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**Author(s) name and affiliation**

Lorenzo Malerba, CIEMAT

Abderrahim Al Mazouzi, EDF

Marjorie Bertolus, CEA

Marco Cologna, JRC

Pal Efsing, KTH

Karl-Fredrik Nilsson, JRC

Petri Kinnunen, VTT

Mariano Tarantino, ENEA

Madalina Rabung, Fraunhofer

Benoit Tanguy, CEA

Miguel Ferreira, VTT

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## List of Abbreviations

AAR	Alkali Aggregate Reactions
ADS	Accelerator-Driven System
AGR	Advanced Gas Reactor
AIM1	Austenitic Improved Material #1
AM	Additive Manufacturing
AMR	Advanced small and medium-size Modular Reactor
ATF	Accident Tolerant Fuel
AOC	Active Oxygen Control
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium Uranium
CCA	Compositionally Complex Alloys
DEF	Delayed Ettringite Reactions
Dpa	Displacements per atom
eATF	enhanced Accident Tolerant Fuel
EERA	European Energy Research Alliance
ESNII	European Sustainable Nuclear Industrial Initiative
ETIP	European Technology and Innovation Platform
EU	European Union
FAIR	Findable, Accessible, Interoperable and Re-usable
F/M	Ferritic or Martensitic
GenII/III	Second/Third Generation (Reactors)
GenIII+	Advanced Third Generation (Reactors)
GenIV	Fourth Generation (Reactors)
GFR	Gas-cooled Fast Reactor
HEA	High Entropy Alloys
HIP	Hot Isostatic Pressing
HLM	Heavy Liquid Metal
HPC	High Performance Computing
HTR	High Temperature Reactor
IEA	International Energy Agency
JPNM	Joint Programme on Nuclear Materials
LFR	Lead-cooled Fast Reactor
LOCA	Loss of Coolant Accident
LTO	Long Term Operation
LWR	Light Water Reactors
MA	Minor Actinides
MAP	Materials Acceleration Platform
ML	Machine Learning
MOX	Mixed U-Pu OXides
MS	Member State
MSR	Molten Salt-cooled Reactor
MTR	Materials Testing Reactors
NC2I	Nuclear Co-generation Industrial Initiative
NDT&E	Non Destructive Testing and Examination

NECP	National Energy and Climate Plan
NPP	Nuclear Power Plant
NUGENIA	Nuclear GenII&III Alliance
ODS	Oxide Dispersion Strengthening
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SCWR	Super-Critical Water-cooled Reactor
SETplan	Strategic Energy Technology plan
SFR	Sodium-cooled Fast Reactor
SMR	Small and medium size Modular Reactors
SNETP	Sustainable Nuclear Energy Technology Platform
SRA	Strategic Research Agenda
TRISO	TRi-structural ISOtropic particle fuel
TRL	Technology Readiness Level
VHTR	Very High Temperature Reactor
VVER	Vodo-Vodyanoi Enyergeticheskiy Reaktor (water-water power reactor)

## Abstract

Nuclear energy is presently the single major low-carbon electricity source in Europe and is overall expected to maintain (perhaps eventually even increase) its current installed power from now to 2045. Long-term operation (LTO) is a reality in essentially all nuclear European countries, even when planning to phase out and new builds are planned. Moreover, several European countries, including non-nuclear or phasing out ones, have interests in small modular reactors and next generation nuclear systems. In this framework, materials and material science play a crucial role towards safer, more efficient, more economical and overall more sustainable nuclear energy. This document proposes a research agenda that combines advanced materials science practices combined with modern digital technologies to pursue a change of paradigm that promotes innovation, equally serving the various nuclear energy interests and positions throughout Europe. After the presentation of materials needs for nuclear energy, this document overviews the relevant issues concerning four families of materials: metallic and concrete structural materials and fuel element materials (fuels and cladding) used in current generation reactors and envisaged for next generation reactors. It then describes the materials science research lines that are common to all nuclear materials classes, identifying for each of them a strategic research agenda and goals. Among these goals are the creation of nuclear-oriented integrated materials qualification test-beds and materials acceleration platforms (MAPs), extendable to materials that operate under harsh conditions. Another goal is the development of intelligent approaches for materials health monitoring based on different non-destructive examination and testing (NDE&T) techniques. Blending models that suitably combine physics-based and data-driven approaches for materials behaviour prediction can valuably support these developments, together with the creation and population of a centralised, FAIR database for nuclear materials. The document finally indicates the envisaged implementation and milestones for the next 5, 10 and 15 years to reach these goals.



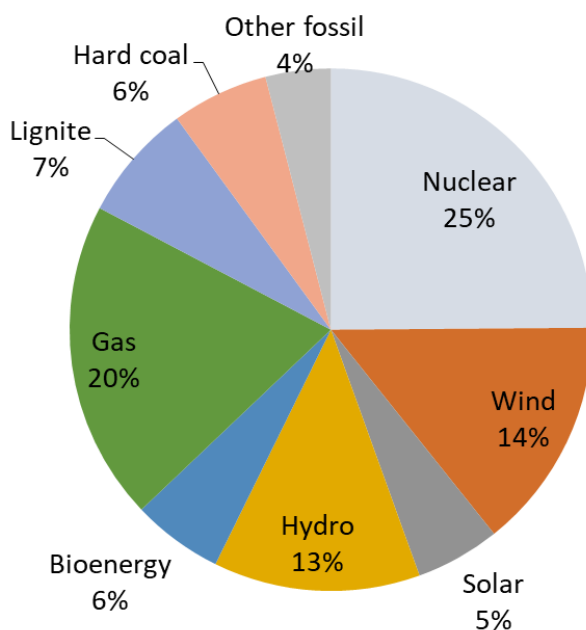
## Foreword

This document is the final version of the Strategic Research Agenda of the ORIENT-NM project. It has its roots in the published article of reference [1]. It was compacted in the introductory section 1, extended to include concrete and fuel cladding materials in section 2 and expanded to provide a position on important topics that had been previously overlooked when describing the research lines and relevant goals in section 3. It also provides a plan for the next 5, 10 and 15 years in section 4, including a short description of the benefits expected by an instrument such as a partnership.

## 1 Introduction

### 1.1 Towards Sustainable Nuclear Energy

With 685 TWh<sub>e</sub> produced in 2020, i.e.,  $\frac{1}{4}$  of the total production from all sources, nuclear energy is the single largest source of low-carbon electricity in the European Union; see Figure 1 [2].



**Figure 1.** Electricity generation by fuel in the European Union in 2020 [2]. The sum of renewables (wind, solar and hydro) exceeds the contribution of nuclear, which, however, represents the single major low-carbon electricity source.

Thus, nuclear energy plays an important role, in alliance with all renewables, towards climate-neutrality in Europe by 2050. Despite widespread perception that nuclear energy is being abandoned in Europe, an analysis of the national energy and climate plans (NECP) and other official sources [3,4,5] reveals that, by 2045, since some countries are progressively phasing out, but others intend to keep using nuclear power and will expand their fleet, the number of operating reactors in Europe will probably be only between 5% and 12% less than now, with almost unaffected total installed power capacity [6]. It may even eventually increase, via long-term operation (LTO), i.e., pro-active extension of the lifetime of reactors, as well as power uprates of operating reactors and also new builds. The European Union (EU) decision to include nuclear energy in the taxonomy for

sustainable finance will facilitate and perhaps amplify this process. LTO is indeed recommended by the International Energy Agency (IEA) as an important affordable contributor to progressive electricity decarbonisation and in the EU the economic case for nuclear lifetime extension is especially strong, even if the decrease in wind and solar photovoltaic costs accelerates [7]. Accordingly, LTO is a reality in essentially all nuclear European countries, even some of those that are eventually planning to phase out [6]. In addition, several countries have expressed their interest in small modular reactors (SMR). SMRs feature a power output between 10 (or less) and 300 MWe and a construction based on the idea of higher degrees of modularisation, simplification and standardisation compared to larger nuclear reactors [8]. A sub-class of them, denoted as micro-reactors, would produce 1–20 MWe and would be fully factory fabricated, transportable and self-adjusting [8,9,10]. SMRs are largely perceived as game-changers by the nuclear industry, provided that national legislations accompany and facilitate standardised modular construction needs in terms of regulations, while global deployment will require a certain degree of harmonised licensing [8]. Three water-cooled SMRs are being designed in Europe [11,12,13]. Water-cooled SMRs may also be used for combined electricity and heat generation, thus expanding the use of nuclear energy to applications such as hydrogen production via high temperature steam electrolysis [14,15], sea water desalination (largely already a reality) [16] and district heating [12,17,18]. In addition, several European countries, including non-nuclear or phasing-out countries, have research and development interests in next generation nuclear systems. In this context, the concerned research community in Europe, especially the nuclear materials community, needs to be at the forefront and ready to support with effective and cutting-edge strategic agendas the continental nuclear developments, in order to guarantee ever increasing sustainability.

Public opinion and also decision-makers, of several European countries express five main concerns regarding nuclear energy that hamper its full-hearted use as a sustainable part of the energy transition: safety of operation and severe accident risk; management of long-lived nuclear waste; economics (especially for initial investments and back-end costs) and long construction times; limitation of fuel resources; and possible misuse of fissile materials. They need to be seriously addressed.

In the short term, these issues need to be addressed with currently operating nuclear power plants of second or third generation (GenII/III), 80% of which worldwide are light water-cooled (and moderated) reactors (LWR). Gen III+ new builds are also LWRs. About 80% of the LWRs are pressurised water reactors (PWR), the remainder being boiling water reactors (BWR). About 11% of the total are heavy-water cooled (and moderated) reactors, e.g., CANDU (CANadian Deuterium Uranium). The resto are graphite moderated, either gas-cooled or water-cooled reactors. All of these types exist (or existed at some point in time) in the EU and associated countries.

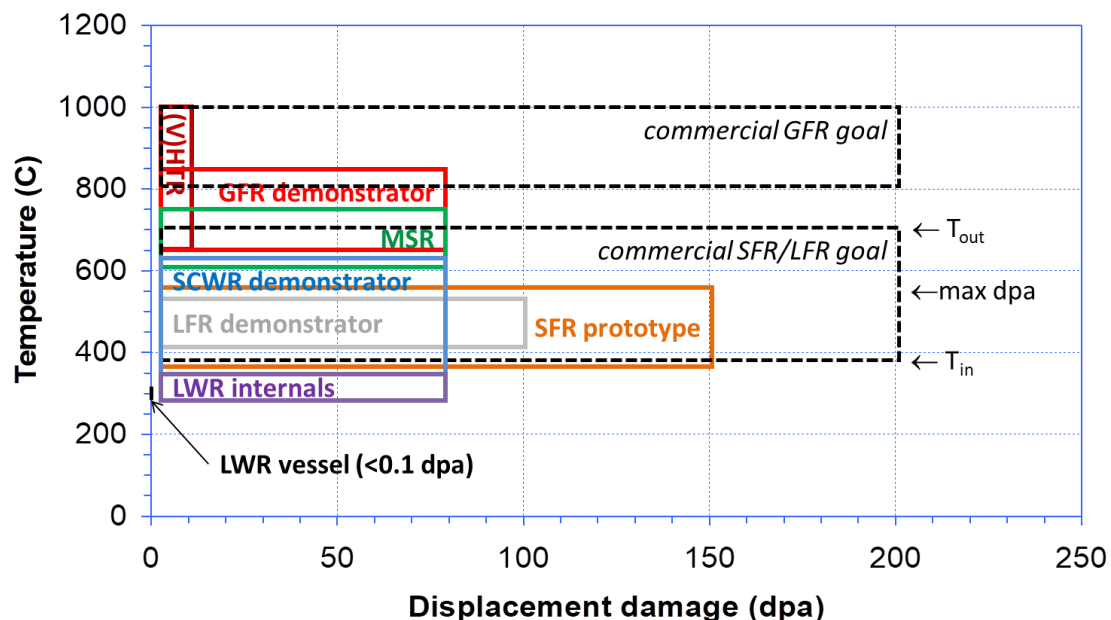
There are still ample margins, through research and development, to increase substantially the safety, performance, economy and sustainability of nuclear reactors of established technology, as well as to further reduce their already low impact on the environment. Continuous improvements of operational practices and nuclear safety of current reactors, in the context of an increased flexibility of the network are routinely pursued by the European nuclear industry, e.g., by optimisation of maintenance strategy, and are already the object of extensive research in Europe and elsewhere [19,20,21,22].

Deep geological disposal of highly radioactive waste is on the other hand recognised as a safe and secure long-term solution by most nuclear countries [23,24], even though some wish to postpone its implementation and evaluate other options [24].

Finally, light water SMRs are based on known technology and can thus be a relatively fast answer to the high capital costs and long construction times that currently hamper new nuclear builds, especially in Europe, while offering better flexibility and adaptability to different uses, in co-habitation and collaboration with intermittent renewables [25,26].

In the longer term, the above nuclear energy issues can be dealt with, and the overall sustainability greatly increased, through the commissioning and deployment of fourth generation (GenIV) liquid metal or molten salt-cooled fast neutron reactors, along with the facilities that are needed to close the nuclear fuel cycle [27]. By pushing the burnup to high values, i.e., keeping the fuel remain longer in the reactor, fast reactors can produce more  $^{239}\text{Pu}$  from the  $^{238}\text{U}$  by neutron capture than fissile nuclei consumed by fission [28]. Fast neutron systems thus enable circular economy: through recycling, they significantly improve the use of natural resources, strongly reducing mining and ensuring fuel availability and self-sufficiency for centuries and perhaps millennia.

Fast reactors must use non-aqueous coolants, because moderation (neutron slowdown) is not sought for. This obliges to operation at temperatures well above those of current LWR (about  $300^{\circ}\text{C}$ ), because liquid metals or molten salts need to remain fluid and must thus be kept above their melting point. Depending on their technology and on whether we consider prototypes or commercial reactors, the operating temperature of GenIV fast reactors will vary between  $400$  and  $700^{\circ}\text{C}$  [29,30,31], the higher value being meant to maximise energy efficiency. These high operating temperatures, together with the higher neutron dose, enable much better use of the available resources in terms of energy harvesting. Figure 2 illustrates the operating regimes in terms of temperature and irradiation damage envisaged for GenIV prototypes/demonstrators in Europe, including possible commercial plant target conditions, compared to current generation LWRs.



**Figure 2.** Schematic and indicative illustration of operating conditions envisaged in European GenIV prototypes/demonstrators designs, as compared to current LWRs (assuming 60 years operation) and commercial GenIV reactors. The temperature range is defined by inlet/outlet temperatures (Cf. Table 1 for abbreviations). The maximum dpa concerns structural components. (dpa, displacements per atom, measure the radiation dose received by materials [32,33]).

Another virtue of GenIV systems is that, since Pu is removed from the fuel for reuse, they enable the long term radiotoxic impact of waste to be abated. This is especially true

when minor actinides (heavy elements present in low quantity, but significantly contributing to long term radiotoxicity and heat production) are transmuted in the reactor itself into shorter lived fission products, after sufficiently high burnup [34], or using dedicated devices such as accelerator driven systems [35]. These practices can reduce volume of remaining radioactive waste and emitted heat flux by one order of magnitude, and the radiotoxicity timespan to a few hundred years, thus significantly relieving the requirements of anyway necessary geological disposals. In addition, new fuel designs and appropriate reprocessing strategies protect against diversion of fissile materials [36,37]. GenIV reactors will also feature high safety standards because the use of liquid metals or molten salts as coolants enables operation at atmospheric pressure and facilitates the design of passive systems [38].

In summary, fast GenIV systems significantly reduce the quantity of the transuranic waste and its long-term hazard, optimise the use of fuel resources available on earth and enable high safety and security standards. They are thus expected to be attractive for the public opinion at large as a fully sustainable low-carbon source of energy.

However, despite existing experience with these systems [39][40][41], see also Table 1<sup>1</sup>, for a number of reasons that span from technological to economic and political, no widespread commercial deployment of GenIV systems seems likely until beyond the mid of this century, at least in Europe. GenIV reactors, therefore, will probably not contribute to the decarbonisation of society and economy by 2050. Nor will fusion, which targets the demonstration of the connection to the grid for the first time in 2050 [42], and is unlikely to be commercially viable and deployed before the end of the present century.

In this context, gas-cooled reactors targeting high operation temperature may be a bridge between current and future nuclear generation. Graphite moderated power reactors cooled with CO<sub>2</sub> that reach outlet temperatures in excess of 600°C [43] are still operated in the UK. Graphite-moderated high temperature reactors (HTR) that adopted different fuel designs and employed He as coolant have been operated in the past, with outlet temperatures round 750°C [44,45,46]. HTR are thus known technology and could be already considered for low-carbon industrial heat production in addition to electricity (cogeneration), including hydrogen production by thermal, rather than electrolytic, processes, provided that they are considered attractive enough by industrial heat and hydrogen consumers. Importantly, the SMR concept can be extended to any nuclear technology, leading to the design of advanced modular reactors (AMRs) that use non-aqueous coolants. Therefore, small and modular graphite moderated, gas-cooled HTRs that operate above 600°C appear as an especially attractive technology that is already at reach to flexibly provide carbon-free industrial or district heat [47,48]. High safety levels are guaranteed here by the combination of the high thermal stability of graphite with the reduced power of the system, which should indeed enable significant reduction of the Emergency Planning Zone [49], and ideally its removal. In the longer term, liquid metal or molten salt cooled AMR also appear to be attractive solutions [50] and might anticipate the deployment of GenIV systems to before 2050 [51]. In fact, the GenIV portfolio foresees two so far never built gas-cooled concepts that target operating temperature in excess of 800°C [52]: the very high temperature reactor (VHTR) [53] and the gas-cooled fast reactor (GFR) [54]. Both could provide heat for a wide variety of industrial applications, while producing electricity with very high efficiency (~50%–60%), the GFR additionally including the benefits of fast systems. Yet, they are both considered very long-term developments. Finally, another GenIV concept that is often considered as an evolution of LWR, and thus in principle more readily available, is the super-critical

<sup>1</sup> Sodium-cooled fast reactors were operated in Europe [48] and are still operated in Russia [40], while a prototype is being built in India. In addition, a lead-cooled fast reactor demonstrator is being constructed in Russia [41].

water-cooled reactor (SCWR) [55]. Table 1 summarises the main features of GenIV technology concepts and illustrates the existing experience; Annex 1 includes some information on related design work in Europe.

**Table 1.** Main features of next generation nuclear systems and existing experience, following GenIV-related nomenclature and references [53,54,55,56,57].

System Abbreviation	Coolant	Neutron Spectrum	Reactor Type Already Built	Power Reactors in Operation
SFR	Liquid sodium	Fast	Yes	Yes
LFR	Liquid lead	Fast	No <sup>1</sup>	No
GFR	Gas (He or other)	Fast	No	No
SCWR	Super-critical water	Thermal or Fast	No	No
MSR	Molten salt	Thermal or Fast	Yes	No
HTR	Gas (He or other)	Thermal	Yes	Yes
VHTR	Gas (He or other)	Thermal	No	No
ADS	Lead-bismuth eutectic	Fast	No <sup>1</sup>	No
Fusion	Water/He/Pb-Li/...	(Very) fast	No	No

<sup>1</sup>PbBi was used as coolant in submarine fast reactors. LFR is under construction in Russia.

In this planned journey towards safer, more efficient, more economical and overall more sustainable nuclear energy, materials and material science, thus research on materials, play a crucial role.

## 1.2 Role of Materials and Materials Science for Sustainable Nuclear Energy

One of the main reasons why not all GenIV systems are technologically ready yet and that determines the shorter- or longer-term deployment of these systems is the fact that the targeted high temperatures, combined with very high neutron dose in core components (due to the high burnup) and with the use of non-aqueous coolants, will subject materials and components to especially degrading conditions.

As an extreme example, in the GFR temperatures around 2200°C may be reached at the centre of the fuel in normal conditions, while temperatures may exceed 1000°C in structural materials in off-normal conditions. These temperatures, coupled to temperature gradients up to 500–1000°C/mm [58] in some cases, will inflict severe thermal and mechanical stresses on the fuel and plant components, requiring materials with high thermal stability and resistance to cyclic loading. In addition, cooling fluids are chemically hostile environments with detrimental effects on structural materials in terms of corrosion, dissolution, or erosion [59,60,61,62,63]. All of these processes lead to thickness reduction, which can be strongly penalizing, especially for thin components such as cladding. In addition, all of these coolant effects are exacerbated by high temperature, to the point that they are often the main limiting factor for the outlet temperature. Inside the fuel pin, finally, chemical interactions between cladding materials and fission product compounds is a serious concern [64].

Furthermore, core materials in GenIV reactors are expected to be exposed to varying and generally high levels of irradiation dose and dose rates: 1 dpa/day in the fuel [65] and 100 dpa or beyond in the cladding over its time of irradiation [66], although likely less than 5 dpa in the in-vessel structures over the whole reactor lifetime [67]. Exposure



to irradiation is known to produce a number of detrimental consequences on materials. In structural materials, these range from hardening and embrittlement with loss of elongation to changes in dimension and shape due to swelling and creep [68, 69,70,71]. In addition, if the neutron spectrum leads to transmutation with production of helium ( $\alpha$  particles) and/or hydrogen (protons) depending on material composition, the mentioned effects may be significantly exacerbated and the temperature ranges of susceptibility increased on the high side. This problem is especially serious for fusion and Ni-containing materials. Radiation-induced hardening with subsequent loss of elongation and embrittlement typically occurs when irradiating at low temperature (where “low” depends on the material. For instance in steels, the threshold is roughly below 400°C, but in tungsten alloys it is below 800°C [72]). Hardening, and subsequent embrittlement, appear to some extent from the very beginning of the irradiation and increase with dose, but generally saturate at some point in time. In contrast, dimensional changes typically appear above a certain irradiation temperature (about 400°C in steels) [73] and occur only at high enough dose, beyond 10 dpa, without necessarily saturating with increasing irradiation (only the rate does). Clearly, these high temperature/high dose effects, which are hardly observed in current generation reactors, are expected to be significant in next generation ones.

Currently, no material of industrial production can sustain the target GenIV operating conditions for sufficiently long time to provide the reliability and availability that is required from crucial components, so as to ensure economical commercial viability of systems of this type. Thus, the availability of materials with superior resistance to irradiation and corrosion in a wide enough temperature window is essential to make GenIV reactors a reality [74]. The realization of thermonuclear fusion on earth largely shares similar, if amplified, challenges [42,75,76]. A staged approach initially proposed for the GFR is therefore proposed for all the GenIV systems by designers, with a start at temperature and irradiation levels compatible with currently available materials, to be increased in later stages. Once the demonstrator is in place, it can be used as a laboratory for further materials upgrade for increasingly demanding conditions, before commercial plants can be designed (see Annex 1). Research on materials can thus be split into a number of steps, enabling a distinction between near term and long term application. The availability of a large palette of materials for various objectives, with superior resistance to irradiation and corrosion in a wide enough temperature window, is crucial to make nuclear energy fully sustainable.

Concerning current generation reactors, lifetime extension can be (and indeed has been) granted with current materials technology, while light water-cooled or high-temperature gas-cooled SMRs can be designed by making use of known and proven materials. However, innovative materials solutions enabling safety and efficiency to be increased, and costs to be abated, with equal or improved efficiency and safety, or ensuring that the component supply chain can be efficiently maintained or improved, are a clear asset. These materials solutions include crucially the use of advanced manufacturing techniques and processes for timely, efficient and targeted repair and replacement of components. In this same context, tools that are capable of better predicting the behaviour of materials and components in operation and in accidental scenarios are an obvious support to increased safety. In addition, aspects of circularity and life cycle assessment necessarily require specific attention in connection with sustainable decarbonisation using nuclear energy. These aspects range from a closer attention to the supply of raw minerals to the optimization of component lifetime by appropriate maintenance and replacement, via monitoring of materials’ and components’ health in operation, and to recyclability or (if possible) reusability, thus anticipating decommissioning issues.

These are all issues to be addressed with the tools of modern materials science, which is crucial to increase the sustainability of nuclear systems of any design. In order for innovation in a wide sense to be boosted, there is a particular need to move, also for nuclear applications, in the research approach direction that has been clearly identified for all other technology fields where materials are important [77,78]. With total independence of the technology (or market) of final application, modern materials science is indeed based on a unique paradigm, which can be expressed in terms of two **guiding principles**:

1. Materials should be designed from the start in view not only of their final application, but also maximizing their sustainability in terms of: (1) replacement of critical raw materials with less critical ones in their chemical composition; (2) full consideration of their possibility of second use after their first life.
2. The processes of materials discovery and development need to become significantly faster and more sustainable than now; manufacturing processes also need to become more sustainable and better controlled; the whole material/component lifecycle, from fabrication to recycling or re-use through of course operation needs to be monitored to ensure functionality and made more sustainable.

In 2019, the Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA JPNM) — see Annex 2 — produced a Strategic Research Agenda to ensure that suitable structural and fuel materials are available for the design, licensing, construction and safe long-term operation of GenIV nuclear systems [29]. In parallel, the Sustainable Nuclear Energy Technology Platform (SNETP) and its three pillars — see Annex 2 — updated their Strategic Research and Innovation Agenda, addressing the whole spectrum of nuclear reactor generations, including considerations on materials of specific relevance for current generation reactors [79]. In 2021, a more structured discussion was launched concerning the need to organise the European nuclear materials research community into a better structured collaboration framework, with a single vision through reactor generations, as part of the ORIENT-NM project [80]. As a result, we propose here a research agenda that, based on the exploitation of advanced materials science practices combined with modern digital technologies, pursues a change of paradigm, which is deemed suitable to promote innovation and should be the way to go for the future in the nuclear materials field, in Europe and elsewhere, with the crucial involvement of not only research organisations, but also, and importantly, industry, technical support organisations and, crucially, regulators.

The structure of the document is as follows: Section 2 overviews the relevant issues concerning four families of materials: metallic and concrete structural materials and fuel element materials (fuels and cladding) used in current generation reactors and envisaged for next generation reactors. Section 3 describes the materials science approaches that are common to all nuclear materials, identifying for each of them what the goal of a research agenda should be; these goals are finally discussed in Section 4 in terms of opportunity, feasibility and envisaged implementation, leading to the conclusion in Section 5.

## 2 Materials for Current and Future Nuclear Systems and Relevant Issues

Seven classes of materials are involved in nuclear reactors, where they play a significant role in their safety and efficiency of operation, see Figure 3. We present here the main aspects to be considered for four of these materials classes: metallic and concrete

structural materials, as well as fuel and fuel cladding materials. Details on the application of these materials and needs for research, as well as references, are given in the materials ID cards prepared in ORIENT-NM [81]. The fact that no materials ID cards could be produced for the other three classes is a sign of the fact that the corresponding European research communities are not yet ready to identify a roadmap for those classes. This is why we limit ourselves in the present document to four of the seven classes.

	Concrete	Metallic alloys for structural components	Refractory materials for structural components	Polymers for cables and structural applications	Fuel cladding materials	Nuclear fuel materials (fissile and fertile)	Materials for neutron control: absorbers, moderators, reflectors
Safety	External containment, last barrier to release of radioactive material, protection of reactor core from external agents	Vessel: main barrier to release of radioactive material	Maintain integrity at high temperature in both operating or accidental conditions	Efficient transmission of energy or signals	Barrier to radioactive material release into coolant	Inherent barrier to fission product release Heat production even after shutdown	Control of reaction
Efficiency		Piping and supports define inlet/outlet temperature	Higher temperature brings higher efficiency		Define possibility of high burnup	There is no reactor without fuel! Defines neutron spectrum, burnup, etc.	Define neutron spectrum and criticality

**Figure 3.** Classes of materials constituting nuclear reactors and roles in safety and efficiency of operation.

## 2.1 Metallic Structural Materials

### 2.1.1 Metallic Structural Materials for Current Generation Reactors

The main pressure boundary components in LWRs, i.e., the reactor pressure vessel (RPV), the pressuriser, and the steam generator shells, as well as the turbine (except the blades) and the condenser, are generally made of low-carbon, low-alloy ferritic (bainitic) steels. The secondary circuit piping in PWR is also made from steels of this type. Austenitic stainless steels, particularly AISI 304 and/or 316L in P/BWR, and Ti-stabilised (similar to AISI 321) in the Russian PWRs (VVER), dominate as core structural materials, as well as for the primary circuit and its components. Steam generator tubes are often made of Ni-based alloys. Austenitic stainless steels and Ni-based alloys are selected because of their good resistance to water corrosion up to high temperature. Thus, austenitic steels (AISI 308 or 309) are also used as liners on the inside surface of pressurised vessels for corrosion protection. Low-carbon, low-alloy steels have, in turn, the advantage of superior weldability through thick sections and prices that are 4–5 times lower than austenitic steels. Both are important items for large components such as the pressure vessel. In the case of heavy-water reactors of CANDU design, low-neutron absorbing Zr alloys are used for the pressure tubes that contain each fuel assembly, allowing the use of natural uranium as fuel. Because of industrial constraints and safety requirements, the materials choice for all these components is unlikely to change: it is indeed recommended that these components are manufactured with proven, easy to use materials, the properties of which are vastly known from many years of experience. Minor changes are however possible for new builds, in terms of minor compositional and heat



treatment tuning, within specifications, as well as the introduction of more restrictive specifications. They are part of the continuous improvement that, in the past, led to changes of composition for materials of a specific components based on field experience. With a view to continuously increasing safety, in the case of these materials and components what matters most is: (1) to be able to predict increasingly better their behaviour in operation in order to estimate correctly their residual life, optimise inspection plans and foresee timely repairs and replacements, thereby guaranteeing that all components and systems maintain their integrity and functionality at all times and in all circumstances; (2) especially in a framework of LTO, to be able to optimally replace and repair components, making sure that this is done in full compliance with nuclear safety regulations.

## 2.1.2 Metallic Structural Materials for Next Generation Nuclear Systems

Only a few classes of materials have the potential to sustain the above described operating conditions in Gen IV reactors for the required operation time, depending on the function of the corresponding component and the type of system [84]. These classes of materials are wide, because no final choice has been made yet and because the variety of next generation nuclear systems is significant. The overlap with the materials that are being used in current LWR is small, as is made explicit in Table 2. However, materials for next generation reactors are in fact also considered for enhanced accident tolerant fuel (eATF) claddings for current reactors [82] (see section 2.4). These materials are briefly overviewed in what follows.

The GenIV demonstrators and prototypes planned in Europe (Annex 1) and outside envisage the use of austenitic steels as the dominant family of structural materials, almost irrespectively of the type of coolant. Particularly, 316L(N) is considered for most components, including the vessel, in almost all systems. The reason is that these materials are a good compromise between several requirements. With these materials, however, no design solution will ever enable the conditions that are targeted for highest efficiency and best economy in commercial GenIV plants to be reached, especially in terms of high burnup. Thus, prototypes and demonstrators will have to work at temperature and irradiation dose regimes that may be significantly less ambitious than those targeted in commercial plants (Figure 2), following a staged approach, as described above. However, the existing return of experience from use of these austenitic steels in fast reactors that were built and operated in the past, such as, e.g., Phénix and Superphénix in France, provides a wealth of experimental data. On these bases, design rules have been already established for them and introduced in standard codes: this is crucial for executive design and timely licensing.

Depending on the system, other known materials may also enter demonstrator and prototype designs, e.g., ferritic / martensitic (F/M) steels and, for higher temperatures, Ni-base alloys or graphite. However, in demonstrators and prototypes these two metallic materials are mainly considered for out-of-core components, such as steam generators. In contrast, graphite is considered for HTR cores thanks to the significant experience that exists already on its use. There are reasons to consider F/M steels and Ni-base alloys also for core components, particularly for systems cooled with liquid metals or molten salts. But this will likely happen only in second phases of demonstrators or in perspective commercial reactors, provided that these materials, or more likely improved versions of them, are previously qualified for the relevant operating conditions and codified for design. For instance, F/M steels exhibit better thermal properties and only swell above 200 dpa, which is crucial to attain high burnup, but they suffer from other

limitations that need to be overcome, e.g., low temperature embrittlement and unsatisfactory creep resistance. Oxide dispersion strengthening (ODS) steels have been long studied as a solution to this issue [83], but they are not yet sufficiently developed for component design and operation. As a perhaps shorter-term alternative, pathways to improve the swelling resistance of conventional austenitic steels do exist [84].

Systems that target operation around or beyond 800°C can only be conceived using, as structural materials, either Ni-based superalloys, such as alloy 800, or, more appropriately, refractory metallic alloys. Higher temperatures are the realm of ceramic materials: graphite, the base core material for the VHTR, SiC<sub>f</sub>/SiC composites, which are main target material for GFR core components, as well as a plethora of other materials, depending on component and function. However, these materials are generally not fully defined: especially for refractory alloys, innumerable possibilities and combinations exist. They are therefore far from being qualified and codified for design under the target conditions. In such a long term perspective, further gateways to improved future reactor performance are opened considering other perspective materials [84], e.g., ODS-Mo alloys, high entropy alloys (HEA), better called compositionally complex alloys (CCA), or MAX phases. The spectrum of possibilities is very wide and it may be difficult to orientate in it. The relevant issues and R&D challenges for this vast class of materials can be found in the respective materials ID cards [81] and are therefore not repeated here. Some will emerge in the following sections, especially 2.3.1 and 2.4.2.

### 2.1.3 Summary of Structural Materials Used or Envisaged

Table 2 lists the various structural materials and indicates in which systems they are used, including use in current generation reactors, if any.

**Table 2.** Summary of structural materials through reactor generations. RPV = reactor pressure vessel, F/M = ferritic/martensitic, ODS = oxide dispersion strengthened, AGR = advanced gas reactor, (V)HTR = (very) high temperature reactor, GFR = gas-cooled fast reactor, HEA = high entropy alloys, CCA = compositionally complex alloys.

Materials	Use in GenII/III	Use in GenIV	Notes
Low alloy bainitic steels	Pressure vessel, pressuriser, steam generator shell, turbine, condenser	None	Upper limit of operation temperature window < 400°C
Austenitic steels	Core components liner RPV	Vessel, core components	Experience from use in thermal and also fast reactors. Improved swelling resistance (by, e.g., Ti stabilization) and corrosion protection in heavy liquid metals (using, e.g., coatings or Al-containing alloys) needed
Zr alloys	Power channels in heavy-water reactors	None	Historical example of material development specific for nuclear [85]
F/M steels	None	Core components where swelling must be low	Swelling-resistant, good thermal physical properties. Creep and corrosion resistance need improvement using e.g., ODS, and coatings / Al-containing alloys, respectively
Ni-base alloys	Steam generator tubes	Steam generators, in the longer term core components for high	Good corrosion and temperature resistance. Susceptible to embrittlement due to He and H

		temperature operation	production via transmutation when irradiated: improvement needed using, e.g., ODS
Refractory alloys	None	In-core and out-of-core components (also vessels) where operation temperatures round 800°C are expected	Wide spectrum of possibilities: Ni-base and Ti-base alloys may enter this category, composed by Mo-, Nb-, Ta- and V-alloys (W-alloys for fusion)
Graphite	Still used as moderator only in the core of UK AGR	Moderator with structural functions as well in (V)HTR concepts	Vast experience on its use. Very high thermal stability. Since it is a moderator, its use is limited to thermal spectrum reactors.
Ceramic materials (SiC <sub>f</sub> /SiC, other)	None	Core components in VHTR and GFR	Composites and other ceramics have been long studied, but are still far from being fully qualified and codified. Design rules need to account for brittleness. Often costly
Prospective materials (HEA/CCA, MAX phases...)	None	Mainly coatings, but not clearly identified	These materials are investigated because of their promising properties, but even more because of the possibility of applying modern materials development techniques based on combinatorial fabrication

## 2.2 Concrete Structural Materials

Concrete is a heterogeneous material composed of cement binder, fine aggregates (sand) and coarse aggregates mixed with water which hardens with time. There is an extremely large variety of compositions depending on the types of cement and aggregates, as well as their proportions. Furthermore, certain admixtures can be added to the mixing process to enhance certain fresh and/or hardened concrete properties, e.g., plasticizer for workability in the fresh state; air entrainment for resistance of hardened concrete in freezing environments.

Reinforced concrete structures in NPPs are composed of several constituents, including concrete, conventional steel reinforcement, pre-stressed steel, steel liner plates, and structural steel. While unique in application, they share many physical characteristics with conventional concrete structures. Experience shows that ageing degradation of reinforced concrete structures can be a result of exposure to aggressive environments, excessive structural loads, accidental conditions, use of unsuitable materials, poor material and construction quality, and inadequate, or the lack of, maintenance.

Understanding the development of ageing mechanisms and corresponding degradation in concrete structures is crucial for ensuring adequate ageing management and transition to LTO for GenII and GenIII. The nuclear safety-related concrete structures will perform identical functions in GenIV plants.

As concrete ages, changes in its properties will occur naturally as a result of continuous microstructural changes (being complex due to e.g. hydric, thermal and chemical gradients and linked with processes such as drying, leaching, mechanical loading), as well as environmental interaction, leading to adverse performance of the cement paste matrix and aggregates under physical or chemical attack. The effect of age-related degradation often leads to a reduction in mechanical and durability properties of concrete structures, which could result in their inability to meet functional or performance requirements [86]. Although the vast majority of these concrete structures will continue

to meet their functional and performance requirements during the initial licensing period, as well as during periods of extended service, it is reasonable to assume that, with the increasing age of the power plants, there will be cases where the concrete structures may not exhibit the desired durability without some form of intervention [87].

The key processes that need improved understanding, especially when considering ageing and long-term performance of concrete structures have been listed in [86], and are reflected in the corresponding materials ID cards [81].

## 2.3 Fuel Materials

Fuels and fuel elements must (1) Provide the power expected during their whole stay in reactor; (2) Use the fissile elements as best as possible to reduce the cost of energy production; (3) Confine the fission products inside the fuel elements in all operating and accidental conditions; (4) Maintain dimensional stability within design margins.

### 2.3.1 Fuel Materials for Current Generation Nuclear Systems

All LWRs around the world currently use ceramic actinide oxides (uranium dioxide  $\text{UO}_2$  or mixed uranium-plutonium oxides  $(\text{U,Pu})\text{O}_2$ ) as fuel, encased in Zr-based alloy cladding. In most cases, the uranium is enriched to 3–5%  $^{235}\text{U}$ . The oxide fuel/Zr-alloy system has been optimised over many decades and performs very well under normal operation and anticipated transients. However, because of the highly exothermic nature of the chemical reaction between Zr and steam, in case of temporary loss of core cooling with uncoverage of part of it, the resulting excess generation of heat and hydrogen may produce significant undesirable core damage. This happened during the 2011 Fukushima Daiichi power plant accident caused by an earthquake followed by tsunami. Because of this, global interest has expanded in the last ten years to explore fuel elements with enhanced performance during such rare events, the so-called enhanced accident-tolerant fuel elements (eATF). This involves developments on the fuel itself and/or the cladding [82,88]. Both should exhibit higher thermo-mechanical stability and be designed and qualified to remain intact for a sufficiently long time even when subject to accidental conditions. Such type of fuel element, in combination with other systems, is expected to provide sufficient time for intervention in case of accident, avoiding too severe outcomes, while offering additional benefits in case of more frequent off-normal situations, as well as normal operation [89]. On the fuel side, research on enhanced performance has focused on improved  $\text{UO}_2$ , i.e., doped with oxides such as  $\text{Cr}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$  or  $\text{SiO}_2$ , or with high-thermal-conductivity metallic or ceramic phases, in order to enhance the fission gas release process by increasing the grain size and optimise mechanical properties; on higher density fuels (nitrides, carbides, silicides and metals); or on microencapsulated fuels (TRISO-SiC composites). The latter are intrinsically accident tolerant and have been already used in HTR that were operated in the past. The present challenge is to develop similar accident tolerance for LWRs.

### 2.3.2 Fuel Materials for Next Generation Nuclear Systems

Nuclear fuels and fuel elements for next generation reactors may differ widely, depending on the reactor concept, in geometrical configuration, composition, cladding and even physical state. Reactor fuels are based on compounds of one or more fissile and/or fertile nuclides, mainly of U and Pu. They can be either refractory oxides, typically U oxides and MOX, which are also used in current generation reactors, or other ceramics, such as carbides, nitrides and silicides, as well as metallic alloys. Other fuel concepts

consider ceramic/ceramic or ceramic/metal composites, as well as fluid molten salt fuels. Solid fuel may appear in various geometries: rods, plates or pellets. U oxides and MOX are the most industrially used fuel materials [90]. MOX is indeed currently the reference fuel for most fast neutron reactor demonstrators and prototypes in Europe, mainly because this family of fuels was used in the European fast reactor programme that led to the construction of Phénix and Superphénix [91]. The licensing of future fast reactors systems can thus take advantage of the extensive knowledge base on MOX fuel. The fabrication method has a large influence on the fuel performance, since it determines essential properties such as the porosity, the size of the Pu-rich agglomerates and the impurity levels. Furthermore, reactor core designs have evolved, so different pellet geometries are considered, e.g., high-density pellets with an annulus to regulate centre-line temperatures or low-density full pellets. Finally, reactor cores also differ because of the choice of the coolants and may be operated at various temperatures and power ratings [92], thus they necessitate further specific investigations. ADS, in addition, bring distinct issues that may impact fuel performance, for example the thermal stresses induced by frequent proton beam trips [93,94].

The sustainability of the fuel cycle can be significantly increased by Pu multi-recycling. Advanced nuclear fuel cycles foresee the extraction of minor actinides (MA), namely Am, Np and Cm, later introducing them in fresh fuel for their transmutation in fast reactors [29]. This can be achieved in homogeneous mode, by diluting a low content (a few % of heavy atoms) of MA in conventional fast-reactor fuel, exploiting the structural similarity of the various actinide oxides and their reciprocal solubility. This has minimal impact on reactor safety parameters and facilitates qualification, but implies that all fuel elements will contain some MA. Heavy shielding and remote handling will therefore be necessary for fuel fabrication and assembly production, because MA exhibit high neutron emission, thermal power and toxicity. In another concept, the heterogeneous mode, MAs are located only in specific assemblies that are placed at the periphery of the core of the reactor, which minimizes the perturbation of the behaviour of the core [29,95]. In this case, the number of MA bearing assemblies remains limited and these may be manufactured in dedicated plants. In both cases, however, a large R&D effort is required to ensure MA-bearing fuel qualification.

In the longer term, the adoption of mixed U and Pu carbides and nitrides (denoted as MX) could enable core performance optimisation [96]. These fuels moderate less, thus leading to harder neutron spectra, with shorter doubling times (time to produce twice as much fuel as consumed). They have similar melting point as MOX, but higher thermal conductivity. This enables operation with a larger margin to melting (safety margin) or with a higher linear power (economic gain) compared to oxide fuel. However, achieving high purities in these fuels poses some challenges in the fabrication process. In addition, the volatility of actinide carbides and nitrides at temperatures below the melting point may complicate Pu multi recycling if it was proven that the built-in Am component is more volatile than the U and Pu constituents.

HTRs also use fissile element oxides, but in the TRISO (TRi-structural ISOtropic) particle fuel form [97]. The TRISO particle is made of a fuel core that is currently composed of  $\text{UO}_2$  or U oxy-carbide (a mix of U oxides and carbides) and in the future may contain U nitrides. The fuel core is enrobed in a porous carbon buffer layer, a first pyrolytic carbon layer, a SiC layer and a second pyrolytic carbon layer, which altogether act as very effective barriers against fission product release. TRISO particles have a diameter of less than 1 mm and are very robust, being designed to resist neutron irradiation, corrosion, oxidation and especially high temperatures. In conventional TRISO compacts, the particles are encased in a graphite matrix, which in future systems may be replaced



by silicon carbide. The whole system is conceived to avoid the possibility of fuel melt in the reactor under any circumstance.

Finally, in molten salt reactors (MSR), the fuel can be dissolved in the coolant salt, so that fuel and coolant are one single medium. Molten halides (fluorides or chlorides) are used as carriers of the fissile (U, Pu) or fertile (U or Th) elements. The fuel synthesis route has thus very little in common with the established solid fuel pellets fabrication. Challenges lay in the optimization of the composition for what concerns neutronics and clean-up conditions. The in-reactor behaviour is also very specific of this type of fuel, for example in the aspects as follows (i) radiation effects are less important, (ii) thermal transfer depends on fluid dynamics and fluid thermal properties (heat capacity, thermal conductivity, density, viscosity and surface tension), and (iii) the solubility of the fission products in the fuel plays a major role for reactor safety. While many fission products are soluble in the fuel, noble gases and metals are not and need to be extracted during operation. This on-line separation of the fission products, which is needed to allow continuous operation, is a current topic of research. The impact of long-term corrosion towards structural materials also deserves attention.

### 2.3.3 Summary of Fuel Materials Used or Envisaged

Table 3 lists the different types of fuels and indicates in which systems they are used.

**Table 3.** Summary of fuels through reactor generations. MOX = mixed U-Pu oxide, MA = minor actinides, MX = carbides, nitrides..., TRISO = TRi-structural ISOtropic particle fuel, (V)HTR = (very) high temperature reactor, GFR = gas-cooled fast reactor, MSR = molten salt reactor.

Type of Fuel	Use in GenII/III	Use in GenIV	Notes
UO <sub>2</sub> /MOX pellets	All reactors	Mainly liquid metal (or supercritical water) cooled reactors, certainly in prototypes, including GFR prototype	Vast experience on their use, but modifications needed for GenIV (geometry, architecture, micro-structure...). Qualification needed for various coolants.
MA-bearing oxide fuel	Envisaged for recycling in PWR	Prospectively in all fast reactors	Homogeneous vs. heterogeneous modes studied almost exclusively for liquid metal (sodium) cooled reactors
MX	Envisaged as eATF	Long term use (with or without MA) in all fast reactors for higher efficiency and safety margins	Fabrication not trivial. Potential issues in connection with Pu multirecycling. Qualification open
TRISO concept	None (but used in formerly built HTRs)	(V)HTR, GFR	Inherently accident tolerant fuel (see text)
Liquid (molten salt) fuel	None (but used in early prototypes and experimental reactors)	MSR	Totally different type of fuel. Offers possibility of online processing

## 2.4 Fuel Cladding Materials

Fuel cladding is the thin-walled outer jacket of a nuclear fuel rod or pin for designs with solid fuels. It prevents corrosion of the fuel by the coolant and the release of fission products into the coolant. The lifetime of a fuel assembly in reactor is determined not

only by the evolution of the fuel itself during its stay in the reactor core, but also by the performance of the structural alloys of the core component, especially the cladding, in the nuclear environment. High burnup can only be achieved if the performance of this component is satisfactory up to very high exposure.

### 2.4.1 Materials for Current Generation Nuclear Systems

Fuel pin cladding in all current LWRs are made of Zr alloys, which exhibit very low neutron absorption cross section [98]. As mentioned in section 2.3.1, enhanced accident-tolerant fuel elements are being investigated to provide sufficient time for intervention in case of temporary loss of core cooling and decrease the consequences of such an event.

Possible eATF cladding materials, all of them still necessitating qualification, range from suitably coated Zr alloys [99] (the simplest solution from an industrial point of view), to advanced ferritic/martensitic (F/M) steels with improved creep resistance [100], refractory metals, like Mo, and SiC fibers in bulk SiC (SiC<sub>f</sub>/SiC) composites [101]. Interestingly, except for coated Zr alloys, all eATF cladding materials are also considered as structural materials for next generation reactors (see Table 4 and next section).

### 2.4.2 Cladding Materials for Next Generation Nuclear Systems

The attainment of the economy, circularity and sustainability targets of the fast reactors depend strongly on the maximum burnup of the fuel. Fuel cladding steels will necessarily be exposed to high irradiation dose and dose rates. In the temperature windows foreseen for the GenIV designs, the main concern is irradiation creep, swelling and ductility losses. The 15Cr-15Ni Ti-stabilised steels (also denoted as D9 or 1.4970) are the reference materials for the fuel pin cladding of the sodium fast reactor and the choice of the “first” cores in the development roadmap of the other ESNII systems [102].

Thanks to the improvements of the chemical composition and cold work in the last few decades, the French 15Cr-15Ni-Ti steel AIM1 (Austenitic Improved Material #1) [102] can sustain radiation damage doses of up to 100 dpa with acceptable performance in terms of dimensional stability and mechanical properties. The 15Cr-15Ni-Ti steel is stable in contact with the fuel and demonstrated good performance in molten sodium environment. While this guarantees the viability of the SFR, R&D efforts are needed to improve its performance beyond 100-dpa dose, to reduce cost and improve sustainability requirements. Currently, the short-term choice materials for the SFR are the advanced austenitic steels in track with the optimization process that led to the AIM1 steel. In the long term, the aim is to transition to other advanced alloys, such as F/M ODS steels [103], which promise resistance to radiation up to 200 dpa and even beyond.

Regarding the LFR, the austenitic steels suffer severe dissolution corrosion by the molten lead alloys, with an attack thickness in the range of hundreds of  $\mu\text{m}/\text{year}$ , depending on the experimental conditions (microstructure, coolant chemistry, temperature, temperature gradient etc.). The environmental control, namely the operation under controlled oxygen content (Active Oxygen Control, AOC), has proven to be effective in handling corrosion issues by promoting the formation of a self-healing oxide film on the steels surface, therefore reducing steel corrosion and coolant contamination. This strategy has been reported to provide adequate corrosion resistance up to about 470°C in pure lead, after which dissolution attack quickly occurs. Considering that the temperature may exceed that of the coolant by hundreds of degrees in hot spots, their use in the LFR cores makes it impossible to guarantee the containment of the fuel and the fission products. For the PbBi cooled MYRRHA ADS, the low melting point of the eutectic allows margins to decrease the coolant temperature. For the Pb-cooled

reactor, however, the high melting temperature of Pb (327.5°C) and the risk of lead or lead oxide freezing in the pipes impose operations at which oxidation is not protective. The current approach is to use a protective coating made of aluminium oxide on the 15Cr-15Ni-Ti steel and the core structures. Work is in progress to assess the viability of this solution. A long-term strategy foresees the development of a new class of materials resistant to the oxidation in heavy liquid metal (HLM) environment and able to withstand the neutron radiation damage up to elevated doses. As an example, self-passivating alumina forming steels have shown good performances compared to the conventional steels. Additionally, technological advancements are expected to enable the fuel cladding of LFR concepts to operate to higher temperatures (700°C or higher). Materials capable of higher temperature exposure will be needed to support these high temperature systems and will likely differ from those presently envisaged.

The GFR reactor ALLEGRO will serve as demonstrator and, hosting GFR development technological experiments, as a test infrastructure to develop fuel and core materials (see Annex 2). The ALLEGRO reactor will start operations with a uranium oxide (UOX) core, or mixed oxide (MOX) core, contained in 15Cr-15Ni-Ti steel cladding. The target to be pursued by the ALLEGRO project is the testing and demonstration of a core that will enable high temperature operation of the GFR, largely exceeding those of the present systems. Data on potential ceramic (particularly, SiC/SiC) and refractory alloys for cladding materials are limited for the design, if not inconsistent. These materials still need significant developments to cope with the specific GFR loads (e.g. thermal gradients, interaction fuel-barrier, dynamic loads), regarding composition, structure and microstructure.

### 2.4.3 Summary of Fuel Cladding Materials Used or Envisaged

**Table 4.** Summary of cladding materials through reactor generations, F/M = ferritic/martensitic, HEA = high entropy alloys, CCA = compositionally complex alloys, ODS = oxide dispersion strengthened, ATF = accident tolerant fuel element, AGR = advanced gas reactor, (V)HTR = (very) high temperature reactor, GFR = gas-cooled fast reactor,

Class of Materials	Use in GenII/III	Use in GenIV	Notes
Austenitic steels	None	Most reactor prototypes	Experience from use in thermal and also fast reactors. Improved swelling resistance (e.g., Ti stabilization) and corrosion protection in heavy liquid metals (e.g., coatings or Al-containing alloys) needed.
Zr alloys	All LWR reactors	None	Historical example of material development specific for nuclear [85]
F/M steels	Improved versions are considered for eATF cladding	Most commercial reactors target their use	Swelling-resistant, good thermal physical properties. Creep (e.g., ODS), and corrosion resistance (e.g., coatings or Al-containing alloys) need improvement.
Refractory alloys	Some are considered for eATF cladding	Might be considered in the long term	Wide spectrum of possibilities: Ni-base and Ti-base alloys may enter this category, composed by Mo-, Nb-, Ta- and V-alloys (W-alloys for fusion)
Ceramic materials (SiC <sub>f</sub> /SiC, other)	Considered for eATF cladding	VHTR and GFR	Composites and other ceramics have been long studied, but are still far from being fully qualified and codified.



			Design rules need to account for brittleness. Often costly
Prospective materials (HEA/CCA, Max phases...)	Envisaged use for eATF cladding	Mainly cladding and coatings, but not clearly identified	These materials are investigated because of their promising properties, but even more because of the possibility of applying modern materials development techniques based on combinatorial fabrication

## 2.5 Other Materials

It should be noted that important materials for reactors, which are also the focus of research, are polymers for cables and tubes, as well as materials for neutron control. Also important are functional materials such as for sensors. These, however, are not addressed in this document, because no materials ID cards could be produced for these classes. Work of the concerned research community is needed in order to identify needs and establish a forward strategy.

## 2.6 Nuclear Materials Sustainability Issues

An important challenge for nuclear energy, as well as for any energy technology, is to increase the efficiency of the use of primary resources and reduce the amount of waste produced per unit energy produced.

LTO is an important affordable contributor to the move towards better use of materials resources and thus waste reduction. GenIII+ new reactor builds and future GenIV systems alike need to be designed for as long a lifetime as possible (at least 60 years are targeted), in both cases calling for suitable design criteria in terms of materials performance, although of course the task is made easier by previous component operation experience. In this framework, any materials science-driven technology that is able to increase the lifetime of components for any reactor generation is part of the overall move towards improved circularity and increased sustainability, with the non-negligible side effect of significant economic benefits.

The materials solutions adopted for light water SMRs do not need to differ significantly from those adopted for standard LWRs. Likewise, the materials of choice for SMRs of GenIV technology can be in principle the same as those for larger scale re-actors. However, this one-to-one translation of materials solutions through reactor scales, which is certainly useful for faster licensing of prototypes and first-of-a-kind reactors, may not necessarily be the best choice in general terms. For instance, moving to a different, and so far unexploited, type of alloy, with overall not astonishingly better mechanical or corrosion resistance properties, but with better properties from a circularity and sustainability perspective, for example such that critical raw materials are excluded from its composition, may eventually provide increased sustainability as a balance to slightly lower performance or higher costs. These are thus variables that acquire ever higher importance and need to be included in the equation for the selection of nuclear materials for reactors of any technology readiness level, including established technologies. They become an important push towards the development of new materials, in addition to the traditional and obvious need to improve their properties in connection with operational requirements.

Concerning reinforced concrete, when looking into the future, there is a need to adapt current understandings of cement and concrete chemistry to new raw materials, new concrete constituents, especially novel binders, other than traditional cement. This is

required to both improve the sustainability of the nuclear structural materials and take advantage of the notable benefits of such alternate materials (e.g., reduced permeability, potentially improved stability under irradiation etc.) [86].

The fuel cycle is also an important aspect to improve the economy, circularity and sustainability of nuclear energy, as it enables the extraction of higher amounts of energy from the same quantity of uranium ore [104]. This can be done by going to higher fuel burn-up in GEN II/III reactors, while better controlling the evolution of fuel during its irradiation in reactor. Being able to burn a much larger proportion of actinides or even producing burnable actinides using fast reactors would dramatically reduce the primary resources needed and the waste produced. Spent fuel management strategies including single and multiple recycling of plutonium [105,106,107] and partitioning and transmutation of minor actinides [108,109] must also be put into play to make progress in the circularity and sustainability. This will, however, affect the Pu concentration and its isotopic vector in the fuel and lead to higher Am contents (from  $^{241}\text{Pu}$ ), which will increase the radioprotection requirements during fuel fabrication [110].

Both LTO of operating reactors and extended lifetime cycle of future ones demand the ability of guaranteeing the integrity of all parts of the plant for the required operation time, by timely repairing or replacing any repairable or replaceable piece and by monitoring the overall health of materials and components, which also has crucial safety implications. Traditionally, this has been done through planned inspections and subsequent testing of key component materials. The surveillance programme of RPV steels, with pre-located capsules containing specimens to be periodically extracted for mechanical testing, is the earliest and best example of this practice [111]. The increasing use of non-destructive examination (NDE) techniques for monitoring, also applied to RPVs, represents a crucial move towards continuous monitoring [112,113], valuably complementing and, eventually, partly replacing planned inspections and destructive testing. Modern approaches of this type are based on the application of optimised multi-parameter methodologies for the *in situ* characterization of degradation in materials and components through sensors, thereby capturing the material properties (“materials DNA”) right from the start of its development, including control of the manufacturing procedure, until the end of its operation [114,115,116,117]. Their interpretation more and more often requires the help of machine learning for pattern recognition [118]. This approach contributes crucially to a thorough plant lifecycle assessment and resonates and connects with the digitalization trend in the nuclear (and not only) industry, which also involves the development of digital twins for the key plant components [119]. These are virtual copies that, by combining *in situ* data collection with either physical or data-driven computer simulation techniques and models (see Section 3.2), allow the behaviour of the component in operation, or under off-normal conditions, to be anticipated, thereby optimizing its functioning, while enabling timely interventions and replacements, whenever required [120].

Importantly, the development of robust technologies that are capable of determining in-service material performance, not only by monitoring, but also through modelling, depends on both model accuracy and data reliability. Hence, there is a need for collecting reliable key experimental data, which need to be captured in a consistent manner under realistic operation conditions, or else to provide physical information on materials behaviour to be used to feed suitable models. In the case of operating reactors, there is clearly an interest, in this context, to harvest service-aged material to enhance the knowledge base. In the case of future reactors such data collection process needs to be foreseen and designed according to modern conceptions. The corresponding models can be both physical and based on data-driven approaches, using machine learning (see Section 3.2). In both cases, and especially in the latter, the inherent consistency and the

appropriate collection, storage and management of data are crucial. Non-destructive methods for materials characterization of components during operation, or in experimental operando conditions, through sensors, can be helpful to provide also such key data, provided that they can be translated into quantities that the models can handle.

The repair, or fabrication and replacement, of component parts, especially when these are not classical spare parts and/or possess complex geometries, may benefit from modern manufacturing techniques, such as additive manufacturing (AM, 3D printing) [121,122] and hot isostatic pressing (HIP), which are also used in combination [123]. Additive manufacturing is suitable for components of complex geometry, but limited size, for which suppliers may be difficult to find. HIP allows shape and material homogeneity and composition to be controlled and is especially suitable for heavy components (elbow pipes, pipes with integrated nozzles ...). Both are extremely powerful and open the way to revolutionary ways of not only replacing, but also fabricating parts and components, or even a complete reactor [124]. In this way, the supply chain of repaired or new components according to specifications would be significantly improved or even bypassed. However, the safety constraints that apply to nuclear installations require that suitable qualification paths and standards are developed, because an additively manufactured material, although chemically identical to the reference one, will generally have significantly different microstructural features and thus different macroscopic properties [122].

NDE and advanced manufacturing, when applied to the concept of SMRs, open the way to envisaging largely automatized, robotic, intelligent systems that, in addition to being small, compact, factory-fabricated and transportable, are also able to self-monitor the health of their components and replace them autonomously on-the-fly. While still largely speculative, this scenario is not totally science-fictional. These concepts remain valid for current and future generation reactors alike.

### 3 Towards a Paradigm Shift in Nuclear Materials Science and Engineering: Paths to Innovation

Irrespective of the application, the ability to foresee the lifetime of materials and components as reliably as possible is obviously one of the goals of materials science, in order to ensure their optimal use from the point of view of economics and sustainability. This requires predicting the moment when, due to the action of degrading agents and processes, the material used to manufacture the component is likely not to be any more suitable for correct operation, or becomes unsuitable to face off-normal conditions in case of an accident. For this we need to know how the properties of the material change after exposure to operational conditions, starting from known initial properties that depend both on its chemical nature and its microstructure and/or its architecture; the latter being determined by the manufacturing process. We also need to know how a component made with a material with those properties will function under given conditions. This knowledge enables the design lifetime to be defined and the maintenance and replacement to be planned, as well as the eventual re-use or recycling to be guided, with all the related safety, economic and sustainability consequences. This knowledge also enables demonstration of the safety and functionality of the component in the process of licensing, or in connection with LTO [125].

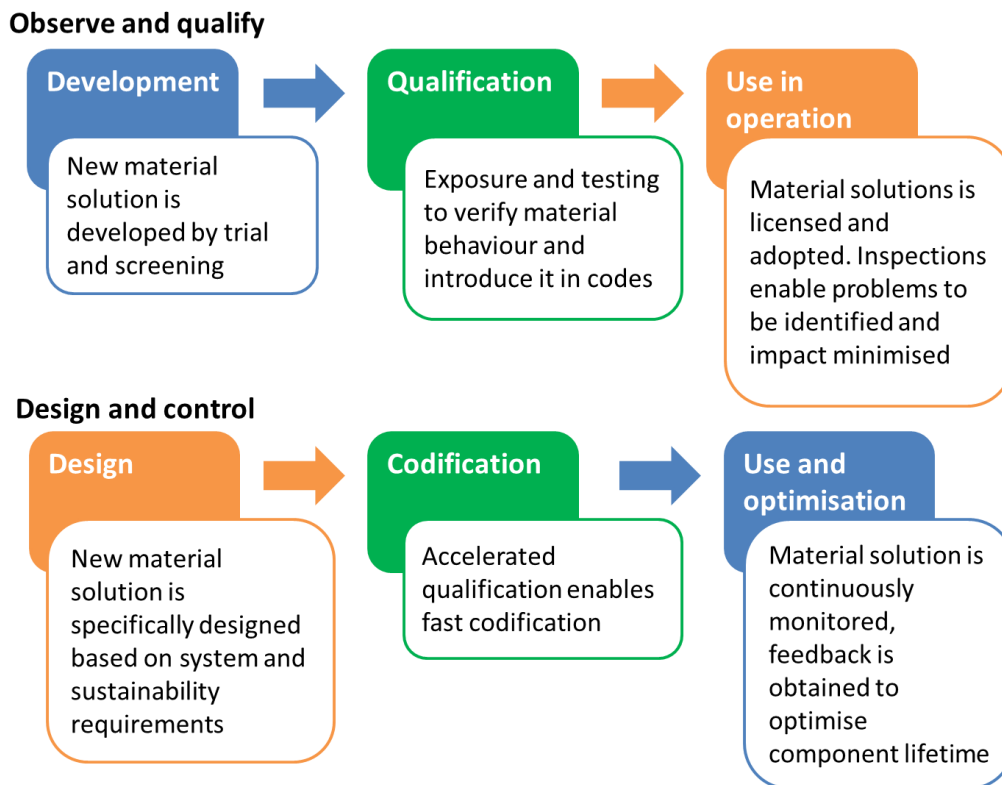
In order to obtain this knowledge, materials scientists and engineers dispose of a number of methodologies and approaches that have traditionally enabled materials to be tested and characterised by measuring their properties using appropriate techniques (often, but

not always, standardised) under various conditions: as-fabricated, exposed to different degrading agents and during operation, as well as at the end of their life. Testing and characterization techniques may be destructive or not and generally require appropriately prepared specimens. The data obtained in this way are then transferred to models that enable their rationalization and interpretation, allowing interpolations and possibly also extrapolations. The models, which can be empirical, theoretical or a mixture of them (e.g., data-driven models), guide the component design, maintenance and replacement plan, minimizing costs while maximizing safety and efficiency, possibly taking into account also all aspects related to the optimization of their whole lifecycle.

All of the above assumes that the reference material for a component that works under given conditions is established and cannot be changed. This is obviously not true and another important goal of materials science in view of improved sustainability and economics, is the development, based on the knowledge of the causes of materials degradation, of either system design solutions to reduce degradation, or innovative materials solutions. We define innovative nuclear material solution any one that “enables significant improvements in reactor design and operation”, for instance leading to increased safety and efficiency, enhanced flexibility and/or prolonged component lifetime [126], as well as, potentially, cost abatement. Innovative material solutions for nuclear energy are created and adopted in four steps, some of them partly overlapping: (i) adoption (if already available), development, or possibly discovery, of new materials solutions, which often are improvements of the features of existing solutions based on designers’ requirements or declared industrial needs; (ii) industrial upscaling of new materials solution’s fabrication, including joining, to make a supply chain possible; (iii) materials solution’s qualification for the target application to enable design, licensing and eventually construction; (iv) application of material and component health monitoring for optimised lifecycle. The imperative to foster innovation is that all these steps should become easier, faster and cheaper than they are now.

The way of proceeding in which: (i) the observation of the materials performance under a variety of conditions, unavoidably limited to relatively few data, is the main ingredient in their qualification and licensing; (ii) the development of innovative materials solutions occurs almost by serendipity; (iii) only the subsequent steps confirm their suitability of the desired application, correspond to the “observe and qualify” paradigm, where models are used *a posteriori* to guide actions. This practice is still used today and will continue to be used, but it must progressively undergo a shift to the “design and control” paradigm. The latter is based on the key postulate that good models, directly or indirectly based on the understanding of the physical processes that are responsible for materials changes during operation, should also be able to provide paths towards improved materials. These are materials that, because of their inherent properties and the selected manufacturing procedure with respect to a known reference, enable by design the component lifetime to be increased, the intervention for maintenance and replacement to be minimised and the possibility of re-use or recycling maximised, while possibly using non-critical chemical elements.

Modern materials science approaches, therefore, are based on the two guiding principles of Section 1.2 and pursue the new “design and control” paradigm, which inverts the process by asking first the question of how materials should be selected, improved and manufactured, i.e., designed, in order to optimally fulfil the requirements imposed by the targeted operating conditions, i.e., by controlling their performance. This change of paradigm, applicable to all classes of nuclear materials, including those not addressed in the present document, and beyond, is illustrated in Figure 4.



**Figure 4.** Schematic illustration of the “Observe and Qualify” and “Design and Control” paradigms. The colours help to show that in the latter case the point of view is inverted: material solutions are designed from the start based on operational and sustainability requirements.

The related materials science and engineering practices remain the same in both cases, namely: development, qualification, use and monitoring, with the common denominator of data management and modelling. In what follows these practices are listed and described, although in a different order to make their presentation easier. Moves towards the new paradigm are also proposed and the resulting research lines are discussed.

## 3.1 Materials and Components’ Qualification

### 3.1.1 Goals of qualification

Materials and components’ qualification means “generation and maintenance of evidence to ensure that they will operate on demand, under specified service conditions, by meeting system performance and safety requirements”. Crucially, the qualification is made before the material is used and the component installed, to enable the design of the component itself with sufficient *a priori* guarantee that it will respect performance and safety requirements. Qualification is thus the pre-requisite for the establishment of rules for the design of components, which are collected in design [127,128] or performance codes [129,130,131,132], according to the best available engineering practices and scientific knowledge. The related research is defined as pre-normative, with reference to the goal of establishing norms and standards. This qualification needs to be completed for each material of interest for applications or, in cases that are more and more frequently encountered, for whole components or assemblies. For instance, fuel elements need to be qualified in their entirety for the target environment and conditions and require, for design and safety purpose, the development of fuel performance codes.



These enable the simulation of the behaviour of the fuel element in the reactor from the thermal and mechanical point of view, as well as its evolution overtime, as functions of irradiation and thermal parameters in any condition: normal, incidental and accidental. The description of the very complex relationships between these parameters and the evolution in time requires appropriate models. It is considered that better models can be produced by shifting from currently used fully empirical correlations to partly or totally physical/data-driven models (see Section 3.2). In addition, modern techniques of component fabrication (AM, HIP) often require the qualification of the whole component, because the properties of the material become linked to the method and the process used for its fabrication. This requirement involves the development of suitable standards, that currently only partly exist, especially in the case of next generation reactors and relevant materials [133].

### 3.1.2 Needs for qualification

Design codes include guides for the introduction of a new material in them, where a “new material” is not always really “new”: it can also be a known one that was never used before for a given application or in a given environment, and thus needs qualification for the conditions to which it will be subject, i.e., the conditions to which it is going to be subjected are new, rather than the material. Alternatively, the “new material” may be a one that was already used, but was fabricated according to different standards or adopting different processes, as is the case of advanced manufacturing. These guides to introduce new materials in codes are sorts of checklists of the type of information and properties that need to be provided through qualification and pre-normative research, together with indications about how to execute the relevant measurements and tests, referring, whenever available, to standards that are developed for this purpose by dedicated organizations. These standards give prescriptions on how to conduct tests and often also on how to analyse data, to assure that the measured material properties are independent of who performs the test and where. In some cases, however, for operation in environmental conditions and parameter ranges that concern specific new systems, the design codes may fall short and require extensions. For instance the RCC-MRx design code, which was developed in France to support specifically the SFR technology, has been recognized as the most appropriate design code for all European GenIV prototypes. It covers the design and construction of components for reactors that operate at high temperature, including auxiliaries, mechanisms for examination and handling and irradiation devices. It also includes specifications on manufacturing. However, it does not advise on rules for environmental effects, with the exception of thinning by corrosion. It does not cover high temperature ranges for GFR and (V)HTR, either. Moreover, the reference operational life for material property curves and design rules is 40 years, while the goal of increased sustainability requires extension to at least 60 years.

Filling these gaps for a given material requires that dedicated experiments are performed to collect comprehensive and reliable sets of relevant data. In the case of nuclear core materials, irradiation experiments also need to be included. Materials need to be exposed to specific environments in suitable and often expensive infrastructures, such as autoclaves and loops, or bespoke facilities for irradiation, if possible up to the time or dose expected in service, or else getting data that can be possibly extrapolated. For fast reactor systems this should ideally happen in facilities with the correct neutron spectrum. In their absence — as is currently the case in Europe — Materials Testing Reactors (MTRs) are used, compatibly with their dwindling number. These are, however, characterized by a predominantly thermal neutron spectrum, which limits safe extrapolation to different spectra and higher doses. This problem, which hinders full

qualification for GenIV reactor materials, is even more burning for fusion, because the neutron spectrum is in that case significantly different, with a 14 MeV peak that has significant consequences, especially in terms of transmutation, i.e., helium production. It becomes therefore necessary that a bespoke facility should be built to irradiate under fusion-relevant conditions, which is the purpose of the IFMIF-DONES project [134].

The level of degradation after or during exposure needs to be assessed in terms of changes of properties of engineering interest, by testing and examining these materials, using a series of suitable and possibly standardized (certainly reproducible) testing methods. Standardization is very important in order to guarantee reproducibility and to produce consistent data. The problem is that, in order to cover most conditions through testing, particularly those with safety implications, the qualification process may currently last for decades. The return of experience from previous use, when applicable, does reduce the qualification time. However, in several cases this process is system specific, thus the return of experience may not be fully of relevance. Moreover, new and bespoke standard procedures may need to be developed to execute the exposure, the characterization and the tests in new environments. Furthermore, the qualification of a new material, or material combination, in its baseline version is not sufficient: efficient procedures for joining pieces made of that material need to be developed and equally tested and qualified. One of the important advantages of fabricating components using advanced manufacturing methods is that welds and joints can be avoided, as the component is given a shape while the material itself is produced. However, this advantage should not be offset by internal stresses and porosity. Finally, both new materials solutions and joining procedures are typically developed in the laboratory, but, crucially, before the solution can be actually adopted in commercial plants, there needs to be an industrial production upscale, which is not always obvious. In particular, upscaling may imply *de facto* changing some of the features of the materials solution that was developed in the laboratory, potentially requiring further qualification. Eventually, the data that are gathered for each code-candidate material through this long and expensive procedure need to be rationally translated into robust design rules for components, or laws and models for the assessment of fuel performance.

### 3.1.3 Nuclear materials test-beds

The qualification process would greatly benefit from the development of standardized accelerated exposure and testing paths, which would reduce the associated time and costs, with significant impact on innovation and thus economics. Identifying these accelerated qualification paths, however, is not simple, because their relevance to real operating conditions needs to be proven. Advanced modelling (Section 3.2) is crucial for accelerated qualification, as it provides the required links between properties and should enable the effects of degradation processes to be more precisely assessed, based on physical insight. Likewise, monitoring (Section 3.3), such as in the case of RPV surveillance [135], is crucial to ensure the integrity and functionality of materials and components while in operation, even in case of partial failure of the qualification procedure, as well as to provide an *a posteriori* feedback to the design rules or to existing correlations for damage versus time. Yet, monitoring is possible only when the reactor fleet or at least a prototype/first-of-a-kind has been deployed. Thus monitoring does not generally support materials and component qualification, although it does compensate for the fact that not all possible combinations of conditions could be explored *a priori*.

With a view to making qualification more efficient and affordable, and possibly accelerate it, the concept of “test-beds” should be pursued and adapted to the case of nuclear materials or, more generally, materials operating under harsh conditions. The concept of

test bed, with different nuances of interpretation, is being applied to a large number of frameworks and technologies. In the case of healthcare, a test bed is a real life study, on a portion of population located in a specific region, of the effect of introducing innovative procedures, generally digitally-based, for the treatment of specific types of illness or patient condition. The study concerns all levels, i.e., not only or not necessarily the effects of specific drugs, but more importantly also how in practice the patients are treated with them and their conditions followed to check improvements. The UK National Health Service launched an interesting initiative of this type already several years ago [136]. In 2020 a similar initiative has been proposed, also in the UK, to test the implementation of innovative technologies related with climate change mitigation and adaptation, circular economy, clean energy, etc. [137]. In the case of advanced materials, the EU supports test beds focused on nanotechnologies and functional materials [138], in the sense described below.

Test-beds are integrated platforms for conducting thorough and replicable tests on (new) materials, according to an established protocol that is specific for the target application (qualification path). The definition provided by the EU commission is “entities that offer access to physical facilities, capabilities and services required for the development, testing and upscaling of advanced materials in industrial environments” [138,139]. Developing protocols for standardized qualification paths is a crucial part of the establishment of a test-bed. Note that the parts of a test-bed may or may not be physically in the same place, i.e., they can be more realistically the result of coordinated characterization, in a structured way, using different techniques by different specialised laboratories. These, however, need to develop and establish a common and shared way of working, possibly under suitable quality assurance, in order to produce consistent and lab-independent data. The key is that these integrated platforms should offer to any type of customer the possibility to obtain an exhaustive and integrated characterization, under or after suitably representative exposure conditions, of materials belonging to the classes of interest for the target applications. Single-entry integrated platforms of this type, if sufficiently flexible, can help making the qualification steps of baseline and joined materials shorter and more affordable, including support to industrial upscaling.

Platforms of this type dedicated specifically to nuclear materials do not currently exist in Europe. However, nuclear materials test-beds can give a great boost to the nuclear materials community at large and the nuclear industry in Europe, provided that there is willingness to integrate facilities, infrastructures and assets in general, which are spread all over Europe, under a single umbrella of coordinated, flexible and advanced exploitation. The spectrum of potential customers increases significantly if the test-bed is dedicated in general to materials operating under harsh conditions, of which irradiation is only one of many agents.

A test-bed of wide application can be built incrementally, starting from pilot experiences that have limited targets and involve a limited number of participants, and then progressively moving towards higher levels of integration and flexibility. Suitable and, especially, generalizable case studies need to be selected, around which small groups of laboratories will start developing a joint way of working, sharing facilities and infrastructures and establishing common protocols of operation. From these nuclei, more branched structures can be developed, progressively extending qualification capabilities, scope and flexibility. Already these small pilots are expected to provide higher quality services to stake-holders for specific types of materials characterization than any single laboratory, and perhaps even than a single country.

Building these integrated platforms corresponds in a way to institutionalizing what is customarily done in a collaborative research project for its limited duration, where the same material is characterised by different laboratories, each using the technique in



which it is specialised, or for which it can offer established, and perhaps unique, expertise. The combination of the results and their implementation in suitable models (see Section 3.2), is the added high value of this collaboration, which, in the case of a test-bed, should become stable in time.

Specific attention should be given to identifying, developing and standardizing accelerated non-destructive characterization methods (see Section 3.3), taking advantage of the possibility of using multiple techniques or multi-parameter blending techniques in a coordinated way and fusing their results, following protocols or designs of experiments that still need to be firmly established and, quite obviously, with the support of dedicated models. One significant issue when fusing results from different techniques is the use of a unique data format in order to be able to merge all these data in a common database (see Section 3.5). Harmonised guidelines based on lessons learned when different laboratories apply the same physical principles of a method, using different ways of processing signals and data, need to be agreed upon.

The technological challenge of creating a nuclear test-bed is significant, but it also has an important legal, as well as political and managerial, dimension, which must be adequately addressed. In addition, progress is needed in the harmonization and stabilization of transport regulations of irradiated materials, especially nuclear fuels, between the various MS. The absence of common rules or their frequent modifications have too often been the cause of long delays in nuclear materials research projects.

To conclude on this topic, it is important to underline that test-beds should be built in the spirit of offering a high quality materials qualification service to research and industry alike, although likely with different entry fees. In that respect, a test-bed should be regarded as a flexible tool that can be equally applied to public and private research, in the latter case under confidentiality agreement to protect the intellectual property.

### 3.1.4 Irradiation in connection with nuclear test-beds

It is quite obviously not possible to think of a test-bed for accelerated nuclear materials qualification that does not include at some stage irradiation under representative conditions. This is in fact the sorest point concerning nuclear test-beds, because of the scarcity of neutron irradiation facilities in Europe and worldwide, the high cost of in-pile irradiation, the long time required to prepare and execute irradiation campaigns, as well as the fact that, nowadays, experimental nuclear reactors are much more profitably used to produce isotopes for medical applications than to irradiate materials. There is no simple solution to this problem. Increasing the number of facilities requires investments that can only be afforded by national states, assuming a clear and profitable strategy for their exploitation can be identified, compatibly with their political position concerning nuclear energy. There is little that the nuclear materials research community can do here, besides using these irradiation facilities, thereby justifying the investment *a posteriori*. Being users is, however, also not simple, because paying for irradiation campaigns in the framework of EU research projects requires that the EC and the MS should be ready to provide sufficient financial support, which is not granted. Thus the qualification paths will have to address with care and effort the variable of irradiation campaigns, perhaps considering alternatives, such as charged particle irradiation (ions, protons, electrons...) whenever suitable with the *caveats* discussed in Section 3.4, or schemes of joint coordination of the use of available neutron irradiation infrastructures, that also sponsor access to them [140].

## 3.2 Advanced Modelling and Characterisation

The previous section makes it clear that exposing materials to real conditions costs time and money and requires infrastructures, even though the process can be accelerated by creating test-beds. Moreover, in practice, the conditions that can be explored correspond to simulations or approximations of real ones and data can never cover all ranges. Exposure times or doses comparable with the lifetime of the reactor are only rarely accessible, or they may be accessible at higher dose rates using MTRs, as is customarily done to evaluate RPV steel embrittlement [141,142]. The combination of effects and their synergy are also difficult to simulate in a laboratory. Finally, until the system is operated, no feedback can be obtained through materials health monitoring (Section 3.3). Extrapolation of data is therefore unavoidable, but purely empirical extrapolations have limited reliability. Relying only on the observation of the materials performance under a variety of conditions, unavoidably limited to relatively few data, as main ingredient in their qualification and licensing, corresponds to the “observe and qualify” paradigm. Shifting to the “design and control” paradigm requires the help of advanced models. These can be of two complementary types, as described in what follows.

### 3.2.1 Advanced physical modelling

Advanced physical modelling through numerical simulation and modern materials examination methods are at the heart of the “design and control” paradigm. This is made possible thanks to the vast increase in computational power experienced over the last decades, combined with ever greater power of techniques for microstructural and micromechanical characterization of materials, which enable in-depth observation and testing at all scales [143,144,145]. This approach is expected to become increasingly robust, initially only underpinning, then gradually improving the traditional empirical approaches that are still used, e.g., in fuel performance codes or in dose-damage correlations for LWR vessels. The “design and control” approach bears the promise to significantly enhance our predictive capability, by enabling the physical description of the evolution in time of both the microstructure and the microchemistry of materials exposed to irradiation and/or high temperature and/or coolants. The output of these models acts then as input to meso- and macroscopic length scale models, in a multiscale modelling framework and spirit, thereby enabling prediction of the changes experienced by the materials properties in operation. Since the modelling tools are generally computationally costly to run and often use parallelised software, the use of high-performance computing (HPC) can be a crucial asset; although in reality the bottleneck to physics-based model development is not only and perhaps not really computing power, but mainly and most often the correct identification and parameterization of all important physical mechanisms [146]. Eventually, physics-based correlations of fast application such as those used for RPV steels [147], or improved performance codes such as those used for fuel, should be able to make use of the background information that these models provide, using better parameters and models and including more correct underlying mechanisms, possibly under a single platform [148,149].

Physical models require suitable data for calibration and validation, from so-called modelling-orientated experiments. In these, materials are exposed to external factors, as for qualification purposes, but the objective here is to better understand mechanisms, by separating variables and effects, rather than to measure engineering properties [150]. In experiments of this type, key variables, such as temperature and irradiation dose or dose rate, are accurately controlled and varied over sufficiently wide ranges. For this, specific exposure facilities are needed, especially for irradiation, and the use of charged particles (ions, protons, electrons...) can be a valuable and affordable tool (some

*caveats* are discussed in Section 3.4) [151,152,153]. Next, microstructure and microchemistry characterization are essential parts of modelling-orientated experiments. The combined use of various advanced characterization techniques is crucial, because each of them provides complementary pieces of information, which are all indispensable in order to actually take advantage of the added value of modelling-orientated experiments. Suitable mechanical characterization is equally important, including micromechanical experiments from specimens at single grain scale (nanoindentation, micro-pillars...), often the only possibility in the case of specimens irradiated with charged particles, due to the limited penetration of the latter [154]. Moreover, mechanical tests addressing uni- vs. multi-axial load, cyclic load, relaxation, load sequence, non-proportional loading, etc., in correlation with the observed microstructure, are of interest, depending on material type and purposes and models to be developed. These experiments are invariably delicate to perform and may be longer than, and almost as costly as, those performed for qualification. They provide, however, a higher level of fundamental physical understanding, as opposed to the collection of engineering data for the production of correlations that is typical of traditional qualification procedures. They thus clearly contribute crucially to the paradigm shift towards “design and control”. An advantage, with respect to qualification experiments, is that in this case it may not be strictly necessary to irradiate under conditions that are fully representative of operation, so long as models can reproduce them. This opens the way to performing so-called “piggy-back” irradiation experiments, i.e., experiments in which space left free by other experiments is used to irradiate materials for modelling purposes, instead of filling the volume with dummy materials.

### 3.2.2 Blending physics and data-driven models

The main current limitation of physical computational models is that they still have difficulties to take into account, at all scales, the effects of the complexity of materials chemistry and related mechanisms of degradation, even more when the interaction with the environment (e.g., coolants) has to be accounted for. This difficulty is likely to require significant time and effort to be overcome. An alternative path has therefore recently started to be intensively pursued, which consists in using modern digital techniques such as machine learning (ML) — also used for the analysis of data obtained from materials health monitoring (Section 3.3) — to extract relevant materials features from large amounts of data: so-called (big) data-driven modelling [155,156]. These techniques make the best of the data that can be made available, by identifying complex correlations between, on the one hand, the parameters that define the materials or the components (e.g., composition and fabrication features), as well as the exposure conditions (e.g., temperature, exposure time, radiation dose, dose rate...), and, on the other hand, the final properties of interest. This is achieved by providing a large amount of examples, on which the method is trained.

The application field of ML can be roughly divided into two groups, supervised and unsupervised learning, to which the semi-supervised group may be added [157,158].

- In supervised learning, so-called targets (the variables to be predicted) are available in addition to the features (the independent variables). The model aims to predict the targets based on the features. The accuracy is then tested by contrasting the outcome of the ML scheme with data that were not used for the training. This is by far the most frequent type of application in materials science.
- In unsupervised learning the goal is to draw conclusions about the input data, rather than predicting the corresponding output variables. This approach searches for patterns in data that have not been detected before. For instance, it may identify ways

of grouping unlabelled data, thereby providing a data classification. The algorithm thus identifies trends of potential use and interest to rationalise the dataset, so available data can be presented in a novel way. Thus, structures in the data are recognised and the aim is not to predict the target property, but to present the training data in a more comprehensible way (clusters) for humans or subsequent supervised learning algorithms. Curing the training dataset to avoid implausible data, like errors, outliers or missing data is customary in all cases, also in supervised learning, i.e., the collected data always need to be pre-processed, the volume of data, the uncertainties associated with each data value, as well as their heterogeneity, all being important aspects of data pre-processing. What unsupervised algorithms do is to help in the pre-processing, by reducing the number of dimensions of a multidimensional feature space, through rotation and subsequent projection onto so-called principal axes, thereby removing redundancies and irrelevant data, without significant loss of information.

These sophisticated algorithms turn out to be often very powerful. The specific example in the nuclear materials field where a ML-based approach is being applied with some degree of success concerns correlations for RPV steel embrittlement versus neutron fluence and other variables [159].

One of the main problems with data-driven modelling procedures is that they are too often blind: in supervised learning the ML produces a sort of “black box” transfer function between input and output, *a priori* devoid of any physics, even though sometimes this procedure manages to improve also our physical understanding [159, 160]. The more data are available, the higher are the chances that the procedure provides probative results, although it remains dangerous and unwarranted to rely on extrapolations [161]. In general, a trial-and-error approach is used to identify the most performant ML and relevant training method.

In the case of RPV steels, a large amount of data is available from surveillance and MTR experiments, thus this approach is especially promising. This situation, however, is not necessarily common in the nuclear materials field. In general, the number of data that are available for pre-normative research and for modelling, from exposure to a variety of environments and irradiation conditions, is limited, due to the high cost and thus relative scarcity of relevant irradiation experiments (see considerations on neutron irradiation in Section 3.1.4)). Thus, a completely blind approach based on “big data” analysis techniques is of hardly any use in the case of nuclear materials, for which data are in fact generally rather “scarce” than “big”. ML methods that are able to find logic in scarce sets of data exist (few shot learning) [162]. Their principle is that, whenever high fidelity data are missing, pseudo-examples based on lower fidelity data are used as complement, with appropriate weight. Their application relies on the availability of various ways to obtain data and reaches its highest efficiency when input is received from both experimental high quality data and data of different fidelity level, e.g., coming from physical models. It is also believed, and has been shown in some cases, that the inclusion of microstructural data from advanced characterisation in the set of input variables greatly improves the predictive capabilities of ML algorithms, because of the added physical content that this involves [163]. Therefore, in the field of nuclear materials and components, the marriage between data-driven and physical modelling (blending models), especially exploiting “few shot learning”, combined with advanced microstructural examination, is likely to be the most promising path to follow in support of materials development, qualification and monitoring. Other methods to reduce the “black box” effect inherent to ML, for a different application, are discussed in the next section.

Bringing this objective to practice builds on the fact that Europe has a long, well-rooted and established history of projects dedicated to predicting the behaviour of nuclear materials in operation, especially under irradiation [148]. These projects have produced tools, skills and expertise especially in the framework of multiscale modelling approaches. These tools, skills and expertise need to be exploited at their best by blending them with emerging data-driven approaches, taking into account the specificities of nuclear materials issues. Among them, the most burning one is the almost chronic lack of sufficient data for model validation/calibration, as well as for qualification. While this can be partially offset by suitably integrated dedicated test-beds, or by piggy-back experiments, blending models are expected to enable complex problems, for which purely physics-based modelling tools are still lacking (e.g., corrosion issues), to be addressed in a more effective way, so as to become usable for assessments also at industrial level. The challenge is here mainly theoretical and technical and will require the coordinated involvement of scientists of all ages, with a wide spectrum of expertise, providing the opportunity for young researchers coming from non-nuclear fields (e.g., digital techniques) to become involved in nuclear materials, and nuclear energy, applications.

## 3.3 Materials and Component Health Monitoring

### 3.3.1 Non-destructive testing and evaluation methods

The key for materials and health monitoring is the application of non-destructive testing and evaluation (NDT&E) methods. These have the advantage of being able to characterise the progressive change of the material properties of the same specimen in *operando* conditions, also applied to actual components. Continuous monitoring of the structural health of components has indeed demonstrated its added value in industries such as aviation and aerospace, as a complement to in-service inspections at programmed intervals [164], and is progressively making its way into the nuclear industry too. The key is that macroscopic physical properties and microscopic effects are correlated based on physical principles [165]. Depending on their physical principles and applied sensors, NDT&E methods can provide local or volumetric information about the material or component condition [165,166]. Moreover, many of them can be used on activated materials (under harsh environment) and *in situ* [167,168]. However, tests performed non-destructively do not generally determine directly the material properties as they are measured in destructive tests. To quantify the material properties non-destructively, measured parameters/features must be first correlated with the material properties of interest, which are customarily measured destructively [169].

Until recently, NDT&E were mainly used to detect defects in components and products as part of quality assurance procedures [170,171]. Thus, NDT&E techniques have been often designed, for many applications, as an after-thought, instead of being an integral part of their design and manufacture. As an example, an early overview on the NDT&E versus linear dimensions of microstructure and defects relevant for material strength and toughness is given in [172].

Today, NDT&E methods do more than purely detecting and locating defects in components: they address the characterization of material properties and their progress and can therefore contribute to all stages of the product life cycle, from the development of materials and products, to cover their maintenance, repair, and finally recycling [173,174]. Last but not least, the development of sensors that are able to capture microstructural patterns emerging from production processes [175] and to combine them in the form of individual fingerprints is also part of NDT&E: this corresponds to a sort of “product DNA” that can be deposited in “digital product files”.



### 3.3.2 Intelligent Materials Health Monitoring Systems

Intelligent NDT&E systems should enable the collection of, and access to, essential comprehensive data of materials/products along their entire lifetime at different scales, starting with their design/development (in the lab) and ending with their end-of-life over production and operation. Moreover, intelligent NDT&E methods that include cognitive, auto-adaptive sensor technologies may enable the understanding of the physical mechanisms that determine the response of the material under given conditions of manufacturing or operation [176].

For this to happen, each change (intended or not) of the material properties of a product along its lifetime must be detected and stored in a sort of product memory. To allow an as comprehensive material characterisation as possible, the application of multi-physics, multi-parameter NDE methods is needed. Depending on their physical principles, they provide information about different parts of the investigated material/component, i.e., near-surface or volumetric information. The multi-parametrisation enables materials characterisation similarly to having different human-senses [176,177,178].

A current limitation of the multi-parameter approaches is the unavailability of uniform data formats for data obtained by different NDE techniques: the issue of uniformised data format is therefore crucial for all applications, see Section 3.5. An additional limitation is caused by the risk of obtaining big datasets that contain many irrelevant data. ML algorithms of the same type as those used for data-driven modelling (Section 3.2) are thus equally helpful here for data collection and analysis to build models based on collected data and make predictions or take decisions [179], provided that the training data are appropriately treated. They can be applied to various stages in the NDE: data collection first, then data analysis or prediction of the targeted material property.

Supervised machine learning models generally necessitate large databases for their training and for their validation. In the case of NDE the issue of scarce data refers to guaranteeing the relevance of the training data, removing signals from faulty sensors or spurious signals.

By applying unsupervised machine learning, future NDE systems will be enabled to collect only relevant materials data. If, after the cataloguing, the experimental data acquired are not enough for performing reliable trainings, then the quantity of data can be increased artificially, without the need for large amounts of specimens, thanks to the prior clustering. Thus, specific data augmentation techniques based on unsupervised algorithms can be designed in order to obtain a sufficiently large, and optimised, database. An example of unsupervised learning is principal component analysis. High-dimensional and correlated NDE datasets have to be analysed in terms of outliers and missing data and mapped in a reduced, decorrelated and thus interpretable feature space, using unsupervised machine learning algorithms. This ensures the ability of the model to be developed to deal with possible failures, inaccuracies and errors (i.e., outliers, missing data), thereby reducing the “black box” component.

The combination of supervised and unsupervised ML-algorithms can be used to extract relevant features from NDE and so build models for predicting material properties, much in the same way as in data-driven modelling (Section 3.2), although using approaches that are specific for this type of analysis. Once the data pre-screening is performed, a prediction/modelling of the material properties of test-specimens can be carried out. NDE data, in combination with the associated reference data and the use of supervised machine learning algorithms (e.g., linear and nonlinear regression models), are then



used for trustworthy robust model building, from which reliable non-destructive predictions of the targeted material properties can be determined.

AI algorithms embedded in NDE sensors will thus enable the collected data to be pre-processed and the key relevant data to be selected. ML-based multi-parameter NDE systems (merging different NDE sensors and ML algorithms), which can predict individualised material properties, can be used as an added-value option in the framework of materials development, product design, manufacture, predictive maintenance and traceability of material properties for secondary raw materials. They can provide reliable key experimental data collected non-destructively in all stages of the entire product life cycle [180,181].

### 3.3.3 Needs in the area of NDT&E for nuclear applications

The three main steps needed in the area of NDT&E for nuclear applications are as follows:

- (New) NDT&E methods for the material characterization at macroscopic level need to be developed, validated and qualified.
- Non-destructive examinability needs to be considered at materials design and manufacturing level, for the replacement of components or retrofitting.
- Ageing models, fed with data from continuous monitoring and in-service inspections need to be developed and used for predictive maintenance (as opposed to scheduled maintenance); these need to be aggregated, enabling the development of digital replica or digital twins of components.

The development of NDE for (future) nuclear applications is currently quite fragmented in Europe, due to different strategies adopted in different MS, as well as to the significant conservativeness of the nuclear industry. Harmonization in the development of NDT&E for (future) nuclear applications needs to be pursued by:

- Identifying past and ongoing European and national research activities on this topic, including the review of the state of the art;
- Mapping experimental NDE facilities involved in NPP related R&D activities;
- Identifying research gaps and needs;
- Elaborating common priorities.

## 3.4 Development of Advanced Fabrication Processes and Innovative Nuclear Materials Solutions

Materials with better initial properties and performance in terms of resistance to degradation enable safer, more efficient and more economical design of installations. Advanced manufacturing techniques and processes, such as additive manufacturing and hot isostatic pressing, might also help increase the performance of components and enable their on-site repair or fast replacement, made necessary by inadequate or even faulty performance, possibly detected by intelligent materials health monitoring systems (Section 3.3). Component or installation lifetime is thereby increased and shutdowns become less frequent and/or shorter, thereby improving the availability and the economy of the installations, as well as their sustainability, because increased component lifetime leads to better use of resources and minimised environmental impact. The push to find material solutions with improved performance in operation is therefore strong and the equation to find the best materials solutions should also include variables such as criticality of raw elements, component monitorability (Section 3.3) and materials recyclability (or possibly re-use), as well as safe and easy disposal when this becomes

unavoidable. The forces that oppose the push towards the development of new materials solutions originate, in the case of new nuclear systems, from the need for designers to identify rapidly suitable materials that are already, or can be readily, codified, so as to enable timely design. In the case of already deployed nuclear systems, the “counter push” comes mainly from the (cost of the) industrial production transformation that the new solution implies (industrial upscaling and supply chain). In both cases, the need to be convincing with regulators for swift licensing is also an issue.

### 3.4.1 Development of new materials solutions

New materials solutions may be: (i) existing materials that are expected to be suitable for given conditions, or more suitable than previous ones, or simply cheaper, but were never used before under those conditions; (ii) materials with purposefully or expectedly improved properties and performance, thanks to, e.g., tuned composition or revised architecture; (iii) materials of the same type as those already used, but fabricated or joined according to different standards, processes or methods; (iv) combinations of the previous two cases, or coupling of different known and new materials, to better mitigate degradation due to specific agents (e.g., coatings against corrosion); (v) entirely new materials solutions that were developed with targeted properties for a specific use. In practice, the last case, which best corresponds to the “design and control” paradigm and appears at first sight as the most appealing one, is by far the least frequent one.

Each time a new material solution is proposed for a nuclear reactor, a long and costly process of full qualification and codification is required (see Section 3.1). Thus, qualification steps can currently be taken only for a reduced number of promising materials, which have emerged from a selection based on a previous screening. This is currently doable in practice only for very few candidates, generally selected based on existing knowledge. The screening is performed essentially in the same way as the qualification of materials, i.e., by exposure and testing (the “observe and qualify” paradigm), but here the goal is not to fully define the design rules for licensing and construction: it is rather to give a first assessment of the behaviour of the few candidates, so as to identify the most suitable one(s), on which to focus attention. Thus typically a small set of properties of interest is selected to be measured, after exposure to a reduced set of representative and, especially, affordable conditions. However, even these small sets may currently correspond to significant work and cost, particularly when neutron irradiation is involved (Section 3.1.4). There remains a certain probability that all materials in this small set (sometimes a set of only a couple of materials) have to be discarded at some point, because of some unacceptable behaviour under conditions of relevance for the target system. Clearly, this is a risky and inefficient way of screening, which eventually may lead to using a non-optimal materials solution, simply because it is the one for which, after several years of work, there are more or less sufficient data for codification and therefore design of the component.

The lengthy qualification process and the costly screening of new material solutions combined with the hurdle of licensing make nuclear industry often overly conservative and incremental, i.e., there must be generally very strong reasons before changing to a different type of material solution. Changes of materials did happen in the past in the case of GenII LWRs [85,182]. However, “not-too-different-solutions” from those already adopted are generally preferred [85], because easier and less costly to adopt in practice, especially in order to be convincing with regulatory bodies. It is clear that, in order for innovation to be boosted in the nuclear field concerning materials solutions, it is not only necessary that accelerated and integrated qualification paths are created and followed (Section 3.1), but also that from the start the materials are designed to be suitable for the envisaged application.

### 3.4.2 Nuclear Materials Acceleration Platforms

To enable materials development to bring all its possible benefits, the screening procedures need to become faster and more efficient, possibly including from the start in the searching tool all the important variables to robustly identify the best candidates that are later worth undergoing full (accelerated) qualification. This corresponds to adopting a full “design and control” perspective. Relying on an efficient and affordable screening procedure becomes even more important now that developing new material solutions does not only concern better intrinsic engineering properties (e.g., resistance to operation at high temperature, to corrosion or to irradiation), but also lifecycle improvement for increased sustainability (less use of critical elements, monitorability, recyclability or re-use, and so on), i.e., the number of variables to be included in the process of development and selection of materials solutions is increasing. Finally, regulators should be ideally involved from the start of the development process, in order to take into account safety indications at materials conception/design level, while monitoring the change of paradigm this implies.

Improving the efficiency of the screening procedures requires addressing mainly three aspects: (i) apply suitable fast fabrication and post-fabrication treatment methods to produce an as large as reasonably possible number of batches of materials, with various compositions and/or architectures and/or microstructures, among which the best candidates need to be selected (high throughput combinatorial fabrication [183,184,185]); (ii) identify experimental methods to accelerate exposure and subsequent testing by rapidly measuring relevant quantities (perhaps using NDT&E techniques) that are considered as suitable indicators of the expected long term performance (high throughput characterization and calculation [186], automated microstructure recognition and analysis [187,188,189,190]); and (iii) make use of advanced characterization and digital techniques as guidance to the development of new materials, by using a quantitative methodology that goes straight to the target (data-driven and blending models [163,191, 192,193,194]), instead of proceeding by trial-and-error, solely based on the (invaluable but fallible) experience or intuition of the researchers involved.

High throughput experiments and calculations quickly explore the wide phase space of the variables that characterise the materials to identify the regions of interest. Combinatorial fabrication corresponds to making sequences of samples of a certain type of material, in which variables such as composition or architecture vary according to a large number of combinations (for example, mixing different chemical elements in different proportions). Key target properties are then systematically measured in these samples, thereby obtaining a large amount of homogeneous data. High throughput is achieved if the measurements are fast and easy to repeat, automatically and sequentially, in a large number of samples, which should be small to optimise the process also in terms of use of resources. The measured quantities and the way of measuring them (e.g., after suitable exposure to specific conditions) in microsamples must be indicators of the behaviour of the material/component in operation. To complement the experiments, a large number of relevant property calculations are performed using high fidelity physical methods, such as methods describing materials at the atomic scale, implemented in high performance computers (HPC). Finally, machine learning techniques are applied to analyse the collected data, to establish correlations between the fundamental variables that characterise the materials (their “genes” or “DNA”) and the properties to be optimised. As in the case of modelling (Section 3.2) and monitoring (Section 3.3), these digital techniques are used to deduce complex deterministic laws that depend on multiple variables, based on examples provided in the

form of large amounts of data. As in the other cases, the quantity, quality, homogeneity and representativeness of the data are crucial (Section 3.5). By collecting data in an iterative fashion, these correlations are expected to enable the identification of the subset of the most promising candidate materials for the target set of properties. These should be looked at with more attention later, using more “traditional” qualification approaches, also from a perspective of industrial upscaling. The test-beds suggested in Section 3.1 are the ideal tool for these following steps.

Accelerated development through systematic screening is eventually best achieved by the creation of suitable platforms in which, with the help of robotic systems, the above described methodology of combinatorial manufacturing and high-performance characterization of materials, as well as ML methods, are incorporated in an integrated and automated way, thereby becoming autonomous materials discovery systems (autonomous materials discovery), as put forward and explained in [195], specifically for nuclear applications in [126]. Platforms of this type, called Material Acceleration Platforms, MAPs [196] are being developed and applied with some degree of success in the case of functional materials, such as for lithium batteries [186], also in Europe (BIG-MAP project [197]), and for carbon nanotubes [198].

The challenge of applying these approaches beyond the existing examples to materials for extreme conditions is daunting. Yet MAPs are preconized to revolutionise traditional materials research and development in the next decade(s), also in the field of energy materials [199]. The combination of nuclear-materials-dedicated MAPs and test-beds (Section 3.1), therefore, can be a way to boost innovation, the need for which is strongly felt in the nuclear energy field [200,201] (see also Section 4).

It is clear, however, that the development of MAPs is exceptionally challenging in the case of nuclear materials, because of the complexity of the combined exposure, often under load, to irradiation, temperature and chemicals (fluids), with the subsequent difficulty of integrating the rapid and iterative evaluation of these effects on a single automated platform, using indicators of long-term degradation resistance that are far from obvious to identify. Modelling and digital techniques are clearly of crucial importance here, as well, and here, too, advances can be made incrementally, by focusing on specific problems or techniques and then progressively integrating different aspects. A promising pathway consists to start from the collaboration with MAPs that are under development for materials under extreme conditions, though not including irradiation, and work towards adaptation for nuclear needs.

While the goal may appear science-fictional, it is nevertheless essential that nuclear materials scientists do not lag behind and strive to make use of these new methodologies, adapting them to their specific needs and possibilities, because no-one else will do this for them. The potential benefits that these emerging materials science approaches may bring are tremendous in terms of reducing costs and times towards the much needed nuclear innovation. The development of a “nuclear MAP”, similarly to the “nuclear materials test-beds”, is a challenge that only close collaboration at European level may have the chance of tackling. Like in the case of test-beds, such MAPs, dedicated to materials for harsh operating conditions, may then also serve other energy technologies and would maintain the long tradition of nuclear applications to be the crucible for materials of wider application than just nuclear [202,203,204,205,206].

It is also clear that one of the main challenging aspects of nuclear MAP is that the performance of materials under irradiation needs to be explored. Here, irradiation with charged particles (ions, protons, electrons ...), which is probably of questionable use for qualification, is likely to be the only convenient method. Charged particle irradiation is significantly faster and cheaper than neutron irradiation and enables variables such as

temperature and dose to be more easily varied and controlled (not so dose-rate, though). This enables a wider spectrum of parameters to be more affordably explored compared to neutron irradiation, although at the price of only affecting a surface-close layer of material. The latter limits the possibility of characterization to a few microstructural examination techniques, which need to characterize more than bulk properties. Thus, mechanical properties cannot be assessed using the same approaches as for neutron-irradiated materials. Moreover, contrary to bulk-techniques for mechanical testing, no good practices are fully established for those applicable to charged-particle irradiated specimens, e.g., nanoindentation [154,207]. Finally, serious issues of transferability to neutrons exist, because charged particles are injected at higher dose rate, have different energy spectrum, generally produce damage gradients in a limited penetration thickness and often inject foreign species, including impurities [208,209,210,211,212,213,214]. Thus, theoretical and modelling work to ensure transferability, and a clear definition of suitable protocols for charged particle irradiation, though already started [215], is still needed in order for these irradiation means to become fully usable as screening tools, to be integrated in nuclear MAPs.

One final aspect to be addressed concerning MAPs is their industrial interest, especially in terms of intellectual property protection. It can be argued that the same MAP, if it has the capability of exploring large regions of the variable space, can be used by different industries for different purposes. While the tool is the same, and can be public, the result of its use is not and can be intellectually protected. In addition, MAPs are essentially sophisticated materials screening tools, thus in any case a second phase of qualification and perhaps modification of promising candidates is needed, which remains separate from the use of the MAP. It is therefore possible to think of a joint development of the tool, also with industrial involvement and participation, which will not interfere with the protection of the intellectual property coming out of its use.

### 3.4.3 Advanced manufacturing

MAPs are likely to make use of advanced manufacturing techniques such as 3D printing, because this approach is the most suitable one for the fabrication of, e.g., sets of materials of the same kind with different composition nuances or different architectures. However, advanced manufacturing techniques are also extremely promising for industrial applications, in connections with replacement and repair of obsolescent components, as well as, eventually, as standard, weld-free component fabrication techniques, with virtually no limitations in terms of component shapes.

Main drivers are: (i) the ability to produce directly parts with the right shape, significantly reducing machining time and also the quantity of raw materials that are required to produce them; (ii) reduced lead times as these manufacturing methods can often deliver components in weeks or months, as opposed to conventional manufacturing methods (forging, casting, extrusion, etc.) which can often take years; (iii) flexible production of limited quantities of unique shapes: components can be produced essentially on demand in the needed quantity, eliminating the need for warehousing of parts, alternative supply chains, or minimal quantities for the production to be profitable; (iv) overall reduced costs, because of all the previous points.

However, the safe and controlled application of technologies such as AM and HIP require increased understanding of how they work, before they can be readily applied to new build construction or component replacement. The fact that so many techniques that fall under these categories exist, each with its own features and recipes to obtain materials with the required properties, makes this endeavour especially challenging. Components produced by AM techniques may have the same chemical composition as the reference



materials, but these will be characterised by a very different microstructure, with risks of porosity and internal stresses, so that the properties and especially the mechanical behaviour are not going to be the same as for the reference material and need to be characterised, while reproducibility of good properties needs to be ensured. These properties will majorly depend on the specific technique used, the fabrication parameters applied, and even the type of component that is fabricated, especially its size. Scaling to large components remains challenging. Standards and codes are still largely lacking and this makes regulatory approval more difficult. Qualification paths need to be defined, which as a topic belong more to test-bed development than to advanced materials, but in connection with the latter research is needed to be able to rationally select the most appropriate technique and, within it, the most appropriate parameters, to obtain the best reproducible result, trying to reduce as much as possible trial-and-error approaches. This is therefore also a type a work that has several features in common with the concept of MAPs, as it requires screening through a wide range of parameters, applying fast characterization (preferably of non-destructive type) and eventually using ML methods, to identify the best choice and set for the best material and component, eventually setting accepted standards that will facilitate acceptance by the regulator. For a recent analysis of the aspects related with advanced manufacturing in the nuclear field, see reference [216].

## 3.5 Data Management

Data management is becoming an intrinsic constituent of the mainstream research process in all fields [217,218,219,220,221]. The specific reasons can be many, but the substratal motivations are improved science and greater opportunities for innovation. In the specific case of materials, data management enables the application of modern techniques, such as those described in the previous sections (data-driven modelling, materials health monitoring, autonomous materials discovery, ...), while facilitating more traditional qualification approaches, where the formulation of design rules for relevant codes is hindered by the scarcity of data.

### 3.5.1 Needs for data management in the nuclear materials field

Over past decades plenty of test and measurement data have been generated through national and international research programmes, but these are often difficult to access and retrieve. While web-enabled databases have been and are being developed [222,223], potential data providers often do not add their data there, for three main reasons: (i) they are proprietary data protected by confidentiality and therefore cannot be shared; (ii) there is no sufficient motivation for data producers to spend unpaid time and resources for data upload; (iii) the hard, skilled and time-consuming work of data search, often data analysis and always data adaptation to the format of the databases, is hardly ever considered a task in itself, to be duly funded. Given the cost of generating materials qualification data, however, it seems obvious that appropriate data collection, storage and preservation in suitable repositories, with easy access in full respect of intellectual property rights, should be standard practice.

Yet, barriers need to be overcome to make it attractive for data generators and proprietors to put their data in the database. The issue of respecting intellectual property rights is especially thorny: agreements are hard to reach and are often too specific to be easily generalised. International organisations such as IAEA or OECD/NEA may be able to partially help in this respect, by providing pre-existing legal frameworks for data sharing [222]. To help, databases should also offer flexible and adaptable tools, for example to guarantee protection of sensible data while allowing access to the parts of



them that can be disclosed, which may not be sensible any more when extracted from the context (e.g., data on pressure vessel embrittlement without revealing the plant); or provide the possibility to apply an embargo to data accessibility for a number of years; and so on. There is also a “chicken-and-egg-type” problem to be solved: it is attractive to spend time and effort to provide data to a database if this gives access to data that otherwise would not be accessible; however, if the quantity of data in the database is minimal or the data are anyway openly available, this motivation largely vanishes.

The issue of unleashing skilled data retrievers can be in principle solved with adequate funding. But an associated problem affects old data, i.e., these may eventually turn out to fail to comply with modern data quality requirements, especially in terms of accompanying data (metadata) that enable them to be reproduced and therefore re-used, or protocols that were applied for their generation. Thus, the retrieval of old data for either materials qualification or model calibration/validation in the future, although important and to be added to the “to-do” list, is alas unlikely to contribute significantly to future advances in materials qualification and development. However, the combination of newly produced data in current and future projects that do enforce suitable data management policies should, little by little, but steadily, succeed in creating a critical mass of data, which will partly enable accelerated materials qualification, provided that suitable and attractive databases are created.

Ideally, these should: (i) be user-friendly, i.e., they should not only enable the user to easily access and upload data, but also to “play” with them to address issues of user interest, even several years after the data were generated; (ii) apply clear and flexible, but unbreakable, rules of data protection; (iii) use simple and flexible formats that, as much as possible, match the expectations of expert data producers and are sufficiently clear for less expert data users; (iv) apply clear and strict data quality criteria, while also being able to self-search for new data through established ontologies; (v) eventually connect directly with the software that analyses the data, to by-pass the need for humans to upload and retrieve data, so as to solve the chronic problem of filling the database with data.

### 3.5.2 Nuclear Materials FAIR Databases

For data-driven modelling to be applicable, not only the quantity, but also the quality and consistency of the data are crucial. Machine learning methods can find the logic in a set of data only if these have been generated and collected in such a way that such logic exists. Thus they must have been all produced by applying consistent procedures. This is generally broadly guaranteed in the case of standardised mechanical or corrosion property tests or data coming from sensors that all work and have been calibrated in the same way. Not necessarily so when microstructural characterization or modelling data are considered. In these cases, inconsistencies between data may be originated by the different features, limitations and possibilities offered by apparently similar types of instruments or techniques used to produce them, as well as by different operator-dependent procedures or choices of measurement conditions, or as a consequence of different parameters and assumptions that may be used for raw data analysis. Data from different laboratories, therefore, too often cannot be merged [224]. Data of qualitative nature, e.g., micrographs, also pose problems of juxtaposition.

Finally, all data must be accompanied by all the important specifications that enable their reproducibility, but the completeness of these specifications may be challenging. Before machine learning methods can be systematically used to include microstructural examination results as data-driven modelling variables, therefore, there is a need to define accepted good practices, protocols and possibly standards for the application of

microstructural techniques, as well as for the analysis of their results. Furthermore, consistently complete and consensual data formats and possibly ontologies need to be established. This should allow full interoperability and provide higher guarantee of reliability, reducing scatter and uncertainty, irrespective of the number of data that can become available. This process of standardization, or at least definition of protocols, which needs to be extended to microstructural characterization techniques and relevant data format, is also essential in view of developing MAPs (Section 3.4), because only standardised characterization procedures can be automated, while only interoperable data can be effectively used to make conclusions based on data analysis. Defining standard good practices and formats, however, needs to be extended to all existing techniques and requires consensus amongst the experts, thus being a heavy task in itself.

It is important to emphasise that the establishment of good practices, protocols and possibly standards for (materials) data is a general problem, which concerns all technologies, and not only for the part that concerns materials. It is thus inherently a cross-cutting issue, irrespective of the target application to materials. The FAIR (Findable, Accessible, Interoperable and Re-usable) Guiding Principles for scientific data management and stewardship [225,226] are of universal application. Interoperability and re-use require consistency of the data coming from different laboratories and to facilitate transfer between different information systems, irrespective of the application. Standard formats for materials data need to be established in order for the highly interconnected information and communication technology infrastructures that have emerged in recent years to become effective in appropriately storing data and ensuring their availability for the purposes of future re-assessment.

Producing a centralised European nuclear materials database is overall a formidable challenge because of the issues that this goal raises also from the legal and political points of view. It is, however, a clear and undeniable need, to which effort has been already and is still being dedicated in Europe, e.g., in the project ENTENTE in the case of RPV steels [223], in the projects ESNII+ and ESFR-SMART in the case of MOX fuels [227] or with the development of the MatDB database [228]. Many of the related challenges can be addressed with the help of suitable digital tools and, especially, with the skill of database masters that should make its use fully fit for the purpose according to requirements, having the data providers and the data users' needs as the main criteria for the design of the data-base.

## 4 Strategic Research Agenda Implementation

### 4.1 Objectives

The strategic objectives for the proposed research agenda on nuclear materials, as described in Section 3, are to:

- Create **integrated test-beds** dedicated to nuclear materials, and in general materials for harsh operating conditions, as an effective pathway for accelerated materials qualification and industrial upscaling, based on the coordinated exploitation of existing and future facilities and infrastructures in Europe and on the elaboration of standardised qualification paths, at the service of both industry and research, in full respect of intellectual property.

- Develop new predictive capabilities by **blending** by now “traditional” **physically based multiscale tools and approaches** (the development of which has absorbed much effort in the last few decades [148]) **with more recent data-driven approaches**, e.g., making use of few-shot learning techniques, as an effective methodology to accelerate application for design and safety purposes at industrial level.
- Establish **intelligent materials health monitoring systems** extended to material properties over the whole component lifecycle: multi-parameter-based approaches combining different NDE techniques to efficiently characterize materials’ properties (“material DNA”) similarly to having different human-senses, thanks to machine learning algorithms that remove irrelevant or spurious data, best blended in cognitive sensor systems, for advanced digital twin concepts of industrial applicability.
- Develop **Materials Acceleration Platforms dedicated to nuclear materials**, or more generally materials for harsh operating conditions, as an ambitious, but extremely promising goal to apply a “design and control” paradigm for materials screening and perhaps discovery, with high potential to boost innovation in a field that needs it, allowing variables related with circularity and sustainability to be included from the start (“fitness and sustainability by design” [229]). Likewise apply similar structured screening to **bring to full maturity the use of advanced manufacturing techniques in the field of nuclear energy**.
- Create **FAIR nuclear materials databases** and, importantly, populate them with data, to provide a modern, user-friendly, flexible, efficient, protected and especially attractive framework to store, cure, analyse and exploit data, coupled with the consensual definition of materials examination protocols and relevant data format, as a crucial prerequisite for the success of the above endeavours, in full respect of the protection of intellectual property.

## 4.2 The Need for a European Partnership

The ambitious goals and effort sketched above and in the previous sections, especially the change of paradigm that is explicitly pursued, can only be achieved by promoting close, structured and continued collaboration between academia, research organisations and industrial partners all over Europe, including the involvement of technical support organisations and regulators. This will enable the European nuclear materials research community to maximise the effect of the assets and financial resources that are available in Europe, avoiding duplication and fragmentation and achieving European self-sufficiency. Such structured collaboration is expected to provide orientation, prioritization and, primarily, continuity to the five above nuclear material science research lines, leveraging also significant national and industrial support towards the corresponding strategic objectives. This is not fully achieved with the current EU financing model, which is based on smaller, independent communities and projects that almost exclusively rely on the limited support of Euratom.

For example, in the Horizon 2020 framework programme, Euratom funded about 20 single nuclear materials’ research-related projects, overall 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, nor did it lead to a unified structure around which a wide spectrum of stakeholders could gather. Each project had its own advisory board or end-users group, often with overlaps and inherent duplications, but without anyone reaching an overall vision on the activities

dedicated to nuclear materials in Europe and with only limited interaction between projects. Moreover, it is important that the research community becomes more deeply involved in deciding priorities, together with the industry, than in the current model based on independent projects, prepared in response to the topics identified at Euratom and programme committee level.

Beyond doubt, the instrument to achieve the above purposes is a European partnership on nuclear materials, to be built around the stated strategic objectives, that will bring the core of nuclear materials activities under the same umbrella, enabling inter-project communication, providing instruments for the research community to define priorities and the stakeholders with a single entry point to obtain a global view over the research done in Europe on nuclear materials, with the possibility of steering it towards faster innovation.

Such a unified framework is also beneficial for education and training (E&T) and researcher mobility, by enabling the creation of a single nuclear materials competence platform. As described in [230], this platform will centralise E&T activities dedicated to nuclear materials, avoiding duplication and fragmentation and being able to target its initiatives to consensually identified needs. Provided that sufficient resources are allocated by EC and MS, it would be the right framework to set up a European training network, with the possibility for students to perform their master or PhD thesis work between two different centres, including the possibility of considering stays at industries.

The partnership will enable the retention and expansion of multidisciplinary scientific knowledge and cooperation between stakeholders 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, through the largely cross-cutting channel of materials science. 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 [77], with which the proposed partnership's goals are entirely consistent. In 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.

## 4.3 Implementation and expected results of the partnership

### 4.3.1 First five years

It is important to emphasise that the legal structure and way of functioning of the partnership have been defined in bespoke documents [231, 232], to which implicit reference is made here.

During this period the work will be limited to the four classes of nuclear materials for which ID cards have been developed, i.e., structural materials (metallic and concrete) and fuel element materials (actual fuel and fuel cladding). Concerning the three other classes of materials (polymers, refractory structural materials and neutron control materials), strategic activities will be launched to (re)build the corresponding European

research communities and write the corresponding ID cards. The focus of the projects in the first five years will be on fission applications only, although contacts with the fusion community will be taken in terms of joint workshops, in preparation of a possible future expansion of scope towards fusion materials and applications in the continuation of the partnership, provided that fusion will also contribute to the funding.

Emphasis will be put on innovation for the benefit of any reactor generation, by selecting simple, but diversified, case studies in each research line as steps and milestones towards the objectives put forward in Section 4.1. The criteria applied to select the case studies, i.e., the projects, will not be related with the chosen nuclear system, but rather with the efficacy and extendibility of the methodological plan that the project proposal puts forward, as a clear contribution (milestone) towards the goal of the research line. Projects may have a content that is cross-cutting through research lines; however, upon proposal one and only one main objective has to be chosen and this choice will determine to which research line the project is assigned.

Projects will be set up in three phases and **the objectives of all projects along the different phases will define the milestones of each RL**, partly predefined and partly defined while the partnership is running

- 1) Small projects (i.e., < 300 k€ EC contribution) dedicated to topics that are considered as essential prerequisites for each research line (in principle one small project per research line) will be identified already at the beginning of the partnership. Possible topics are as follows:
  - RL1 “Nuclear materials knowledge & data management”: definition of data and metadata format in view of storage in relational databases for selected experimental and modelling techniques, continuing the work started in current Euratom projects;
  - RL2 “Materials and component qualification: testing, standardization and design rules”: definition of common practices for the performance of experimental characterization and testing for all those techniques for which standards do not exist (possible collaboration with OECD/NEA on this topic) and/or definition of standardized qualification paths for specific applications of wide interest;
  - RL3 “Advanced materials modelling and characterization”: identification of case studies that are particularly apt to demonstrate the possibility of improving predictive capabilities by blending physics-based and data-driven models and/or by linking methods and plan their development.
  - RL4 “Non-destructive examination and materials health monitoring”: classification of materials/components which shall/may be monitored or inspected and identification (feasibility study) of NDE techniques which can be applied to these components as monitoring or inspection technique.
  - RL5 “Advanced materials development and manufacturing”: perform a feasibility study of a nuclear MAP, starting from existing examples dedicated to the discovery of materials for harsh conditions and design it, defining the steps to be taken towards its completion.
- 2) A first call for projects will be launched during the first year of the partnership. The text of the call will be prepared by the RL leaders and advisors, listening to the advice of scientific advisory board and innovation group, with the endorsement of the General Assembly (top-down prioritization). Within these boundaries, the proposals will be the result of the convergence of a consortium towards a given topic (bottom-up prioritization). One or two projects per research line will be finally selected on the basis of their compliance with the requirements defined in the call. The selection will



occur in a transparent way by means of an internal evaluation committee that will rank proposals based on the score of external reviewers, the result of which will be approved by the general assembly.

- 3) Provided that Euratom increases the budget for the partnership, and proportionally to the increase, a second call will be launched, probably at the end of the second year of the partnership

One important point concerns the planning of in-pile instrumented neutron irradiation campaigns. These are costly and a priori not affordable with the sole support of the partnership. It thus becomes mandatory to identify external schemes of which the partnership can make use, offering its assets in exchange. Moreover, any in-pile irradiation will have to be strongly connected with the activities carried on in the partnership's projects, which will be selected via the competitive calls. A specific task will be dedicated to the identification of needs and design of an in-pile irradiation programme. The strategy to be followed is detailed in reference [233]. Collaboration with the NEA second Framework for Irradiation Experiments (FIDES II) [140] is envisaged and the use of the schemes for access to infrastructures developed within the OFFERR initiative [234] will be considered, as well.

Finally, throughout the duration of the partnership, the materials ID cards will be open for revision through a consistent and controlled procedure, as well as for expansion of their scope (particularly for refractories, polymers and neutron control materials). Based on the experience of the first five years and on the advice of the innovation group and the scientific advisory board, this SRA will be eventually revised.

The expected results after five years are:

- First steps taken towards an integrated test-bed dedicated to at least a couple of specific material classes and nuclear applications: establishment of common good practices between laboratories, ranging from experimental protocols to consideration of legal aspects related to integration, including harmonised transport procedures for active materials between laboratories; elaboration of standardized qualification paths; actual application to selected materials. These steps will connect and be complementary with ongoing projects, such as INNUMAT for structural materials [235], PUMMA for fuel [236], as well as with OFFERR [234] to regulate the access to infrastructures and facilities.
- First steps taken towards the elaboration of nuclear MAPs: mapping of MAPs that are under development and creation of a connection with those that are of interest for nuclear applications, via suitable extension; identification of characterization and calculation/modelling methodologies for fast screening with respect to selected properties; development of high throughput fabrication, characterization or calculation methodologies (even if not integrated); rudimentary examples of innovative materials design, in connection and complementarity with ongoing consistent projects such as INNUMAT [235]
- Elaboration and possibly standardization of well-controlled, reproducible and qualifiable advanced manufacturing processes, in connection with ongoing projects, such as FREDMANS [237] (for fuels) and NUCOBAM [238] (for metallic structural materials)
- Development or improvement/extension of physics based models of behaviour of materials under irradiation across scales and of blended physically-based/data-driven models, applied to a few selected case studies. Improved design and fuel performance codes towards high fidelity and advanced numerical capabilities;

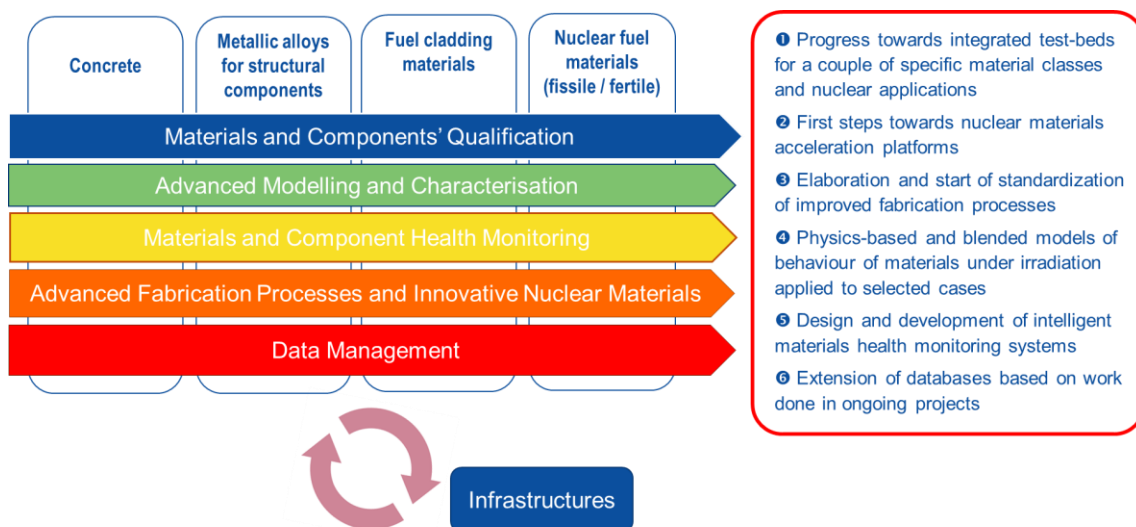


connection and complementarity with ongoing projects, such as ENTENTE [223], STRUMAT-LTO [239], DELISA-LTO [240], OperaHPC [241], PUMMA [236], PATRICIA [242] ...

- Design and development of examples of intelligent materials health monitoring systems, suitable to be extended for material characterization along the entire material value chain, from material development (under lab conditions) until the end of operation (under operation conditions) for at least two of the four selected families of nuclear materials. As a prerequisite, efforts of harmonization of the testing procedures/protocols need to be made, based on common good practices between NDE laboratories. Another pre-requisite is the consideration of legal aspects related to integration of NDE in standards and codes; synergies between ongoing European projects (STRUMAT-LTO [239], INNUMAT [235], DELISA-LTO [240]) and national funded projects.
- Extension of data format and database based on the work done in ongoing projects (ENTENTE [223], EERAdata [243]...); development of ontologies for nuclear materials oriented processes, tests and characterization or modelling techniques; evaluation of existing databases and extension of selected ones for specific materials.

It is important to note that, as to content, currently ongoing projects on nuclear materials can be continued and EERA-JPNM pilot projects can be hosted in the CEP, provided that their focus is explicitly turned towards at least one of its five objectives.

In addition, collaboration with other initiatives focused on materials for harsh environment outside the nuclear domain, mainly through EERA (e.g. with EMIRI and EUMat WG-02 Materials for energy) need to be established whenever relevant. Particularly important is the connection with fusion energy to establish suitable cross-cutting joint activities for the second part of the partnership (if fusion support is received) or for future developments.



**Figure 5.** Perimeter of activities and expected results at the end of the first 5 years.

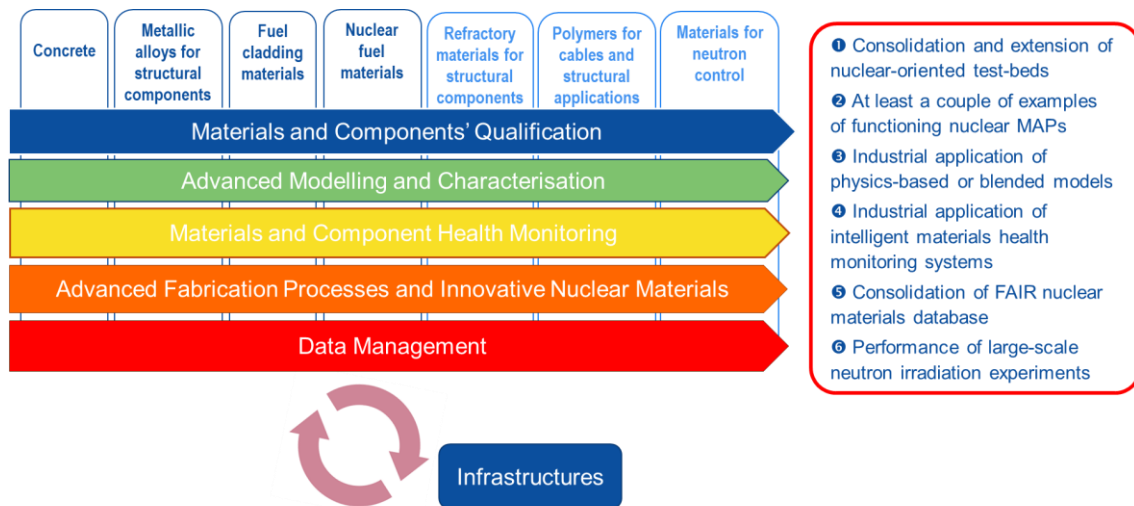
### 4.3.2 Ten year horizon

Assuming increased financial provisions are granted, including fusion support, will be extended to all 7 classes of nuclear materials and the portfolio will include also fission-fusion cross-cutting issues. Case studies of sufficiently ample validity to serve several reactor systems will be addressed.

The expected milestones are:

- Consolidation, extension and application of nuclear-oriented test-beds;
- A couple of examples of functioning nuclear MAPs or MAP-like systems and their application;
- Industrial application of advanced predictive methodologies based on physics-based or blended models to selected cases;
- Industrial application of intelligent materials health monitoring systems to selected cases;
- Consolidation of the FAIR nuclear materials database;
- Performance of large-scale neutron irradiation experiments in support of the work done within the various research lines, according to preparation work performed during the first five years.

The criterion of success will be the extensibility of developed methodologies rather than their specific application.



**Figure 6.** Perimeter of activities and expected results at the 10 year horizon.

### 4.3.3 Projection to 15 years

At this stage the work done within the CEP will have created sufficiently strong foundations, in terms of flexibility and extendibility of the methodologies, to enable the application of the approaches pursued within each research line to the benefit of the nuclear energy world, addressing the most important (in that future moment) requirements of nuclear (and also non-nuclear) systems, trying to move in the direction of being also economically self-sustainable, at least for some of the activities.

## 5 Concluding remarks

A European strategic research agenda on nuclear materials in support of innovation and coherent with the goals of the Green Deal [244], in connection with the clean energy transition, needs to aim at developing and establishing ambitious assets that are specific in nature, but also of broad interest for a large spectrum of (nuclear and non-nuclear as well) industrial applications and of all European member states. This has been the

guiding principle of this SRA, which tries to focus on materials science at the service of nuclear energy, rather than on nuclear systems, thereby emphasising what unites as opposed to what creates divides between EU countries.

As a matter of fact, the number of possible nuclear reactor systems and nuclear energy policy strategies is finite, but still fairly large, and almost all of them are being considered in Europe. Privileging one over another is largely a matter of political choice of a country or a group of them, or of strategic choice of a company or of a cluster of them. The nuclear materials science community in Europe and elsewhere cannot make these decisions, nor can formally interfere with them. This community, however, is called to stably provide the tools, skills and knowledge that should enable safer and more sustainable (in a broad sense) operation and construction of current generation reactors, as well as reduction of costs and time for design, licensing, construction and safe operation of any next generation nuclear system, in the interest of, *a priori*, any country or customer company, and chiefly of the European citizens. Likewise, although the classes of materials that are suitable for application in the nuclear energy field are limited, the possible choices of actual materials and combinations thereof cover a wide spectrum, especially for next generation systems. The definition of a programme of full and complete qualification of a given material solution for a specific nuclear application and design is clearly the task of the organization, or consortium of organizations, that lead the specific project and should bear the relevant costs. However, the nuclear materials science community should stably provide the tools, skills, knowledge and capability to design fit-for-purpose materials according to needs and, as much as possible, also to criteria that go beyond the strict engineering performance, i.e., including aspects of circularity and sustainability at large. Likewise, this community should be able to offer, by joining forces in a coordinated way, the capability of qualifying materials for a wide range of nuclear applications, using at best available infrastructures and facilities, while getting ready to use new ones that will appear in the coming years.

In this context, five goals have been identified as strategic. These include the development and establishment of integrated nuclear materials qualification test-beds and materials acceleration platforms, extendable to materials that operate under harsh conditions, as well as development of smart and intelligent NDE&T systems for materials health monitoring. They also include predictive models of industrial use that suitably blend physics-based and data-driven approaches, in support of nuclear test-beds, MAPs and health monitoring systems, together with the creation and population of a centralised, FAIR database for nuclear materials, which should eventually become a reference for all classes of quality data, including from MTRs and surveillance or monitoring programmes of commercial power plants.

These goals will be best reached as part of a partnership that promotes close, structured and continued collaboration between academia, research organisations and industrial partners all over Europe, with the possible involvement of technical support organisations and regulators, to enable the European nuclear materials research community to maximise the effect of the assets and financial resources that are available in the continent, avoiding duplication and fragmentation and achieving self-sufficiency.

## 6 Annexes

### Annex 1 — GenIV Prototypes and Demonstrators in Europe

Over the last couple of decades Europe concentrated on four industrial GenIV fast reactor prototype/demonstrator projects, namely: ASTRID [245], ALFRED [246,247], ALLEGRO [248] and MYRRHA [35,249], all of them promoted by the European Sustainable Nuclear Industrial Initiative (ESNII—see Annex 2). The first three are, respectively, the sodium, lead and gas cooled GenIV fast reactor demonstrators. The last one is a sub-critical lead-bismuth cooled reactor to be made critical through a proton accelerator and spallation reactions that produce neutrons (accelerator driven system—ADS [34,35,57]. The ASTRID project, which was driven by French EDF, AREVA and CEA, has been recently (2019) cancelled [250]. The construction of the gas fast reactor demonstrator, ALLEGRO, that is being designed by the V4G4 Consortium [251], is more and more pushed towards the future. The lead-cooled fast reactor demonstrator/prototype, ALFRED, promoted by the Falcon Consortium [252], remains on track. Finally, the construction of MYRRHA has been partly enabled by the funding granted by the Belgian government to SCK CEN until 2038. However, MYRRHA is not thought as a power reactor, but rather as an experimental facility that can be used for several purposes, which makes use of, or anticipates, GenIV technology. In parallel, a spin-off company of KTH in Sweden, LeadCold, is working at the design of a lead-cooled SMR [253]. Concerning other GenIV reactor concepts, i.e., the supercritical water reactor (SCWR) and the molten salt reactor (MSR), work is underway in several European countries, although no structured industrial initiative has yet been created around any of them in Europe, e.g., within ESNII. The MSR is currently receiving close attention at research level, especially in France and in the Netherlands [254], as well as in the Czech Republic [255]. In parallel, two start-ups based in Denmark are promoting molten-salt-cooled SMRs for various purposes and with varying detailed features [256,257]. Finally, the HTR is the focus of the NC2I pillar of SNETP [258] (see Annex 2).

## Annex 2 — Nuclear Systems and Materials Dedicated Platforms in Europe

The Joint Programme on Nuclear Materials, JPNM [259], is, since 2010, one of the currently 18 joint programmes (JPs) of the European Energy Research Alliance, EERA, which altogether cover the full spectrum of low-carbon energy technologies and systems [260]. EERA was created in 2008 in support of the European Strategic Energy Technology (SET) Plan [261], which had been launched in 2007. EERA promotes cooperation among almost 250 (in 2021) public research organisations, under the motto “catalysing European energy research for a climate-neutral society by 2050”, and by focusing on low Technology Readiness Levels (TRL < 5 [221]), i.e., mainly dealing with research towards innovation. In contrast, industrial implementation (TRL > 5) characterises the technology platforms and the industrial initiatives, which are described in what follows in the case of nuclear energy.

The Sustainable Nuclear Energy Technology Platform (SNETP), launched in 2007, supports and promotes safe, reliable and efficient operation of Gen-II, III and IV civil nuclear systems [262]. In May 2019, SNETP became an international non-profit association under Belgian law. It is considered by the European Commission as a European Technology and Innovation Platform (ETIP). Its members include industrial actors, re-search and development organisations, academia, technical and safety organisations, SMEs and non-governmental bodies. It stands on three pillars:

- NUGENIA (Nuclear GenII&III Alliance) [263]: It supports the R&D of nuclear fission technologies, with a focus on Gen II & III nuclear power plants, providing scientific and technical support to the community, through initiation and promotion of international R&D projects and programmes.
- ESNII (European Sustainable Nuclear Industrial Initiative) [264]: It promotes Generation IV Fast Neutron Reactor technology demonstrators and supporting research infrastructures, fuel facilities and R&D work. Designing, licensing, constructing, commissioning and putting into operation demonstrators for new reactor technologies is thus the main goal of ESNII.
- NC2I (Nuclear Co-generation Industrial Initiative) [265]: It promotes the demonstration of low-carbon cogeneration of heat and electricity based on nuclear energy, as an innovative and competitive energy solution. Its target is the commissioning of a nuclear cogeneration prototype within 10 years, to serve several energy-intensive industries using this low-carbon energy technology.

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