupling of thermal-hydraulics and neutronics is given in [17].

Nuclear materials knowledge organisation system [18]

This is expected to be a structured framework based on ontologies (semantic technologies [19,20]) and appropriate data formats, respecting both intellectual property rights (IPR) and FAIR (findable, accessible, interoperable and reusable) principles. The goal is to collect, categorize, store, use and disseminate effectively information on nuclear materials to support research, safety and regulatory activities. Knowledge organisation systems applied to materials are currently very rare, often limited to data from specific experimental techniques or modelling methods, largely because of the complexity of materials science techniques and the difficulty of producing the relevant ontologies. The nuclear materials knowledge organisation system candidates, therefore, to be a sort of first-of-a-kind. An example of intelligent semantic industrial data ecosystem dedicated to materials and their manufacturing is given in [21]. Similar technologies have also been used for batteries [11].

2.2 Operational objectives of CONNECT-NM

CONNECT-NM is committed at an operational level to reach a number of objectives, among which:

- apply an open and transparent procedure for the prioritization of case studies, used for the development of the methodologies within each research line, by means of open calls for projects;
- put in place a system of project monitoring and interaction with stakeholders;
- promote access to specific infrastructures, necessary for nuclear material research activities;
- promote high quality and targeted education and training;
- maximise impact, by means of suitable communication and dissemination actions, as well as through the identification of the most effective paths for the exploitation of the results, with the support of ad hoc advisory groups.

3 The research lines of CONNECT-NM

3.1 Knowledge and data management

Methodology

Nuclear materials science produces complex, multidisciplinary data that must be well-managed to support safe, sustainable technologies and enable AI-driven development. This requires a structured system to enable experts as well as non-experts to easily access and manage data, ensuring effective knowledge sharing within the relevant community around materials, models and experiments. Semantic technologies [19,20] play a key role, by enabling an open environment for collaboration and efficient knowledge sharing. Using ontologies, metadata and specialized databases, data can be managed according to FAIR principles (Findable, Accessible, Interoperable, Reusable [22]), while still protecting sensitive information. Semantic systems also allow federated data distribution with a

virtualization layer to improve scalability and reduce fragmentation. Ontology-based Knowledge Organization Systems (KOS) [23] are already widely used in other sectors, for their ability to improve interoperability and minimize data loss.

The primary aim of this RL is therefore to establish a comprehensive knowledge framework for nuclear materials, the Nuclear Materials Knowledge Organization System (NM-KOS). This two-layer framework consists of:

- Nuclear Materials Data Management System (NM-DMS): a lower layer of databases with raw data in appropriate formats;
- Nuclear Materials Knowledge Base: an upper layer that uses semantic technologies, to organize data under FAIR principles for better access and integration.

To succeed, this initiative must integrate diverse datasets and address challenges such as limited incentives for data sharing and the need for FAIR-compliant infrastructure. Specifically, three key actions are needed:

1. expand or create secure databases for nuclear materials data, from properties to models;
2. implement strong data protection and clear policies;
3. develop user-friendly, possibly automated, data upload tools.

With secure, standardized and accessible platforms, NM-KOS will promote data sharing. Its FAIR-compliant design and protective measures will make uploading easier and foster a culture of collaboration in the nuclear materials community. Figure 1 shows the NM-KOS architecture.

Pursued results

This research line will focus on building both layers of the NM-KOS, with a well-documented and functional architecture. Key activities include:

- Database Creation/Expansion: develop or extend databases to store experimental and modelling data in areas like irradiation and characterization, which are relevant for predicting and assessing material behaviour. Projects must involve data-generating organizations (e.g., research centres, companies) and align database design with their needs.
- User-Friendly Interfaces: create intuitive tools for data upload, access and analysis. Data formats should support easy use by non-experts, with each dataset clearly documented and linked to reliable sources. Quality assessment criteria must be included.
- Ontology Development: build a core domain ontology and specific application ontologies for each database, based on the accompanying dataset documentation.

NM-DMS databases should use technologies compatible with graph database virtualization interfaces. The use of established solutions, such as the extendable ENTENTE database [24,25] or JRC's MatDB [26], will make this process faster and more efficient. The latest advances in ontology development will be employed, e.g., EMMO (Elementary Multiperspective Materials Ontology), following the guidelines provided by EMMC (European Materials Modelling Council) and EMCC (European Materials Characterization Council).

3.2 Advanced materials development and manufacturing

Methodology

The timely development of innovative materials is essential to drive nuclear innovation. However, current methods—often based on trial and error—are slow and inefficient. To accelerate progress, a shift toward a “design and control” approach is needed, focusing on materials tailored to specific applications. One promising method is the use of MAPs [10], which combine machine learning, modelling, high-throughput manufacturing and rapid, often non-destructive, characterization. These platforms can quickly screen a wide range of materials to identify those that best meet defined performance indicators. This research line aims to speed up the development of advanced nuclear materials and processes, by creating a nuclear-focused MAP (*n*-MAP). As much as possible, this will be achieved by adapting existing non-nuclear MAPs.

Key challenges include evaluating how manufacturing affects material performance under irradiation and predicting long-term behaviour from a small set of fast-measurable indicators. Advanced predictive tools can help identify valid indicators of this type or integrate measurements with long-term extrapolations. For irradiation screening, charged particles offer cheaper, faster and more flexible alternatives to neutron irradiation, which additionally save the handling of activated materials [27]. These have been long used to try to emulate neutron-irradiation induced damage, but ensuring the results are representative of neutron damage remains a challenge [28].

Finally, advanced manufacturing methods must be fine-tuned to ensure consistent material quality [29]. Applying *n*-MAPs to processes involving active materials, such as fuel fabrication, could further accelerate development. Related approaches focused on process optimization will also be valuable.

Pursued results

This CONNECT-NM research line supports the development of *n*-MAPs, by providing experimental tools and AI-driven models to design, build, or enhance such platforms. It may also contribute directly to their creation and use. Materials screening activities are included if they introduce innovations that speed up the process—especially when combined with physical or AI-based models. Targeted outcomes include:

- optimization of testing procedures to monitor materials properties and performance during fabrication.
- Use of advanced manufacturing and subsequent treatments to produce specimens in larger quantities, exploring different compositions and architectures, while guaranteeing reproducibility of properties.
- Improved fast-testing procedures to monitor properties during fabrication.
- Advanced, often non-destructive, characterization methods to gather data for predicting long-term behaviour.

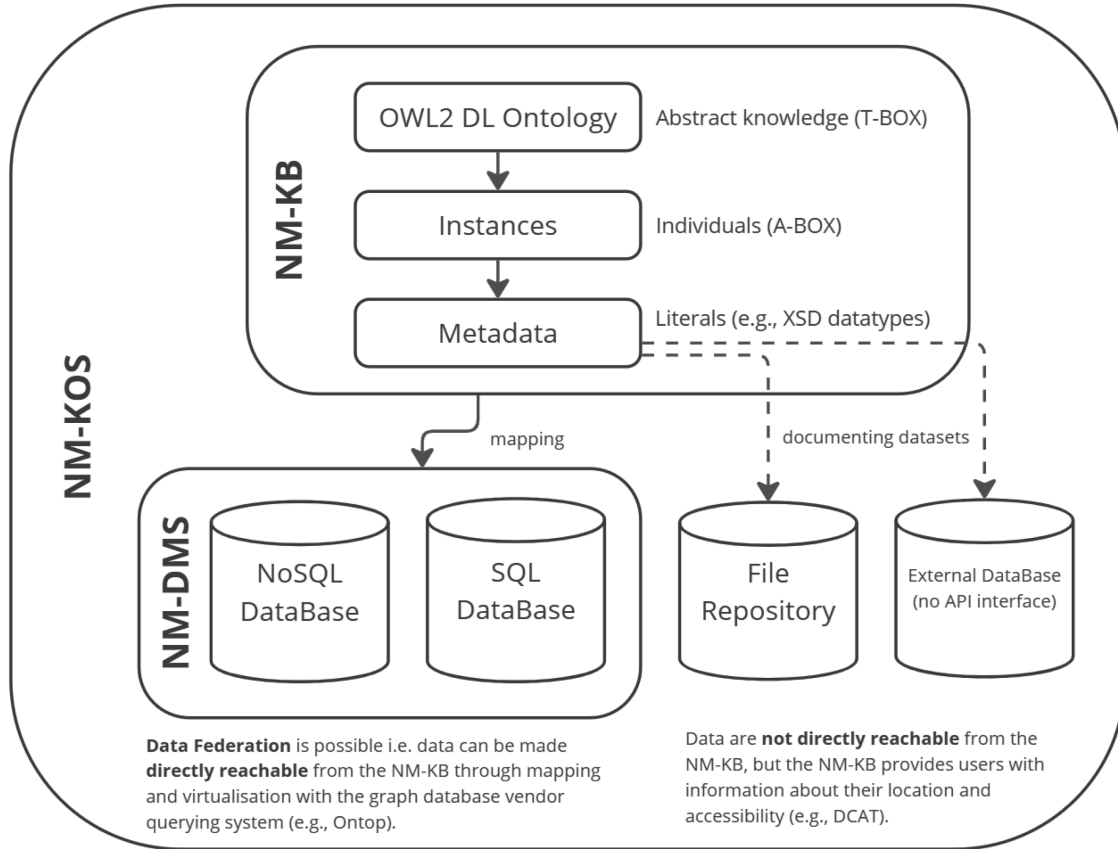


Fig. 1. NM-KOS architecture overview.

- Development of predictive models combining simulations and experiments in explicit support of materials design.
- Identification of fast-measurable indicators of long-term performance.
- Creation of guidelines for rapid testing of key properties (e.g., mechanical behaviour, corrosion resistance, radiation tolerance...).
- Development of standards for fast irradiation testing (e.g., with charged particles) and post-irradiation examination (PIE), addressing result transferability to neutrons.

A key focus is the step-by-step development of n-MAPs, leveraging existing non-nuclear MAPs, through:

- identifying synergies with non-nuclear MAPs.
- Defining the required modules and their acceleration potential.
- Exploring advanced manufacturing as both a MAP module and a development tool.
- Designing a nuclear-specific irradiation and PIE module.
- Developing MAP-oriented informatics tools for data handling, including relevant ontologies.

This line also involves generating new data on advanced nuclear materials to improve screening efficiency within MAP frameworks.

3.3 Materials and component qualification: testing, standardization and design rules

Methodology

Once a new material for nuclear applications is identified, the time for its qualification and codification is currently too often measured in decades, largely due to extensive testing and irradiation requirements. To enable the deployment of next-generation reactors by the 2030s and support the energy transition, this timeline must be significantly shortened. While the use of tailored materials development pursued in the previous research line is expected to facilitate this goal, acceleration can be achieved through two complementary approaches:

- 1) elaboration, evaluation and implementation of AQPs for the various materials and nuclear systems [30,31].
- 2) Creation of (open) TBs that are fully equipped for the implementation of AQPs, including suitable irradiation capabilities [31].

Nuclear materials R&D is inherently time-consuming, with qualification relying primarily on the traditional “observe and qualify” approach. This involves sequential, standardized testing of representative batches, followed by data processing into engineering properties and eventual codification. A major limitation of this method is the time needed for long-term tests (e.g., creep, corrosion, irradiation, microstructure evolution). While test duration itself is hard to shorten, AQPs aim to reduce reliance

on such tests by extracting more and better-quality data from fewer experiments. This is mainly achieved through predictive modelling, targeted non-destructive characterization and machine learning-based data analysis.

AQPs support a shift toward the more advanced “design and control” paradigm. They reduce test volume, increase throughput and enable the use of accelerated methods like ion irradiation, separate effect testing and extrapolation of data to operational conditions. Small specimen techniques play a key role [32,33], even if not always directly usable for licensing under current standards. Their use, alongside ion irradiation, can nonetheless guide licensing, provided that acceptability is timely discussed with regulatory bodies and standardization organizations, starting this dialogue from the very beginning.

Another major challenge to accelerate qualification is to avoid data scatter, due to the frequent lack of coordination across labs, which may stem from inconsistent sample preparation, different testing and examination protocols, control of environmental parameters and/or unequal criteria for data quality. While this situation is generally mitigated by the existence of standards, a further reduction in variability is achieved with TBs. These are conceived as connected, high-quality infrastructures where comprehensive and repeatable material testing is performed under unified protocols by different laboratories. Ideally, these platforms should comprise not only advanced experimental facilities (including for irradiation), but also common modelling and data management tools.

Pursued results

This research line aims to help establish a characterization TB focused on specific challenges and support the development of AQPs by adopting a novel approach based on:

- Integrating modelling and predictive tools and/or NDT&E techniques into current qualification paths to accelerate them.
- Developing new accelerated tests, including appropriate protocols and effective data collection and management methods.
- Creating protocols for tests that are not yet standardized, including small specimen testing.

The definition and implementation of AQPs will be tailored to specific applications, selected as case studies—such as particular nuclear systems or materials—based on deployment needs and priorities identified by the consortium of organisations involved. Furthermore, to effectively implement AQPs, collaboration with regulatory bodies, their technical support organizations and relevant standardization stakeholders across Europe must be foreseen. This collaboration should aim to define the standardization framework, identify applicable existing standards and design the testing plan toward eventual standardization. Key pillars of this effort will include the development of harmonized guidelines, best practices and standards, supported by round robin testing to ensure protocol quality. Additionally, a Quality Management System will be required for the proper operation of the TB, particularly

for applying standardized and accelerated qualification procedures. Advanced data analysis and storage systems must be established to allow partners to share and consult data at dedicated access points, in connection the research line dedicated to the development of the NM-KOS. All produced data must be accessible and reusable, supported by comprehensive metadata.

In summary, this research line pursues the creation of a Europe-wide, integrated TB network functioning as a hub for pre-normative research. Establishing stable legal and organizational structures is intended to allow these TBs to operate as open-access infrastructures, offering a single-entry point for nuclear materials qualification in Europe, while protecting intellectual property and ensuring broad usability.

3.4 Non-destructive examination and materials health monitoring

Methodology

Monitoring the degradation of nuclear materials is essential for safely managing component lifespan [34].

It is therefore crucial to assess the real-time condition of materials, components and products, as well as to implement smart maintenance and repair strategies, ideally at the individual component level. Autonomous repair systems typically rely on sensors that detect material changes through physical principles or mechanical deformation. Advanced sensing technologies, including embedded micro sensors and distributed sensor networks, allow continuous monitoring of material conditions and smart use of data [35]. In the nuclear sector, however, NDT&E has traditionally been limited to periodic defect detection, missing its full potential when integrated from the design phase. Key lessons in NDT&E show that:

- NDT&E can support all stages of the product lifecycle, from material and product development to maintenance, repair and even recycling.
- Continuous in-service inspections are crucial for maintaining high safety standards and reliable operation in existing and future NPPs.
- Structural Health Monitoring (SHM) with permanently installed sensors complements traditional NDT&E by enabling easier, safer and more cost-effective inspections, with the added benefit of continuous or frequent monitoring for predictive maintenance.
- Combining ageing models with physics-based and machine-learning models to create digital twins—updated by sensor data—enhances diagnostics and prognostics.
- Digital twins that evolve with operational data improve safety, assist in component selection, reduce costs and extend component lifespans.

To enable all of this, materials and components must be designed to be easily characterized using NDT&E from the start. Design should also consider future inspection, replacement, or retrofitting. Systems that integrate continuous SHM with digital twins—enabling timely repair or replacement planning—are known as intelligent

materials health monitoring (IMHM) systems. In the long run, IMHM systems will enhance the performance, longevity and efficiency of both structural and functional components.

Pursued results

In this context, this Research Line (RL) of CONNECT-NM aims to develop IMHM systems to evaluate both microstructural parameters (defect location, density, and size) and macro structural states (mechanical properties) of materials during service. It will also account for operational factors such as temperature and pressure cycles, as well as neutron exposure, through continuous inspection. The research line will pursue innovative multi-parameter NDT&E approaches for detecting material and component degradation in NPPs, employing cognitive sensors and digital twins to improve estimates of component lifespan and support material development and qualification.

The work will focus on the operational phase of selected materials or components and define strategies for developing corresponding IMHM systems. Since robust monitoring technologies depend on model accuracy and data quality, reliable experimental data under realistic conditions must be collected. Digital twins are expected to become the ultimate integration platform, where physics-based and data-driven models combine: simulations derived from physical laws will be refined using empirical data and machine learning algorithms. The research will include:

- development and optimization of cognitive, self-adaptive sensors capable of identifying relevant data autonomously, reducing noise and enabling focused multi parameter analysis. Studies on reliability and uncertainty—considering factors such as initial microstructure and material variability—will also be included.
- Application of digital technologies (e.g., digital twins, advanced statistics, AI/ML) to enhance predictive monitoring of mechanical and environmental degradation, and to guide sensor decision-making.
- Identification of defect origins by leveraging prior knowledge made accessible through continuous monitoring, even before formal inspections.
- Development of monitoring systems capable of continuous multi sensor data acquisition in harsh conditions (e.g., radiation, temperature), including data fusion and correlation across NDT&E techniques. These will allow system-level assessments and support predictive decision-making.
- Analysis of fault tolerance in AI-driven decision-making, including embedded methods for assessing and qualifying the reliability of outcomes, which are essential for autonomous operation.
- Development of protocols for training, testing and especially validating machine learning techniques, to enhance transparency in safety-critical applications and support future standardization.

3.5 Advanced materials modelling and characterization

Methodology

Multiscale modelling approaches should enable the prediction of material behaviour under reactor operating conditions—especially regarding radiation effects—through a multidisciplinary strategy. This should combine solid and fluid physics, chemistry, thermodynamics and general materials science theory with computer science, in close interaction with advanced characterization. [15,36]. These approaches can now be complemented by modern digital techniques, such as machine learning and artificial intelligence, which leverage available data to identify complex correlations between large sets of variables and key material properties (so-called data-driven modelling [16]). When blended with physical approaches, these techniques allow researchers to overcome limitations—such as those posed by local chemical complexity when bridging scales—leading to high-fidelity and advanced numerical capabilities [37–39]. The use of machine-learning approaches such as ‘few-shot learning’ [40] is also especially promising, as data in nuclear materials science are often scarce. Finally, materials modelling should be directly integrated with experimental techniques in a two-way process: experiments feed the models, not only by comparison but also in a digital twin logic, and models support the interpretation of experimental results, including by the simulation of the signals produced by specific experimental techniques.

Pursued results

This research line aims to enhance the capabilities of Advanced Predictive Methodologies (APMs) for materials used in current and future nuclear fission reactors—including metallic materials, fuel cladding, fuel and concrete. The goal is to integrate physical and data-driven approaches to make these methodologies directly applicable at the industrial level, under increasingly broad operational conditions. These predictive techniques will work in close interaction with advanced microstructural, microchemical and micromechanical examination methods, including non-destructive and tomography techniques. Activities will include: i) advancing specific physics-based models and analytical tools; ii) improving multi-scale bridging techniques; iii) leveraging datasets through machine learning to discover new solutions; and iv) conducting targeted experiments to generate essential data supporting the above. Examples of this include:

- development or enhancement of novel APMs to address material degradation mechanisms in complex material systems, such as multicomponent alloys, mixed fuels and new concrete compositions. Degradation modes of interest include: radiation-induced hardening/embrittlement, swelling, creep, gas production and its effects, corrosion and stress-corrosion/dissolution/erosion due to fluid or solid contact, thermal creep, various concrete degradation processes and the effects of dose, dose rate and temperature.
- Development or enhancement of APMs to support the design or discovery of materials with improved

structural integrity and radiation resistance, including the use of charged particle irradiation as a screening method.

- Creation of analysis methods that interpret materials simulation results through the lens of specific experimental techniques, aiding comparison and supporting non-destructive evaluation.
- Development of simulation methods that model how an experimental technique would observe a specific microstructure or material state, particularly in studying microstructural evolution and atomic transport under irradiation.
- Development of multi fidelity models that integrate diverse data sources to enhance the predictive accuracy of existing or new engineering and analytical tools.
- Execution of model-driven experiments and post-irradiation examinations, provided they involve novel analytical or interpretive approaches.

This research line will actively promote creativity in developing new methodologies. Special emphasis will be placed on innovative combinations of physics-based and data-driven strategies to significantly boost predictive capabilities. Purely physics-based or purely data-driven approaches must demonstrate a convincingly transformative potential. Methodologies that integrate advanced (and rapid) characterization, physics-based modelling and data-driven techniques will receive particular focus.

4 The operational goals of CONNECT-NM

4.1 Calls for projects and scientific evaluation

Open calls for projects have been identified as the most transparent and balanced method to define priorities. They align top-down general requirements – defined through the SRA, also considering the input of advisory bodies (see below) – with the bottom-up formation of open consortia around specific case studies (nuclear systems, materials, or components). A transparent yet rigorous prioritization process is essential, given that available resources are insufficient to cover the full range of potentially relevant research activities within the Partnership's scope. However, the nuclear materials science community cannot determine which materials and nuclear systems take priority. This strategic choice lies with the consortium of countries and/or organizations sharing common goals. For this reason, the SRA is primarily a materials science manifesto, advocating for top-down methodological approaches that drive innovation, without prescribing specific applications. Application areas emerge through a bottom-up process, but evaluation focuses on how well the proposed project advances the methodological goals, rather than on the chosen system or material class.

Project submission will take place in two phases. In the first phase, project ideas are proposed. Stronger consortia are formed through an open brokerage event, in order to move to the second phase, where these consortia will submit full proposals. The evaluation of the latter will

be carried out by a committee of independent and impartial experts, who will rank the proposals based on scores from external reviewers. Final funding decisions will be the responsibility of the governance bodies, considering the ranking and general balance criteria.

Projects will be monitored by a Scientific Advisory Board (SAB), an advisory body originating from the R&D community. The SAB comprises internationally recognized experts in materials for nuclear energy and provides input to the governance bodies on operational and strategic matters that influence the scientific and technical direction of the Partnership.

4.2 Education, training and access to infrastructures

CONNECT-NM aims to become Europe's main entry point for organizing education and training (E&T) initiatives related to nuclear materials, where a clear, shared need is identified in the Partnership's research lines. These topics inherently require multidisciplinary profiles that are not always readily available. Particular emphasis is placed on combining materials science expertise with skills in digital technologies and innovation promotion. To address identified gaps, new activities are developed using state-of-the-art information. E&T activities will be accordingly built on four main pillars: i) promotion of mobility; ii) training schools and online courses; iii) workshops for young researchers' networking; and iv) training through research.

To maximize resource efficiency, E&T initiatives will be organized, where possible, in collaboration with other entities, ranging from international organizations (e.g., IAEA and OECD/NEA) and European associations to various bodies (e.g., standardization bodies or technical support organizations, TSOs), fusion and non-nuclear energy sectors, specific infrastructures (e.g., Jules Horowitz Reactor community) and other ongoing Euratom projects. Workshops and online training also serve to keep industry and TSOs updated on the latest developments in the nuclear materials field.

Access to major nuclear materials R&D infrastructures will be pursued by establishing appropriate connections and relationships with the main owners and managers of such infrastructures in Europe, through running initiatives such as the OFFERR [41] and the FIDES [42] projects, the former a Euratom-funded action, the latter an initiative of OECD/NEA that gathers all major materials testing reactors that operate in the Western world.

4.3 Communication, dissemination and result exploitation

CONNECT-NM strives to maximise the transfer of results to their end-users by involving them directly in the Partnership and in its Projects. Both private companies (large industries and start-ups or SMEs) and safety organisations (regulators and TSOs), which are no doubt the main end-users of the research done in CONNECT-NM, are participants of the Partnership, some of them being

involved also in the elaboration of strategic choices, i.e., they are involved from the beginning of the research process (see Section 5). To further amplify this transfer, the strategy of CONNECT-NM is based on two cornerstones: i) build a categorised map of stakeholders (international organisations and European associations, standardisation and data management bodies, regulators and TSOs, fusion and non-nuclear energy, infrastructure managers); and ii) elaborate a targeted communication and dissemination plan that is aimed at establishing appropriate interaction channels with each of these categories of stakeholders.

Thus, there will not be a single ‘stakeholder group’, but rather several groups, each of them interacting in the most effective specific way with CONNECT-NM, which will depend on the target of the interaction. Of special importance is the creation and management of a group of representatives of European regulatory bodies (Board of Regulators), as well as of TSOs (Board of TSOs), as advisory bodies for the Partnership. Another crucial part of the plan is the creation of an Innovation and Exploitation Group (IEG), comprised of individuals with expertise in leading business, supporting entrepreneurship and commercializing technology, in representation of the industry. The IEG, led by industrial partners, advises CONNECT-NM concerning strategic orientations in order to boost innovation.

In parallel with all this, more ‘traditional’ dissemination activities will be pursued, i.e., through established nuclear materials related conferences, workshops and symposia in large conferences. In this context, providing support to established initiatives is the most cost-effective way to have an impact and achieve wide visibility.

5 CONNECT-NM expanding consortium and pursued impact

The CONNECT-NM consortium is composed of three main types of participants: Beneficiaries (BEN), Affiliated Entities (AE) and Associated Partners (AP): BENs are Euratom (or associated) national organisations, mandated by the corresponding ministry or agency to manage the participation of the country in the Partnership; AEs are Euratom (or associated) national organisations that have an established link with a beneficiary; APs are generally non-Euratom national organisations that participate entirely at their own cost. The starting Consortium, represented in Figure 2, is rich both geographically and in term of types of contributors (from research centres and academia to regulators and TSOs, as well as private companies). This sets excellent bases for the achievement of the Partnership’s objectives, thanks to the wide range of knowledge, skills, tools but also facilities and infrastructures that are inherently included. This Consortium is expected to grow further, through the open call for projects, involving an even wider spectrum of participants. This Consortium pursues a significant impact, as described in what follows for each research line.

5.1 Knowledge and data management

This activity will enable a significant step toward establishing a unified, open knowledge framework for the European nuclear materials domain. It will provide common access to nuclear materials databases, integrating data from diverse sources while ensuring data quality control. The framework should enable rapid access to well-structured, semantically enriched data, supporting the reuse and understanding of existing datasets and facilitating the creation of meaningful training sets for AI approaches that integrate both modelling and experimental data.

This initiative is expected to greatly accelerate innovation in the nuclear field by reducing the time required to introduce new materials for specific nuclear applications. The duration and cost of materials testing and characterization could be cut by at least half, by minimizing material consumption and optimizing the use of personnel and instrumentation. By increasing the availability of FAIR nuclear materials databases within existing domains and expanding FAIR-compliant coverage to new areas, a more structured and accessible information environment will be created. Ultimately, this will lead to the formation of a collaborative network of stakeholders involved in nuclear materials modelling, fostering shared expertise and mutual support in advancing nuclear materials research and applications.

5.2 Advanced materials development and manufacturing

In this field, CONNECT-NM is expected to play a key role in advancing several strategic objectives. It will boost knowledge on promising, low-TRL materials and support their progression toward near-qualified material solutions. At the same time, it will enable the discovery of innovative new materials by leveraging synergies with non-nuclear MAPs, with the goal of enhancing the design of structural components, core elements, advanced fuel types—such as enhanced accident-tolerant and high-performance fuels—and concrete structures, across various nuclear technologies and systems.

CONNECT-NM will also contribute to optimizing process parameters and qualifying advanced manufacturing techniques for materials already used in nuclear technologies. It will support the development of materials design strategies that tailor specific process parameters in advanced manufacturing to create new materials and will explore and expand the practical application of these processes to the design of nuclear reactor components, identifying the most promising technologies.

Furthermore, the initiative will extend the use of advanced coating technologies for protecting nuclear materials, by deepening the understanding of these techniques and pushing them toward near-qualification. It will also focus on developing screening methodologies, to broaden the range of materials, conditions and manufacturing parameters that can be effectively investigated.

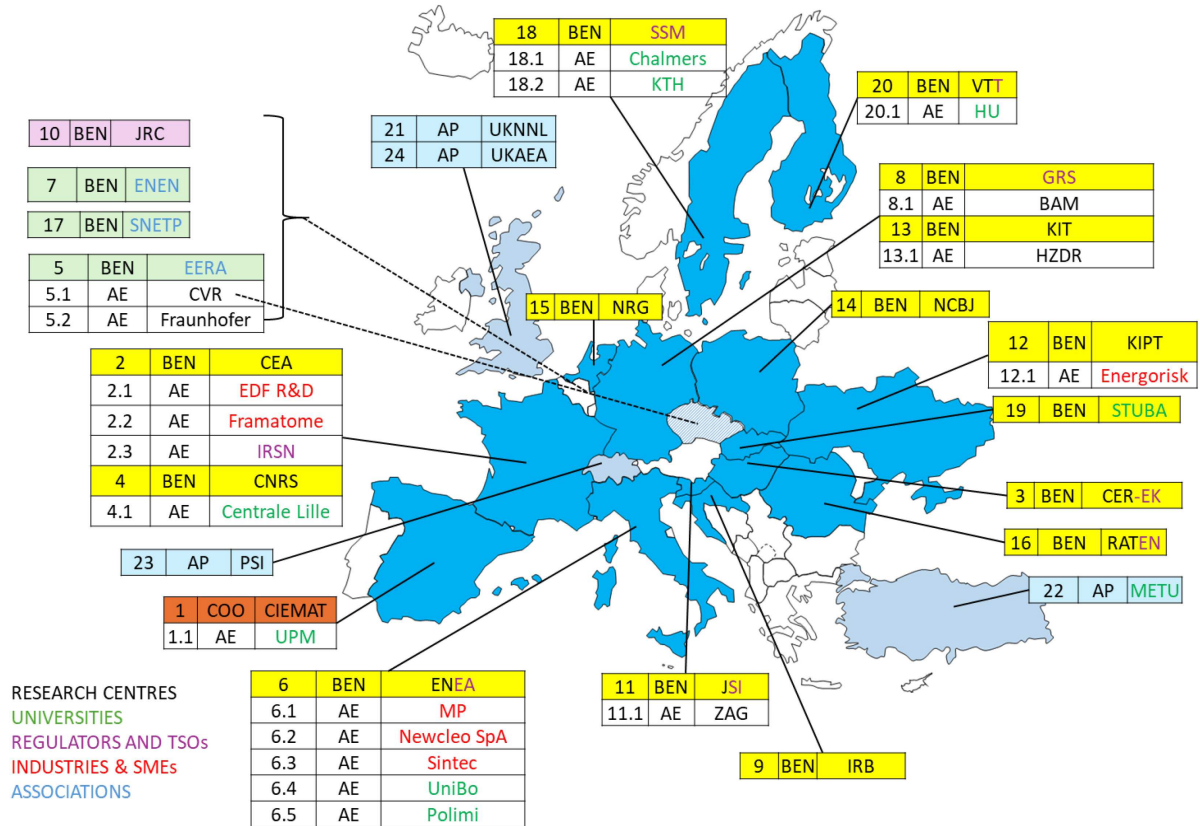


Fig. 2. The starting Consortium of CONNECT-NM.

By facilitating the identification of optimized materials solutions more efficiently, CONNECT-NM will accelerate their development, contributing to enhanced nuclear safety and improved industry sustainability. It will also help identify innovative materials applicable across various nuclear fission technologies, possibly in synergy with fusion and other industries. Lastly, the initiative seeks to minimize both the quantity of materials used and the time and costs involved in the development of new, innovative solutions.

5.3 Materials and component qualification: testing, standardization and design rules

The implementation of TBs through the coordination of existing and future infrastructures and skills are expected to mark a significant step toward the harmonization of European research in nuclear materials. Alignment on qualification paths will enable more effective resource allocation, avoiding redundancies, inefficiencies and missed opportunities. This joint approach will help European players remain at the forefront of nuclear materials R&D, ensuring both the highest safety standards for nuclear installations in Europe and improved global competitiveness in this dynamic technological domain.

Standardized and quality-controlled experimental procedures and methodologies will significantly enhance data reliability, and in turn, the reliability of the qualifi-

cation process. Overall, this action will accelerate the exploitation of innovative material solutions for (i) deploying advanced reactor concepts with improved safety and lower costs, (ii) further enhancing the performance, safety and lifespan of existing reactor fleets, and (iii) achieving greater economic sustainability, by reducing the time and cost involved in licensing innovative materials and solutions. It will also strengthen technical knowledge and expertise in material qualification and standardization, while improving collaboration between the nuclear materials research community and stakeholders, including industrial partners, nuclear regulators and standardization and codification bodies.

5.4 Non-destructive examination and materials health monitoring

The unique feature of NDT&E methods is their ability to continuously detect and evaluate the progressive changes in material properties of the same specimen or component, in situ and/or operando. Activities in this research line are expected to demonstrate the high added value of these approaches in industrial nuclear applications, particularly in terms of increased safety and cost reduction. This is especially relevant for improved estimation and management of the NPP operational lifetime and of their components, while also providing feedback and input to models and design rules, which can, in turn, be refined.

NDT&E techniques are also expected to contribute to the development of *n*-MAPs and AQPs. Therefore, although the focus is primarily on the operational phase, it will also explore how techniques developed for this phase could be applied to other segments, or even across the entire component lifecycle, enhancing the overall safety and sustainability, including economic, of nuclear energy. The developed techniques will enable the monitoring of various material properties from the beginning of component development through to end-of-life. They will also help reduce maintenance costs in a quantifiable way compared to current state-of-the-art methods and contribute to extending the longevity of materials, components and products. Finally, the traceability of materials information throughout the value chain will be improved, enabling the identification of potential defect origins, thanks to the significant amount of a priori knowledge made available before each inspection (including multi scale modelling of structures and correlations between structure and properties).

5.5 Advanced materials modelling and characterization

Developments in this RL shall support *n*-MAPs, AQPs and IMHM systems, and/or take important steps toward advanced methodologies and engineering tools of direct interest and use for industry and/or regulators. These will enhance the capability to predict the behaviour of materials in operation and to assess properties critical for component lifetime management and safety, enabling more reliable safety assessments. This may be achieved by both underpinning and eventually replacing empirical or semi-empirical correlations used at the industrial level, or by supporting more accurate evaluation of potential failure paths, which experimentally require large and costly programs that often yield simplistic results. Digital technologies are intended to help reduce the number of exposure experiments and subsequent testing on activated materials, thus significantly impacting time-to-market and cost reduction. The methodologies shall be applicable under an increasingly wide range of operational conditions and assist in transferring experimental results obtained under different irradiating conditions (e.g., ion irradiation vs. neutron irradiation). Advanced predictive methodologies shall also support the improvement of design and fuel performance codes, along with various analytical tools used to evaluate material properties. Advanced modelling is additionally expected to play a crucial role in accelerated qualification, as it provides the necessary links between properties and should enable a more precise assessment of degradation processes, including long-term effects, based on physical insight.

6 Concluding remarks

CONNECT-NM is the culmination of the work done in the last 10 years within the European research community on nuclear materials, gathered around the EERA-JPNM and in dialogue with SNETP, to organise itself in a structure

projected towards efficiency in research, with innovation as a goal. The corresponding SRA, rather than prescribing research on specific nuclear systems and materials, indicates according to which methodology the work has to be planned and performed, so as to develop skills and tools that enable flexibility and accelerate progress. The idea is that current materials science practices, strongly rooted in modern digital technologies, open up new horizons for the benefit of nuclear energy. All steps of the materials cycle are holistically addressed, from conception to development and qualification, until use in operation and eventually also disposal, privileging reuse and recycling. Concepts such as “safe and sustainable by design”, as well as scientific and technical approaches oriented towards optimised use of available resources are therefore pursued, by promoting a shift of paradigm in the nuclear materials field, from ‘observe and qualify’ to ‘design and control’. This paradigm shift is highly challenging, but is necessary in view of the fact that nuclear energy as a whole is bound to move towards at least two changes of paradigm: (1) toward small installations that, thanks to modularity and standardization, should be financially more sustainable than large plants, whose construction times and costs have grown unacceptably long and high; (2) toward reactors that use resources in a much better way, through fuel recycling and higher temperature. Growth or decline of nuclear energy in the coming years will largely depend on the capability of the nuclear industry to gain this bet and be competitive. Both changes of paradigm rely on the possibility that materials solutions of superior performance are developed and qualified at a much faster pace than in the past and that suitable methodologies to monitor materials performance in operation, supported by advanced predictive capabilities, enhance not only safety, but also the sustainability of the whole material and component lifecycle. In this endeavour, data and knowledge management have an overarching importance. It is the sum of all these considerations that has dictated the challenging strategy pursued in CONNECT-NM.

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Conflicts of interest

The authors declare that they have no competing interests to report.

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