ORIENT NM

Vision paper for a Co-funded European Partnership (CEP) on nuclear materials

Authorship

Lead authors:
A. Al-Mazouzi, EDF & SNETP
M. Bertolus, CEA
P. Efsing, Vattenfall & KTH
L. Malerba, CIEMAT

Contributing authors:
A. Bohnstedt, KIT
M.L. Fernandez-Vanoni, EERA
P. Kinnunen, VTT
D. Malerba, LUC
M. Tarantino, ENEA

Design: Marjolaine Bergonnier

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About ORIENT-NM:
ORIENT-NM seeks to explore the possibility and critically assess the added value of establishing a Co-Funded European Partnership (CEP) to support the development of a coordinated European research and innovation programme on nuclear materials, positively impacting Europe's competitiveness in the nuclear field at world scale. For more information, please visit: *www.eera-jpnm.eu/orient-nm*

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Disclaimer

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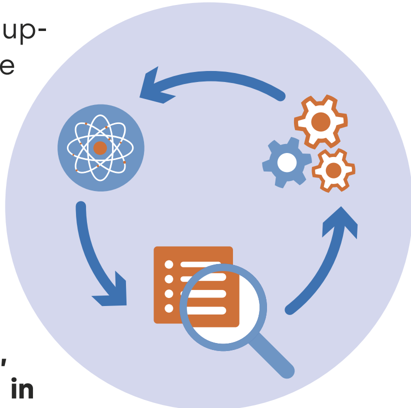
List of abbreviations

EERA-JPNM	Joint Programme on Nuclear Materials of the European Energy Research Alliance
EU	European Union
Gen III/III+	Third (plus) Generation Reactors
Gen IV	Fourth Generation Reactors
IPCC	International Panel on Climate Change
LTO	Long-Term Operation
LWR	Light Water Reactors
MS	Member State
NECP	National Energy and Climate Plans
SNETP	Sustainable Nuclear Energy Technology Platform

Executive Summary



ORIENT-NM is a Euratom-funded Coordination and Support Action (CSA) with the objective of exploring the consensus on a **European partnership on nuclear materials**, establishing a relevant Strategic Research Agenda (SRA), the governing structure and means for interaction with stakeholders based on the SRAs of the SNETP and of the EERA-JPNM.

The ORIENT-NM analysis of the national energy and climate plans (NECP) suggests that, **from now to 2040, nuclear power will be maintained or even expanded in Europe through LTO, power uprates and new builds**. In addition, the recent geopolitical events and game-changers, such as **small modular reactors and advanced designs** of interest throughout the continent, may lead nuclear energy to be even more widespread in 2040 than currently foreseeable.

Research to monitor, understand and predict materials' behaviour in operation and improve materials' performances has always played a crucial role in continuously enhancing nuclear energy's safety, efficiency and economy. The involved materials cover a broad spectrum: from metallic structural alloys, polymers and concrete to nuclear fuel and substances for neutron control.

To meet the challenges posed by the clean energy transition timely, **this research needs to be boosted to accelerate the design, manufacturing and qualification of innovative nuclear materials with improved performance and reduce their time to market.** This implies a shift from the traditional "observe and qualify" to the modern "design and control" materials science approach, which is enabled by advanced digital techniques and suitable models.

With this goal in mind, an integrated European nuclear materials research programme, i.e., a partnership, needs to be set up to make coordinated use of assets spread across member states and associated countries, as well as to give continuity to the pursued research lines. With this, the nuclear materials science paradigm shift will be within reach for Europe. Such a partnership will «need and feed» available schemes and roadmaps for access to and use of infrastructures, such as those designed in the parallel JHOP2040 CSA for utilising Euratom access rights in the Jules Horowitz Reactor, established in the starting OFFERR CSA, or in the framework of international organisations (e.g., OECD/'NEA's FIDES initiative). Such a crosscutting programme is expected to leverage substantial national and industrial support.

To produce fruitful results for all parties, the partnership will pivot around five research lines that are transversal to all classes of nuclear materials and consistent with the activities foreseen in the SET-plan implementation plan on nuclear safety, and with the Advanced Materials 2030 Manifesto: (1) nuclear materials' test-beds, (2) nuclear materials' acceleration platforms, (3) advanced predictive methodologies, (4) improved material and component health monitoring and (5) European nuclear materials' FAIR database.

Because of its **inherent multidisciplinary approach**, the partnership will maintain and build competences. At the same time, its **crosscutting nature** will equally serve all the various national nuclear energy strategies, supporting nuclear industry competitiveness and a robust supply chain, with benefits for fusion and non-nuclear energy, as well.

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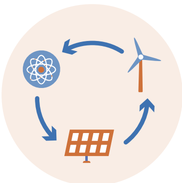
1. Introduction

ORIENT-NM (Organisation of the European Research Community on Nuclear Materials) is a Coordination and Support Action (CSA) partially funded by the Euratom research and training work-programme 2019-2020. It was set up, consistently with the call request, to explore the opportunity of establishing a co-funded European partnership on nuclear materials, following a procedure already adopted in the past for other partnerships. Accordingly, **this document presents the vision of the European research community on nuclear materials**, as represented in ORIENT-NM, which allies the Sustainable Nuclear Energy Technology Platform (SNETP) [1] and the Joint Programme on Nuclear Materials of the European Energy Research Alliances (EERA-JPNM) [2], **regarding**:



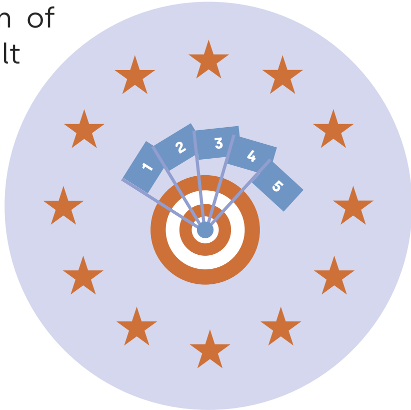
Sustainability: Nuclear systems are crucial components, together with renewables, of a resilient and sustainable Energy Union, helping Europe to abate the use of fossil fuels, reduce European geopolitical dependence and become the first climate-neutral continent by 2050 [3]. Their sustainability needs to be continuously improved, and *this document discusses how.*

Innovation: Materials research plays a crucial role in enhancing the safety, efficiency and economy of nuclear energy by supporting the existing fleet, the new builds and also enabling the deployment of advanced reactor concepts, including small and medium size modular reactors (SMRs), within the time horizon of 2040**.** *This document discusses the relevant research needs.*

Targeted collaboration: The development and qualification of innovative materials solutions, and their monitoring in operation, needs to be accelerated while also accounting for circularity and sustainability principles. *This document advocates that the nuclear materials research community should work toward five identified Grand Goals along the corresponding research lines.*

These five research lines, presented at the end of this document, stemmed from the analysis of the European Union's member states' energy plans and the nuclear industry's short- and long-term needs. They correspond to a shift from an "observe and qualify" approach towards a more advanced "design and control" one, using advanced materials science practices combined with modern digital techniques. The corresponding Grand Goals, also presented at the end of this document, are accordingly ambitious.

Attaining the five selected Grand Goals calls intrinsically for Europe-wide collaboration. These goals are thought to serve equally well different national nuclear energy strategies and policies aimed at improving industrial competitiveness. They can thus be shared between all involved member states and associated countries, allowing their needs to be met by valorising their research and industrial assets. **The European partnership is the tool** to enable the integration and coordination of a single nuclear materials research programme built around the shared Grand Goals. It will make optimal use of national competences, facilities and (present and future) infrastructures to strengthen European leadership. Unlike the present model based on independent projects, it will guarantee continuity along the established research lines.



2. Nuclear energy's critical role for a net zero Europe

1 Nuclear energy assets

Nuclear energy does not produce greenhouse gases (GHG), has stable and relatively low prices [4,5], **and guarantees a secure energy supply. Additionally, it makes minimal use of land and materials and its waste production per unit of energy produced is relatively low.** Several National Energy and Climate Plans (NECPs) [6] include nuclear energy in the secure energy supply section and recognise that the decarbonisation targets cannot be reached without the nuclear contribution during the transition. This is reflected in the recently approved European Commission revision of the taxonomy for sustainable financing [7]. Base-load is also a stabilising factor for the grid operator in an energy mix with an increasing share of intermittent renewable sources. Finally, nuclear power has demonstrated the ability and high potential to provide low GHG district heating and heat for various industrial applications, including hydrogen production and sea-water desalination, which must be duly exploited [8].

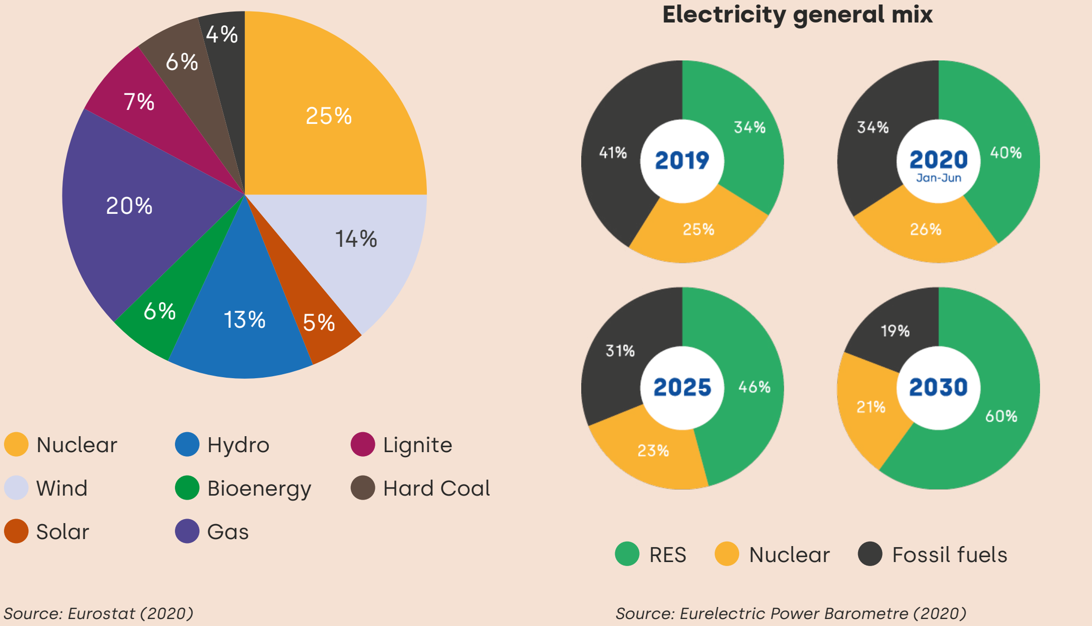
The alliance between renewables and nuclear energy has been portrayed as the most effective response to the challenge of decarbonisation of the energy sector [9]. Consistently, the 2018 "1.5°C report" of the International Panel on Climate Change (IPCC) [10] points to electricity from nuclear power as the key to limiting global warming to 1.5°C. Nuclear energy is, therefore, an asset for Europe in view of honouring the engagement to reduce GHG emissions by 55% by 2030 and towards complete decarbonisation in 2050. This is especially true in the current geopolitical energy crisis context, in which some countries are otherwise forced to revert to sources such as coal, which have long been identified as the cause of climate change and pernicious effects on human health.

2 Nuclear energy contribution to decarbonisation in Europe

The transition from current fossil fuel-based energy systems to low GHG emitting ones is the core of the European Green Deal [3] and a major global challenge to face the climate change emergency exacerbated by the current geopolitical energy crisis.

Figure 1 shows that, despite varying national positions in Europe, several studies agree that **nuclear energy remains the single largest low GHG emitting energy source for electricity production on the continent and will maintain this role in the foreseeable future**.

FIGURE 1 *Left: Electricity generation by fuel in the EU 27, in 2020 [11]. Right: Predicted evolution of electricity generation by fuel [12].*



The analysis of the NECP, prepared in 2019 and revised in 2020 by each EU country, consistently reveals that, up to at least 2040, and likely also beyond, nuclear will represent a significant fraction of the electricity production in Europe [13]. Importantly, nuclear is the only source of energy that can simultaneously provide electricity, heat and hydrogen.

Nuclear energy's role in electricity production is currently mainly realised through the long-term operation (LTO) of current light water reactors (LWR), i.e., pro-active lifetime extension beyond the original design lifetime, as well as power uprates. LTO is already an established reality in all nuclear countries, including in some that are planning to phase out [11]. New builds of evolutionary LWR designs, referred to as Generation III or III+, will also contribute to keeping nuclear electricity production stable. This will enable the European Union to deliver on the commitments of the Paris Agreement and the 2030 Agenda for Sustainable Development [14, 15].

In this context, small- and medium-sized modular reactors (SMR) are expected to be game-changers [16, 17, 18]. Thanks to modularised production, they will significantly reduce the initial capital costs and the construction time while displaying enhanced safety performance through inherent and passive safety features. Interest in SMRs is widespread in Europe, including non-nuclear countries [11, 13].

The attractiveness of SMRs and advanced designs, combined with the overall rethinking of the role of nuclear energy in fighting climate change and securing autonomous energy supply, may lead nuclear energy to be more widespread than currently foreseeable in 2040.

3 The journey towards increasing nuclear sustainability

Five issues hamper the full-hearted adoption of nuclear as a low carbon sustainable energy source in Europe: the worry of severe accident risk and safety of operation; the concern regarding the management of long-lived radioactive nuclear waste; the perceived limited availability of fuel resources; the significant initial investments, back-end costs and long construction times; and the fear of possible misuse of fissile materials.

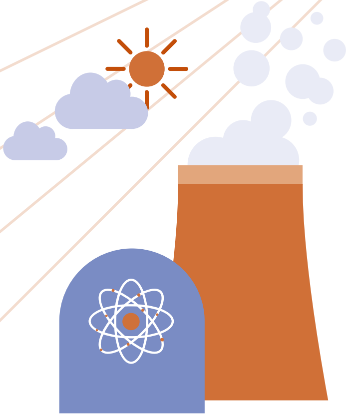
Integrated research programmes that pursue targeted research lines with the required continuity are crucial to tackling these issues, stably enabling the preservation and expansion of competence and expertise and its transferral to young generations of researchers and operators. The above is key to ensuring **continuous improvements in operational practices of current reactors in the context of the increased flexibility of the network, exploiting margins to improve further the performance, efficiency and safety of existing nuclear energy generation**. Advanced monitoring and maintenance of components, the improved supply chain for repair and replacement and innovation in materials and design are all crucial for this purpose and need to be pursued in a structured way. In addition, the higher residence time of the fuel in reactors and partial recycling of fuel will enable improved use of resources even within the current reactor generation, thereby decreasing overall costs and minimising the quantity of waste.

Even higher safety standards and improved efficiency and economy can be achieved in the medium to long term through the commissioning and deployment of fast neutron reactors [19] **combined with fuel recycling facilities**.

These reactors produce more fissile material than they consume. Thus, they significantly improve the utilisation of natural resources, reduce the need for mining and guarantee a stable and secure energy supply, reducing geopolitical dependence. These systems also abate the long-term radiotoxic impact of irradiated nuclear fuel by drastically decreasing the quantity of waste and its radiotoxicity duration, especially when minor actinides are burnt in reactors or dedicated facilities. Advanced design reactors will additionally enable higher safety standards by relying on passive systems, i.e., systems that are activated by physical laws, without any need for external intervention. Finally, they will improve plant economy through higher energy efficiency (higher operation temperature) and the adoption of advanced SMR concepts.

Fusion will finally represent a further step towards nuclear energy's full sustainability by eliminating high-activity waste from fuel.

For Europe to profit from these options, a cohesive, targeted and properly supported European strategy on nuclear materials, including research, innovation and knowledge management is needed. The following section covers these points.



3. Materials' crucial role in current and future nuclear reactor systems

Materials crosscut the entire technology portfolio [20], from energy generation and storage to delivery and end-use. The discovery and development of materials are the foundation of every energy innovation: advanced batteries and fuel cells, solar panels, thermal storage systems, and the capture and use of CO_2. **New or improved materials are a cornerstone in the global transition to a low-carbon future, which is also valid for nuclear energy. As such, investment in research on innovative nuclear materials promises to pay good dividends.**

1 A large number and variety of nuclear materials

A nuclear reactor comprises a large number of materials [21], whose properties are essential for its safe operation, efficiency and performance. The number of different nuclear materials is all the more significant given the large variety of nuclear system designs, from current generation fission reactors to Gen-IV and fusion. The various classes of nuclear materials considered and targeted in this document and their inherent variety are illustrated in Figure 2.

2 Nuclear materials' requirements

All components in a nuclear installation must meet their structural and functional properties under normal and off-normal conditions throughout their design lifetime. They must ensure a high degree of reliability according to specific nuclear standards and regulations, hence the importance of the involvement of standardisation bodies and regulators in materials development. The materials of many of these components, especially those in the reactor core, are exposed to demanding environmental conditions in terms of neutron irradiation, temperature gradients and corrosion under different forms, which all need to be harnessed.

FIGURE 2 *Classes of nuclear materials considered here and their variety.*

Concrete	Metallic allows for structural components	Refractory materials for structural components	Polymers for cables and structural applications	Fuels cladding materials	Nuclear fuel materials (fissile and fertile)	Materials for neutron control: absorbers moderators reflectors
Type II Portland cement Chemical or mineral admixtures Schielding aggregates Reinforcing and tensioning Low-carbon ...	**Customary:** Low-alloy steels Austenitic steels Zr alloys Ni-base alloys F/M steels **Prospective:** AFA steels FeCrAl ODS steels CC alloys ...	Refractory metals' alloys: Mo, Nb, Ta, V, W... Ceramic composites (SiC/SiC) Graphite ...	Polyethilene: polyvinyl chloride (PVC), ethylene-propylene elastomers (EPR, EPDM) cross-linkes polyethilene (XLPE), chlorosulfinated polyethilene (CSPE, Hypalon rubber); ethylene vinyl acetate...	**Customary:** Zr alloys Austenitic steels F/M steels **Prospective:** AFA steels FeCrAl ODS steels CC alloys SiC/SiC **Coatings:** metallic, ceramics, multilayer...	UO_2 (pellets in clad, TRISO, ...) Mox Carbides Nitrides Metallic Minor actinides Thorium ...	AgInCd B_4C Gd or Er or Eu oxydes Zr borides ...

Materials need to be suitably selected by designers at the early stages of reactor conception based on the complete knowledge of the as-fabricated properties, the expected functionality and the operating requirements. Appropriate control, monitoring, maintenance, replacement and repair strategies are then used to control evolution and ageing mechanisms to ensure that the equipment is able to perform its function reliably and safely throughout its time of use. **Research into these issues to improve the relevant practices has thus vast potential to increase the short and long-term safety, security and stability of the nuclear energy supply.**

INITIAL MATERIAL PROPERTIES

Design property data are available for most materials currently in use in nuclear facilities within scatter and heterogeneities. However, **more efficient and less costly manufacturing and welding processes and subsequent thermal and mechanical treatments need to be studied** to guarantee safe and timely replacement, repair and robust supply chain in compliance with regulatory requirements.

Then, **gaps remain concerning materials for the deployment of Gen IV reactors**, where not all relevant properties are available from established experience. Moreover, materials with improved initial properties are needed to achieve better resistance to severe degradation processes due to exposure to higher irradiation dose and temperature than in current generation reactors and the contact with non-aqueous fluids.

AGEING AND DEGRADATION MECHANISMS

All ageing and/or degradation mechanisms that may be active during the required lifetime of components need to be correctly understood, modelled and adequately taken into account from design through integrity assessments, under all operational conditions and in reactors of any generation. Materials' property measurements and degradation analyses through health monitoring using non-destructive examination and testing (NDE&T), coupled with diagnostics, enable accurate and continuous control of the performance of components, together with suitable preventive measures and onsite repair and replacement technologies and strategies.

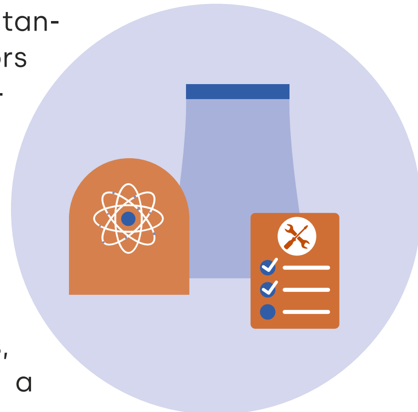
All these materials' science-related methodologies need to be suitably studied, improved and developed. Furthermore, combined with in-depth knowledge of materials behaviour, they bring essential advantages in terms of reduced maintenance costs and increased component lifetime, with positive economic consequences. Furthermore, new materials solutions need to include considerations of overall sustainability regarding materials availability, lifetime optimisation and waste reduction.

Finally, issues such as industrial production scalability, supply chain and standardisation are equally crucial to enable the deployment of a given materials solution on the path towards innovation. **Overall, in-depth knowledge of the properties of a large number of very different materials, many of which are still to be developed, is strongly needed. Such progress should cover the entire materials' service life evolution and account for supply chain and sustainability issues.**

3 Materials' needs for Gen III/III+ reactors

The above challenges need to be met in the short term for currently operating (Gen II/III) reactors and Gen III/III+ new builds.

Materials for Gen III/III+ are selected based on long-standing experience from the operation of Gen II reactors since the 1970s and 1980s. Designs have been optimised to account for the properties of the materials under various operational conditions. Several issues, however, have been revealed recently in connection with obsolescence and repair needs. These issues affect not only core components that have long been the focus of research for safety reasons, but also materials such as concrete and cable polymers, the degradation of which, in an LTO framework, is a point of attention.



The above mentioned issues must be examined thoroughly to ensure the necessary reliability of the components concerned and their compliance with up-to-date codes and standards. **Improved materials and new fabrication methods**, such as additive manufacturing, which also enable better-performing component design, are expected to **increase the efficiency of new builds and reduce construction and maintenance costs connected with the supply chain. This approach will also benefit LTO of operating reactors**, allowing the introduction of new materials or manufacturing processes. It may also facilitate the design of SMRs, especially their modular construction in factories.

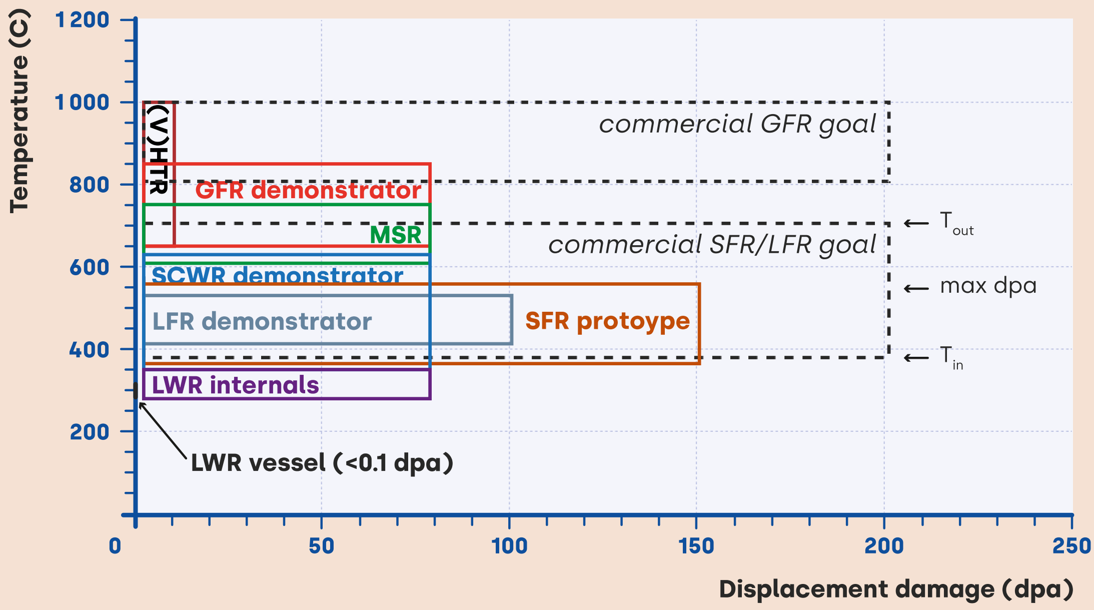
On the fuel side, new materials solutions will further increase safety margins in operational conditions by increasing thermal conductivity, reducing mechanical and chemical pellet-to-cladding interaction and limiting fission gas release. These fuel elements with enhanced accident tolerance will increase the time between departure from normal operation and the moment at which significant loss of geometry of the fuel assemblies occurs and the severe accident starts, thus enabling to prevent them. Solutions to extend the recycling of used fuels in current reactors are also being investigated.

These aspects are extensively addressed in the Sustainable Nuclear Energy Technology Platform (SNETP) Strategic Research and Innovation Agenda 2021 [22].

4 Materials' needs for Gen IV reactors

In next-generation reactors, structural and fuel materials will be exposed to significantly higher temperatures and temperature gradients, as well as increased irradiation levels, compared to today's LWRs, as illustrated in Figure 3 for cladding materials. Materials used in these reactors also need to be compatible with unconventional coolants, such as liquid metals, molten salts or gases, which have a high corrosive and erosive potential and for which in-service feedback experience is limited.

FIGURE 3 *Ranges of temperature (inlet/outlet) and maximum neutron dose in the fuel cladding in European Gen IV reactor demonstrators and prototypes versus LWR, according to current designs. Indicative possible target regimes for commercial reactors are also indicated [23].*

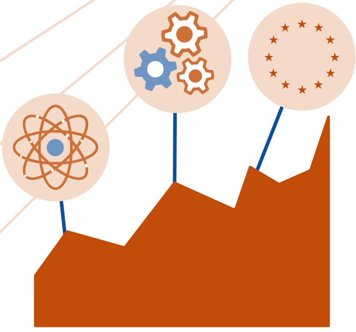


To date, no commercial materials enable the ambitious targets of Gen IV reactor operating conditions to be fully attained. There is, therefore, a clear need to develop and qualify materials with suitable properties. The grand challenges for the development and qualification of materials for next-generation reactors are:

- Elaboration of design rules, assessment and test procedures, for both operating and off-normal conditions, for all the materials of interest;
- Development of physical models coupled to advanced microstructural characterisation to achieve high-level understanding and predictive capability, in combination with suitable data-driven modelling approaches;
- Development of advanced structural, fuel and other core materials solutions and application of advanced manufacturing techniques to achieve

superior thermo-mechanical properties, better radiation resistance and compatibility with fluids;
- Development of materials health monitoring through NDE&T methods applicable at all stages of product lifetime.

The first three challenges for metallic and ceramic structural and fuel materials are amply discussed in the Strategic Research Agenda of the Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA-JPNM) [24]. **Importantly, materials with superior properties in terms of radiation and thermal gradient resistance are also essential for fusion** [25].



4. Answering Europe's materials needs for the development of nuclear systems

The above considerations unambiguously show that materials are crucial to further enhance the safety and overall sustainability of current reactors, to enable the commissioning and deployment of next-generation reactors, and to fusion. Consequently, addressing the issues mentioned earlier that still hamper the full-hearted adoption of nuclear as low carbon sustainable energy source in Europe is critical.

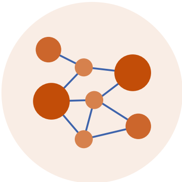
In this context, the European nuclear materials science community is called to provide the tools, knowledge and skills to enable each European country to maintain the desired and needed nuclear capacity and, depending on national policies and priorities, to develop advanced nuclear systems. Thus, the research activities of a European partnership dedicated to nuclear materials should support the following:

- Safe and affordable LTO of current generation reactors;
- Increasingly safe design, licensing and construction of Gen III+ new builds;
- Deployment of light water SMRs within the next decade;
- Reduction of time and costs for the design, licensing and construction of competitive next generation (Gen IV) nuclear reactors, including advanced SMRs, within the time horizon of 2040.

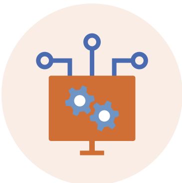
1 Five Grand Goals of the European nuclear materials research

Addressing the challenges described above to influence the clean energy transition requires the application of modern materials science approaches to accelerate materials development and qualification pace. The knowledge of materials' behaviour in operation will be improved thanks to models that underpin empirical performance correlations, extending them reliably to unexplored operational regimes.

Five materials science practices and relevant research lines underlie these endeavours and constitute the Grand Goals to be pursued within the next decade for a complete application also beyond this time frame[1]:



a. **Nuclear materials' test-beds.** The goal is to establish an efficient and integrated European networked system for applying advanced and suitably standardised experimental procedures and methodologies for nuclear materials exposure, characterisation and testing, be they destructive, non-destructive or microstructural. This network is eventually meant to offer the nuclear industry a reference for any specific materials qualification need that may emerge. A connection with initiatives coordinating the use of neutron irradiation facilities is part of this endeavour.

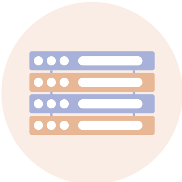


b. **Nuclear materials acceleration platforms (nuclear MAPs).** MAPs are integrated, highly autonomous systems that combine advanced characterisation and modelling with modern digital techniques for materials fitness and sustainability by design. Here the goal is to apply, to the benefit of nuclear energy, methodologies that have already been used in other technology frameworks for the systematised, targeted and accelerated improvement, development, and even discovery of materials, with the promise to drastically reduce time to market and enhance innovation [26]. The inclusion in the loop of charged particle (ions, protons, electrons, etc.) irradiation facilities is one of the specificities of a MAP applied to nuclear materials.

c. **Advanced predictive methodologies.** The focus is on suitably blending physical and data-driven (i.e., artificial intelligence-based) multiscale models for the development of advanced predictive methodologies that, while being characterised by strong physical rooting, are also fast and efficient enough to be of direct application for industrial needs.

1. These Grand Goals are consistent with, and contribute to, the research and innovation activities 1, 2, 7, 8 and 9 of the SET plan implementation plan on nuclear safety (action nr. 10, *https://setis.ec.europa.eu/implementing-actions/nuclear-safety_en*) and support the key enabling condition 5.

d. **Improved material and component health monitoring.** The goal is to develop the key technologies that enable the application of advanced monitoring methods through non-destructive examination and testing. These, coupled with suitable diagnostics and simulation tools, including the above advanced predictive methodologies, enable the widespread implementation of digital twins for optimised component and plant life management and increased safety.



e. **European nuclear materials' FAIR database.** The objective is to draw on underway work to establish an efficient platform, including all relevant ontologies, standards, regulations and procedures for nuclear materials' data collection, storage, management and use, following FAIR (findability, accessibility, interoperability and reusability) principles.

The five research lines described above are transversal to all materials classes and varieties shown in Figure 2, irrespective of the specific nuclear generation application. They profit from the opportunities offered by modern digital techniques, such as artificial intelligence, blockchain, 3D visualisation, data analytics, high-performance computing, robotics, etc. Together, these approaches and tools allow more efficient plant life and safety management, as well as better use of resources, and will thus improve the competitiveness of the nuclear sector.

Nuclear materials test-beds and nuclear MAPs inherently require coordinated use of (present and future) European assets and facilities. Available schemes and roadmaps for access to, and use of, major infrastructures (essentially materials testing reactors and charged particle irradiation facilities) that are being designed in the parallel JHOP2040 coordination and support action [27] or established in the framework of either ongoing projects (e.g., OFFERR [28]) or international organisations (e.g., OECD/NEA's FIDES framework [29]) should be exploited. Possibilities offered by research facilities that will become available in the next decade (JHR, MYRRHA, PALLAS, IFMIF-DONES) should also be considered. In turn, these European facilities and infrastructure plans require coordination with the materials research community, especially in identifying and prioritising the future experimental needs for material studies.

2 Creating an organised European research community on nuclear materials

The ambitious effort sketched in the previous section can only be achieved by promoting close, structured and continued collaboration between academia, research organisations and industrial partners all over Europe. This will enable the European nuclear materials research community to maximise the effect of the assets and financial resources available in Europe, avoiding duplication and fragmentation and achieving European self-sufficiency. Such structured collaboration is expected to provide orientation, prioritisation and, primarily, continuity to the five above R&D&I lines, leveraging significant national and industrial support. This is not fully achieved with the current EU financing model based on smaller, independent communities and projects. For example, in the Horizon 2020 framework programme, Euratom funded about 20 single nuclear materials' research-related projects, worth about 120 M€, when including the member states' contribution. The research community did benefit significantly from this support. However, this model did not enable the structured establishment and expansion of multidisciplinary, stable knowledge around clear targets.

The coordinated use of resources by a European partnership in the specific area of materials will eventually serve equally well different nuclear energy strategies and policies, from current to next generation, from fission to fusion. A large number of EU member states will be able to share the above goals, as they will inherently allow each of them to valorise their own research assets, in terms of knowledge and skills, as well as facilities and infrastructures, irrespective of their specific interests as to current and/or future nuclear systems. Such will be the bottom line of the identification of the transversal Grand Goals sketched in the previous section.

Notably, the methodology presented above is general, widely applicable to various nuclear systems, and goes beyond nuclear use. The final application determines the specific requirements that materials need to meet, the properties of interest, and the conditions under which these properties need to be tested. Nuclear materials belong to the much broader class of materials operating under extreme conditions, such as those used in other high-efficiency, low-carbon energy technologies, e.g., bioenergy, concentrated solar power, geothermal energy, and, to some extent, fuel cells and hydrogen, or wind energy. Resistance to harsh conditions is thus a requirement of wide application. **Therefore, even countries that do not adopt nuclear energy, or are phasing out, can find an interest in developing materials science tools** dedicated to the discovery, development, screening, qualification and monitoring of materials for harsh operating environments.

The whole framework and the steps to reach the Grand Goals of the partnership will be detailed in the SRA that is being developed within the

ORIENT-NM project [23]. The partnership structure, way of working, interaction with stakeholders and the opportunities offered by present and future large infrastructures in Europe will be analysed in separate and dedicated documents.

Beyond doubt, however, the instrument to achieve the above purposes is a European partnership on nuclear materials built around the stated Grand Goals.

3 Expected benefits of a partnership on nuclear materials

The proposed partnership's objectives have been drafted to advance all national nuclear energy strategies through optimised collaboration.

The research conducted by this partnership will further increase the safety, efficiency and economy of present nuclear energy. It is also a significant step toward introducing SMRs, which will reduce capital investment costs for nuclear facilities and provide economic opportunities for exporting nuclear energy, and Gen IV reactors, which will significantly improve sustainability.

The partnership will enable the retention and expansion of multidisciplinary scientific knowledge and stakeholder cooperation for continued technological innovation. This point is especially beneficial for nuclear energy, to which young researchers with varied backgrounds and skills will be attracted by the ambition and ample applicability of the pursued goals.

It will also produce fruitful results for all parties, including fusion and non-nuclear low-carbon energy technologies where operating conditions are extreme, becoming a source of interest for non-nuclear countries.

Because of the goals around which this partnership is built, it can as well be a seed for collaboration on materials beyond the nuclear sector, and act as a starting point for an all-encompassing initiative on materials, e.g., as is put forward in the Advanced Materials 2030 Manifesto [20], with which the proposed partnership's goals are entirely consistent.

On a broader horizon, advancing European nuclear materials research for current and future reactors plays directly into making Europe less reliant on oil and gas imports, increasing the security of energy supply while decreasing GHG emissions.

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