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A NEA review on innovative structural materials solutions, including advanced manufacturing processes for nuclear applications based on technology readiness assessment

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ABSTRACT

The Nuclear Energy Agency (NEA) Expert Group on Innovative Structural Materials (EGISM) was established in 2008 under the guidance of the Nuclear Science Committee (NSC). Its objectives are to conduct joint and comparative studies to support the development, selection and characterisation of innovative structural materials that can be implemented in advanced nuclear fuel cycles, under long service lifetime and extreme conditions, such as high temperature, high dose/dose rate and corrosive chemical environments.

In this context of growing interest and initiatives, the EGISM initiated at the beginning of 2018 an activity among its members to:

- Identify, in a non-exhaustive way, the currently existing programs on innovative materials and fabrication processes in NEA member countries and China;
- Establish a first cartography of the activities that are underway on these topics and identify common subjects and thematic;
- Propose a Technology Readiness Level scale to estimate the maturity of both innovative materials and fabrication processes;
- Carry out a reflection on what the enablers are to quickly climb this TRL scale, as well as the obstacles, in order to identify solutions to overcome them.

This paper first gives definitions shared between the EGISM members on what are considered as advanced structural materials solutions. Next, some international initiatives for the accelerated development of high performance materials are presented both in non-nuclear and nuclear fields. Then, the methodology adopted for technology readiness assessment is explained. A non-exhaustive synthesis of the projects identified among the EGISM members on innovative structural materials and advanced manufacturing solutions such as additive manufacturing is presented. The TRL level of

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these projects is evaluated. A focus is also made on some of these projects to illustrate and explain the TRLs chosen as well as highlighting enablers or obstacles identified to climbing up the TRL scale.

1. Introduction

The development of sustainable energy technologies is presently at the heart of discussions to face the climate emergency and the increasing world energy demand. In this framework, efficient and advanced nuclear fission systems are considered as a solution to further reduce the impact of global warming on the climate and provide safe and secure energy. However, the operating conditions of the fourth generation (Gen. IV) concept nuclear reactors will place significant demands on their structural materials. Requirements on materials for fusion systems are even more demanding. Thus, it is key to identify materials solutions that guarantee the integrity of components for sufficiently long times under extreme conditions, such as high temperature, high irradiation flux and dose, high stress, and chemically aggressive environments, whenever design solutions to ameliorate these conditions are not effective enough or are unaffordable. These materials solutions need to be scalable from lab to pilot to demo industrial size and cost-effective. They must also be selected or developed, and properly qualified paying attention also to their overall environmental sustainability: i) the manufacturing process should reduce, as much as possible, the carbon emissions when compared to conventional ones, ii) sufficiently abundant materials should be used and extracted under environmentally and socially acceptable conditions, and iii) the eventual recycling should be facilitated via a suitable choice of materials and component design. In short, the global sustainability of the materials cycle, from the design to the end of life, needs to be improved in a circular economical approach. Finally, nuclear materials development needs to be significantly accelerated in order to timely answer the materials needs for advanced reactors developed in response to the climate change emergency. The current process of discovering and developing structural materials for nuclear applications still requires considerable time, effort and expense, taking decades (10 to 20 years) to bring new materials solutions to market [1,2]. Therefore, a real opportunity exists, as it is also the case for other energy industries, notably renewables, to reduce significantly the time of development, by building an integrated approach that covers design, fabrication and qualification of the materials using emerging technologies, capacities and advanced processing, such as additive manufacturing (AM), automation and robotics, artificial intelligence and machine learning. This endeavour, however, requires that appropriate support is accorded to these activities.

The Nuclear Energy Agency (NEA) Expert Group on Innovative Structural Materials (EGISM) was established in 2008 under the guidance of the Nuclear Science Committee (NSC) and the auspices of the Working Party on Scientific Issues of the Fuel Cycle (WPFC). Its objectives are to conduct joint and comparative studies to support the development, selection and characterisation of innovative structural materials that can be implemented in advanced nuclear fuel cycles, under long service lifetime and extreme conditions, such as high temperature, high dose/dose rate and corrosive chemical environments.

In addition, the Expert Group organises a triannual workshop on Structural Materials for Innovative Nuclear Systems (SMINS) to stimulate an exchange of scientific information on current and innovative materials research programmes for different advanced nuclear systems, with a view to identifying and developing potential synergies [3,4]. The outcomes of the workshops have provided guidance to the future scope of work of the group, via the status report on structural materials for advanced nuclear systems [5] and an overview of facilities for basic research on materials under irradiation [6].

In particular, the fifth SMINS meeting was held on 8–11 July 2019 in Kyoto (Japan), hosted by the Kyoto University and JAEA, in cooperation with the International Atomic Energy Agency (IAEA) and the European Energy Research Alliance (EERA, www.eera-set.eu) through the Joint Programme on Nuclear Materials (JPNM, www.eera-jpnm.eu).

During this workshop, a specific session was organised on advanced processes and materials and, in line with this topic, a specific panel discussion was held on “how to fast track innovative materials through to application”. Four speakers gave thematic presentations, which covered:

- Integrated computational alloy design [7–9], showing the interest of these tools for developing novel high-performance materials.
- Innovative manufacturing processes [10–15], in an integrated approach for low carbon energy. Examples included AM, advanced coating technologies, nano-manufacturing and hybridation of processes.
- Use of ion and neutron irradiations [16,17] to evaluate and qualify innovative structural materials for nuclear energy applications.
- Optimisation of concentrated solid-solution alloys [18,19] regarding irradiation induced defect production and microstructure evolution.

These presentations, followed by an active and fruitful discussion between the workshop participants, showed the growing interest and urgent need of implementing and developing in the nuclear industry the actual advances and progresses on materials and fabrication processes.

Another initiative is underway in the nuclear field in the framework of the Generation IV International Forum (GIF). A task force on advanced manufacturing was established in May 2018: the Advanced Manufacturing and Materials Engineering (AMME). This task force aims to foster cross-cutting activities and collaborative projects within the GIF countries to reduce the time to deploy advanced materials and their manufacturing.

In this context of growing interest and initiatives, the EGISM initiated at the beginning of 2018 an activity among its members to:

- Identify, in a non-exhaustive way, the currently existing programs on innovative materials and fabrication processes in NEA member countries and China;
- Establish a first cartography of the activities that are underway on these topics and identify common subjects and thematic;
- Propose a Technology Readiness Level [20] scale to estimate the maturity of both innovative materials and fabrication processes;
- Carry out a reflection on what the enablers are to quickly climb this TRL scale, as well as the obstacles, in order to identify solutions to overcome them.

This paper first gives definitions shared between the EGISM members on what are considered as advanced structural materials solutions. Next, some international initiatives for the accelerated development of high performance materials are presented both in non-nuclear and nuclear fields. Then, the methodology adopted for technology readiness assessment is explained. A non-exhaustive synthesis of the projects identified among the EGISM members is presented together with an evaluation of the TRL level of these projects. A focus is also made on some of these projects to illustrate and explain the TRLs chosen as well as highlighting enablers or obstacles identified to climbing up the TRL scale.

2. Definitions

Structural materials by definition transfer or support a mechanical load, having to fulfil a large set of requirements[1]. In contrast, functional materials transfer information or energy of any kind. In this work, we focus on structural and load bearing materials for vessel, internals, heat exchangers…, including fuel cladding.

Innovative structural materials solutions for nuclear systems can be defined as those that enable significant improvements in reactor design, leading to increased efficiency and safety, enhanced flexibility and/or prolonged component lifetime. Generally, these solutions rely on advanced materials and/or on advanced manufacturing or post-manufacturing processes, or both, although in some cases they may simply be the consequence of combining known materials in an innovative way. Advanced structural materials that are considered for use in different reactor components, both in-core and out-of-core, may comprise, but are not limited to:

- Advanced materials in terms of new chemical composition and microstructure, developed to have unique properties, if possible based on *in silico*[2] design. As an example, such developments may be achieved through integrated computational materials engineering; materials or material structures elaborated by novel pathways (i.e. fabrication routes such as AM and/or joining processes), applied to existing or new structural materials;
- Advanced materials in terms of design and architecture (e.g. functionally graded materials) or process of fabrication, including coated systems. Examples could be thin films or coatings deposited by processes such as high-power impulse magnetron sputtering (PVD/HiPIMS), laser processes, direct liquid injection of metalorganic precursors (DLI MOCVD), cold spray…

More and more often, in addition, because of recent trends in manufacturing techniques, the properties and effectiveness of given materials solutions are intimately related with the type of component that is produced, its geometry and complexity, the manufacturing technique and the possibility or not of applying post-manufacturing treatments.

3. Global initiatives

3.1. Accelerated materials discovery

Global initiatives are currently underway on the subject of accelerating materials discovery, in both nuclear and non-nuclear fields.

In connection with the clean energy transition, by further developing renewable and other low carbon energy production and conversion technologies, including capture and use of CO_2, Mission Innovation (MI) is a global initiative of 24 countries and the European Commission (on behalf of the European Union) that is working to accelerate clean energy innovation [21]. As part of MI, Innovation Challenges (ICs) are global calls to action aimed at accelerating research, development and demonstration in technology areas that could provide significant benefits in reducing greenhouse gas emissions, increasing energy security and creating new opportunities for clean economic growth. One of these ICs is dedicated to Clean Energy Materials. The objective of this IC is to accelerate the exploration, discovery and use of new high-performance, low-cost clean energy materials, considering that achieving the urgent transition to a low-carbon economy requires the development of new, high-performance, low-cost materials, that should be safe for humans and environment, recyclable and based on abundant elements. Workshops were organised in this framework in September 2017 and in January 2018 in Mexico. The main recommendation coming from these workshops was to develop materials acceleration platforms (MAPs), which should integrate automated robotic machinery with rapid characterisation and artificial intelligence to accelerate the pace of discovery [22]. Key priority research areas were also identified that comprise the MAP elements emphasising also the need for developing multidisciplinary international teams of scientists with deep international collaborations and long term support. The main axes that have to be worked on in a short term (with the goal of making integrated platforms a reality by 2030) are:

- Artificial intelligence for materials.
- Bridging length and time scales.
- Data infrastructure and interchange.
- Closing the loop by integrating the in situ analysis of materials either during elaboration and/or after fabrication, into a single unit.

In the field of the nuclear industry, the recent launch of the Nuclear Materials Discovery and Qualification Initiative (NMDQi) [23] led by the Nuclear Science User Facility (NSUF) program in the U.S. aims to accelerate both the discovery of new materials that can be applied to the needs of the nuclear industry and the ultimate qualification of those materials. In order to facilitate this acceleration, the NSUF intends to follow the materials design concept and apply the combinatorial and high-throughput (CHT) methodology to the unique challenges of the nuclear materials field. The CHT methodology integrates combinatorial materials fabrication methods, high-throughput characterisation techniques (particularly in the area of high-throughput mechanical property testing and the high-throughput testing of radioactive materials), materials modelling and data analysis, with the potential of incorporating machine learning (ML) and specifically artificial intelligence (AI) schemes. The successful use of the CHT methodology will introduce new materials into the market faster and at lower cost. CHT research includes fabrication and testing techniques for bulk material properties, as well as studies to correlate bulk properties to those obtained from micro- or nano-scale samples. Areas of interest for NMDQi include materials for core, cladding, and structural applications, metallic and ceramic advanced fuels, sensor materials, multi-layer structures (e.g. coatings), interface interactions, and corrosion.

It must be emphasized, however, that in this framework of accelerating materials development, structural materials represent a much more challenging application than functional materials. Structural materials need to fulfil a larger set of requirements and properties. In addition, the properties involved are often not fast and easy to measure, as they are generally revealed only after long times in operation (e.g. creep strength). Models that correlate initial features with the long-term performance of materials become necessary, but also the development of models of this type is challenging. Alternatively, fast measurable indicators of long-term behaviour need to be identified, with all the uncertainties that their identification opens up. In this case, too, reliable models are essential. It is however true that the conceptual separation between functional and structural materials is narrowing: functional materials often require sufficient mechanical properties, while structural materials are often integrating functional aspects as well [24]. Yet, some challenges remain largely specific to structural materials, such as: processing large components and issues associated to the homogeneity of microstructure and properties, mechanical properties, production time, lifetime assessment… and have to be addressed also specifically. Indeed, advanced manufacturing processes such as additive manufacturing, can involve very high temperature gradients and thus generate specific microstructures different from those of cast or wrought alloys. Fine grains, anisotropic microstructures with elongated grains, non-equilibrium microstructures, dislocation density, residual stresses and metallurgical defects, such as porosity due to unmelted powders and

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[1] Mainly mechanical strength, ductility, toughness, fatigue resistance, time-dependent properties (creep, creep-fatigue…), ageing and phase stability, and sufficient tolerance to harsh operational environments.

[2] Performed on computer or via computer simulation.

gas entrapment, are among the common microstructural features of metals elaborated by additive manufacturing [25–27]. The understanding of the link: process parameters/microstructure/final behavior is required to master and optimize these new manufacturing processes; this understanding should then be combined to modelling to accelerate the developments. High-speed cameras and/or in situ instrumentation of these processes as well as implementation of non-destructive techniques should also help this understanding and could lead to "intelligent" automation of the processes. Post treatments including heat treatments but also surface treatments, which can be mechanical, chemical, electrochemical are also an essential part of this work.

All these considerations are even more prominent in the nuclear sector, where licensing requires the regulator's authorization based on codified and demonstrated materials specifications that include the need to evaluate the effects of irradiation, which can be very costly.

3.2. Data collection, assessment, management and use

One of the prerequisites to apply materials development acceleration concepts is the efficient production, collection, storage and use of data related to all materials properties of interest. For example, ML techniques are essentially based on the availability of a sufficiently large amount of qualified data, through the analysis of which predictive laws can be derived (data-driven modelling). Even though AI can also be of help to bridge through scales in a physical multiscale modelling framework [28], the fast analysis of data covering a wide spectrum of conditions is de facto the mainstream use and application of AI, thus a significant component of empiricism remains at the basis of this application. It should also be noted that the application of these techniques is potentially problematic in the specific case of nuclear materials, because irradiation data are in many case scarce, so rather than a problem of "big data" analysis, nuclear materials face the opposite problem of "too small" datasets. One answer to this is the use of so-called "few-shot" AI techniques [29]. Another, and complementary, approach is to encourage data sharing as well as sharing of methodologies to guarantee the quality and the consistency of these data. This is a long-standing problem that becomes mainly a legal intellectual property protection issue, although it may be facilitated by the application of smart rules that allow their usability for the purpose of modelling, while protecting the data and their origin.

For instance, in Europe, several Horizon 2020 projects contribute to the Open Research Data (ORD) Pilot initiative. Submitting data to this initiative is voluntary. The goal is to try to engage data producers in European Commission-funded projects to make their data openly available (at least the data connected with published and non-confidential work), according to the so-called FAIR principles: Findability, Accessibility, Interoperability, Reusability. In the nuclear field, one of the projects adhering to this initiative is GEMMA (GEnIV Materials MAturity) [30]. A large part of this project is devoted to mechanically testing materials (baseline, welds and advanced materials) in contact with heavy liquid metals (HLM), namely Pb and Pb-Bi. One of the problems that had to be addressed within the project, in order to comply with the FAIR principles, especially I&R, was to guarantee, on the one hand, the quality and consistency of the data and, on the other, the appropriate storage of these data. Both require that experts should check the validity of the data after agreeing on how, i.e. on a universal format by which data for a specific test should be stored. The latter is essential to make sure that data are not only easily retrieved, but also accompanied by all the information that is required to make them useful, now and in the future. A data management committee was created in GEMMA to deal with these aspects. The main problem encountered was the definition of the parameters that would affect the susceptibility of the material to liquid metal embrittlement. Not only the characteristics of the liquid metal has to be defined (temperature, oxygen content, etc…), but also other critical information should be added, such as the pre-exposure conditions and the surface finish of the specimens among other. This is an example of the difficulty of defining the data collection protocol when the process of interest is little understood: it is easy that crucial information (for those who will need the data in the future) is missed, despite the best willingness to be complete.

In the case of mechanical tests, the existence of standard procedures for their performance partly facilitates the task of defining the format of the data and the accompanying information. In contrast, it is not straightforward to decide the format and the ancillary information in the case of microstructural examination and also, in several cases, modelling data, i.e. data produced by models (e.g. density functional theory calculations) or data necessary for the application of models (e.g. interatomic potentials, parameters for kinetic Monte Carlo simulations, …). The recently approved Euratom project ENTENTE[3] (EuropeaN daTabasE for multiscale modelliNg of radiaTion damagE) aims at constructing a prototypical database to be used for nuclear structural materials, in which the first example case study is light water reactor pressure vessel steels, a class of materials on which a large quantity of data exists, ranging from mechanical to microstructural and also modelling data. One of the problems to be addressed will specifically concern the format and the ancillary information for microstructural and modelling data.

In 2015, the NEA launched the broad initiative Nuclear Innovation 2050 (NI2050) to accelerate R&D and market deployment of innovative nuclear fission technologies. The project covered a wide scope of technology areas addressing reactor systems design and operation, fuels and fuel cycle technologies, waste management and decommissioning, and applications beyond electricity generation like the potential of the heat market and the corresponding increased flexibility in operation. In terms of advanced materials, a proposed roadmap included the following objectives [31], which also address the above-mentioned gaps:

1. Develop design rules for existing industrial materials, enabling reactor design for 60 years lifetime already in the case of Gen. IV prototypes.
2. Develop industrially manufactured innovative materials with superior resistance to temperature, corrosion and irradiation, for use in future Gen. IV commercial reactors.

International cooperation was suggested in the area of (1) data sharing; (2) harmonized materials testing and characterisation procedures; (3) shared infrastructures and facilities and agreement on model development. In 2019, the NEA within the NSC Working Party on Multiscale Modelling of fuels and structural materials for nuclear systems (WPMM) started an activity on best practice for nuclear material characterisation with the objectives to produce series of short reports on five different characterization techniques.

All these joint endeavours, given as examples, illustrate that accelerating materials discovery is a critical path forward for developing complex energetic systems that should dramatically reduce the time to market. Regardless of their size or goal, these initiatives pave the way for an analysis of various projects on innovative materials solutions specifically in the nuclear sector within the NEA countries. Establishing a specific TRL scale on materials solutions under development worldwide, will help connect the different topics of interest, the various ongoing programmes, assess their technological maturity and make recommendations to promote such developments. This aspect is addressed in the next section.

4. Interest for innovative fabrication processes in NEA countries

4.1. Identification of projects

A survey was carried out among the EGISM members during the time-period 2018–2019 to identify past and ongoing activities on

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[3] EU H2020-Euratom-1. Grant agreement ID: 900,018

innovative materials and fabrication processes. The objective was not to obtain an exhaustive list of worldwide activities, but to collect a representative number of projects that can be categorised, mapped, studied and compared, particularly in terms of technology readiness level. More than 40 activities, national or international projects from eleven member countries and international organisation (EU) have been listed. Their magnitude varies from prospective studies carried out by one laboratory to major coordinated programmes. The following data were gathered in a template:

- Project title and identification information such as website, country, leading organisation, partners, sponsor(s), status and dates;
- Materials studied or developed;
- Process and/or technology used or developed;
- Intended reactor type.

Four main groups of materials were identified:

- Conventional alloys such as low alloyed steels, ferritic martensitic (FM) steels including Reduced Activation FM (RAFM) steels, stainless steels, Stellite®, Ni base alloys, Zr-alloys that may be coated with novel materials;
- Novel alloys including High Entropy Alloys (HEAs) and Alumina-Forming Austenitics (AFAs), as bulk materials or developed as coatings;
- Oxide Dispersed Strengthened (ODS) and other nano-precipitate strengthened alloys;
- Ceramics in general, composites and MAX Phase, as bulk materials or developed as coatings.

The types of innovative manufacturing processes are more complex with at least 5 categories:

- Additive Manufacturing covering Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Direct Metal Deposition (DMD);
- Surface treatments in a broader sense including surface modification, surface coating and/or surface functionalizing by various deposition techniques covering physical vapour deposition (PVD) and advanced PVD processes, Chemical Vapour Deposition (CVD) and advanced CVD processes, laser processes, electron beam processes;
- Powder routes;
- Joining including graded microstructure fabrication;
- Other conventional processes such as melting, casting, thermo-mechanical treatment, hot rolling, machining…
- Regarding the applications, intended reactor types comprise of Gen. IV systems [32] like Sodium-cooled Fast Reactors (SFR), Lead-cooled Fast Reactors (LFR), Gas-cooled Fast Reactors (GFR), Molten Salt Reactors (MSR), Very High Temperature Reactors and High Temperature Reactors (VHTR/HTR), Super-Critical Water Reactors (SCWR); Light Water Reactors (LWR) including Accident Tolerant Fuel (ATF) improvement and fusion systems. Many innovative activities address more than one reactor type and most countries are active for several nuclear systems (see Fig. 1a). Fast reactors, either heavy metal-cooled or sodium-cooled, and ATF generate most projects (see Fig. 1b).

4.2. *Proposed TRL scale for innovative nuclear materials solutions, distinguishing between materials and fabrication process*

Technology readiness levels (TRLs) are a widespread method used by managers to estimate the maturity of technologies during the initial assessment phase of a project. Since it was first theorized by the NASA in the late 1980 s [20] to support planning of Space programmes, the TRL scale has spread to other communities, in some instances with adjustments or tailoring. As a noteworthy example, the European Commission advised EU-funded research and innovation projects to adopt such a scale and TRLs were deployed in assessing the EU Horizon 2020 programme (year 2014–2020). The primary purpose of employing TRLs is to help policy makers and stakeholders in making decisions concerning the development and transitioning of technology. As an extension, this paper uses the TRL scale to provide a framework for mapping technical progress within the NEA community and for identifying needed activities associated with innovative fabrication processes for nuclear materials. It should be viewed as a tool that offers a rational, criteria-based, and documented evaluation; provides a common understanding of a technology's status and assists in comparing projects. As such, TRLs should improve technical communication and help in conveying information about advanced manufacturing technology and innovative materials.

Fig. 2 presents a generic TRL scale. It divides into three major phases:

- Proof-of-Concept: from TRL-1 to TRL-3,
- Proof-of-Principle: from TRL-4 to TRL-6,
- Proof-of-Performance: from TRL-7 to TRL-9.

Some authors [33] add an extra level TRL-10 to distinguish new commercial products (TRL-9) and those that have been in the market for a long time (TRL-10).

Members of the Expert Group on Innovative Structural Materials have adapted the scale as shown in Fig. 2 for innovative nuclear structural materials and fabrication processes in Table 1 by incorporating experimentation, irradiation, and qualification/licensing based aspects. It appeared necessary to develop specific scales for innovative materials, on the one hand, and for manufacturing/joining techniques, on the other hand. This separation comes from the different criteria defined to assess the TRLs between 2 and 6. For example, at TRL-2, the development of a new material is described as "*Key properties determining performance are identified and preliminary evaluation including experimental measurements and modelling is underway on samples or coupons*" whereas for the deployment of a new process TRL-2 would correspond to "*Technical options have been identified and preliminary evaluation is underway. Performance range and fabrication process/joining technique parametric ranges*

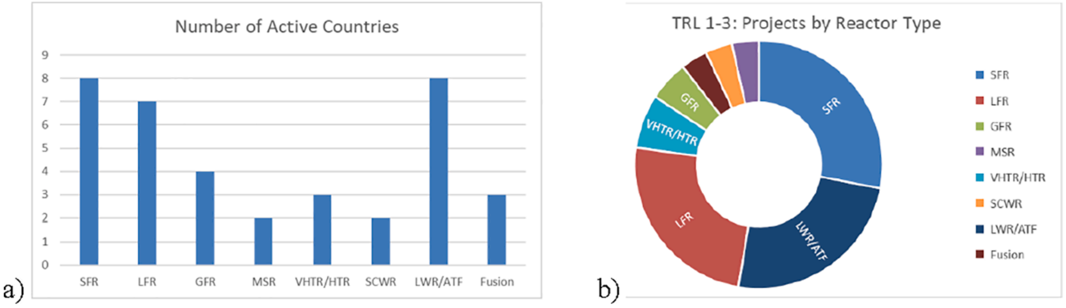


Fig. 1. Results of the EGISM survey: a) number of active countries by type of nuclear system; b) projects by type of nuclear system [Data and graphs presented in this paper are only based on outputs of the survey carried out within the EGISM. They do not reflect all activities performed in OECD countries.]

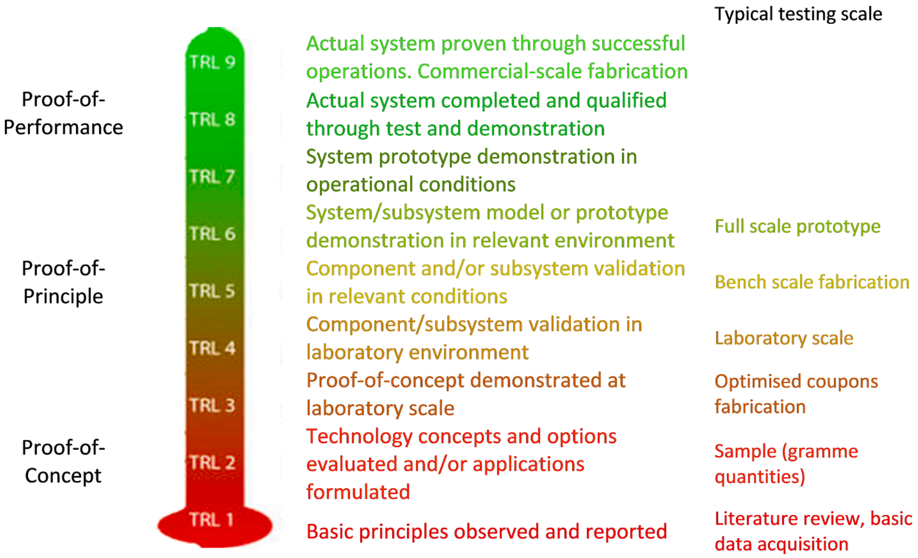


Fig. 2. TRL scale adapted from Mankins [20]

have been identified based on analysis using available data." As such, a project using a mature manufacturing process can address innovative materials such as MAX-phase or HEAs. On the other hand, an advanced manufacturing technique can be applied to a quite mature material even if this "mature" material in terms of chemical composition can have specific microstructure and properties compared to a conventionally elaborated material. This will have to be evaluated specifically with the TRL scale. The Expert Group members coming primarily from Research Institutes, National Laboratories and Universities decided not to further develop the three TRL levels of the proof-of-performance phase, which correspond to activities mainly endorsed by industries.

4.3. Results of the evaluation of the projects using the proposed TRL scale

The TRL scale as depicted in §4.2 was applied to assess the technology readiness of projects identified in the EGISM survey (see §4.1). Again, the authors want to state that the purpose of the survey was not to produce a comprehensive inventory of all worldwide projects but to analyse a limited number of projects on innovation in materials solutions for nuclear systems from a research perspective. Most innovative projects address both advanced materials and advanced manufacturing processes. The TRL of the 'materials solution' then corresponds to the lower level achieved. Other projects are materials specific or dedicated to improving fabrication only.

Fig. 3 illustrates the outcomes of the analysis. Globally, the majority of innovative materials solutions are still in an early stage of readiness corresponding to the proof of concept, with three quarters at TRL-3 or less.

Marked differences in readiness level are observed between materials categories (Fig. 3a). Conventional alloys –such as low-alloyed, FM and austenitic steels; nickel and Zr base alloys– and nano-precipitate strengthened steels are obviously most mature. As an example, four different activities address the design and qualification of reduced activation FM steels, manufactured by classical metallurgy with or without optimized thermomechanical treatments or by laser AM. All materials solutions have achieved a TRL-4. Moving toward a higher TRL is impeded by the lack of test facilities, primarily irradiation facilities like Material Test Reactor (MTR), experimental fast reactors and IFMIF-like facilities, which are necessary to generate basic performance data in a representative irradiation environment. This example will be further developed in the next section. Among these categories, a couple of projects have achieved TRL-5 as activities on coated Zr-alloy for Enhanced Accident Tolerant Fuels (EATF) [13–15,34] and developments on FM ODS steels [35–41]. The long-term developed FM ODS steels have achieved an industrial scale production and have been tested in relevant reactors. One project on ODS steels will be detailed in the next section. The material development has triggered the design and optimisation of a specific, high-tech, multi-step manufacturing and joining process. The main hurdle for the project continuation at this stage is that it now needs to be pulled by nuclear vendors toward an actual industrial implementation phase.

On the other hand, activities on novel alloys including HEAs, AFAs and a variety of cutting-edge materials and ceramics-composites-MAX Phase show lower readiness. The only activity achieving TRL–4 deals with the long term development of SiC_f/SiC composite for fuel cladding which has recently reached the milestone of 1:1 scale manufacturing [13]. Other activities are still at an exploratory stage –an example about the design of HEAs will be given in the next section. A significant number of activities have reached the level of TRL-3. They include for instance HEAs and other multiple element alloys or MAX Phase coatings.

A variety of advanced processes from all categories are being explored: AM, surface modification/ surface coating/ surface functionalizing, powder routes, advanced joining techniques or graded microstructures has reached TRL-3 (Fig. 3b). As an example, the development of radiation-resistant high strength ODS alloys through AM has been shown to be very promising through laboratory scale experiments using commercially available machines. However, moving from TRL-3 upward would require substantial fabrication/joining campaigns to optimize process parameters and demonstrate process reproducibility. This may require technological advances on AM machines or the design of new machines.

Fig. 4 emphasizes the close link between materials development and process readiness through two examples. The successful case study of ODS steels for fast reactor cladding tubes produced by a tailored fabrication route based on powder metallurgy will be developed in the next section. This powder route has been developed and optimised for a given category of Fe-Cr ODS steels and as such is quite a mature fabrication process, with a materials solution reaching TRL-5/6. Starting from this reference materials solution, any change in the alloy composition implies to determine a fresh set of key-properties through experimental measurements and modelling efforts first on coupons, then at lab scale to assess the reproducibility. In that respect, the Cu-base ODS are still at quite a low TRL-2 and new generation of ODS alloys, including alumina forming FeCrAl ODS with enhanced corrosion resistance for fast reactors, have reached TRL-3. On the other hand, changing the fabrication process for Fe-Cr ODS steels in reducing the numbers of manufacturing

Table 1

Proposed TRL scale for innovative structural materials and fabrication processes.

	TRL	Innovative materials	Innovative fabrication process
proof of concept	1	New material is proposed. Paper studies. Technical options are identified. List of performance criteria. R&D for acquisition of basic data.	New fabrication process/joining technique is proposed. Paper studies. Technical options are identified. List of performance criteria. R&D for acquisition of basic data.
	2	Key properties determining performance are identified and preliminary evaluation including experimental measurements and modelling is underway on samples or coupons.	Technical options have been identified and preliminary evaluation is underway. Performance range and fabrication process/joining technique parametric ranges have been identified based on analysis using available data.
	3	Proof of concept validation. Concepts are verified through laboratory scale experiments. Material properties measurements (mechanical, environmental, preliminary irradiation/ion irradiation…) and characterisation are performed.	Fabrication of candidate samples/joined systems to verify concepts through laboratory scale experiments. Reproducible fabrication/joining process to elaborate optimised coupons for testing.
Proof of principle (at TRL-5/6, transfer to industrial)	4	Experimental testing in relevant conditions of the desired reactor system including irradiation evaluation in test reactors (possibly not fully representative: environment + irradiation…). Multi-scale modelling is being developed.	Fabrication/joining process at laboratory scale in reproducible conditions. Optimised parameters defined at lab scale.
	5	Single and multiple effects tests. Data generation should be focused on compiling the basic performance property data needed to understand the material performance and behaviour in a representative reactor system. Acquisition of data for material qualification.	Fabrication/joining at bench scale of systems/subsystems for multiple testing. Acquisition of data for process qualification.
	6	Representative model or prototype system is tested in relevant environment. Irradiation/property testing in relevant conditions. Material behavior laws have been developed for use in performance codes.	Increase to the fabrication/joining of full-scale prototypes. Feedstock materials used in fabrication and irradiation testing are representative of prototypic conditions. Acquisition of data for design and construction rules.
Proof of performance	7	Prototype demonstration in operational conditions	
	8	Material and its fabrication process are code-qualified through tests and demonstration and can be licensed	
	9	Material and its fabrication process commercially developed and used in power plants	

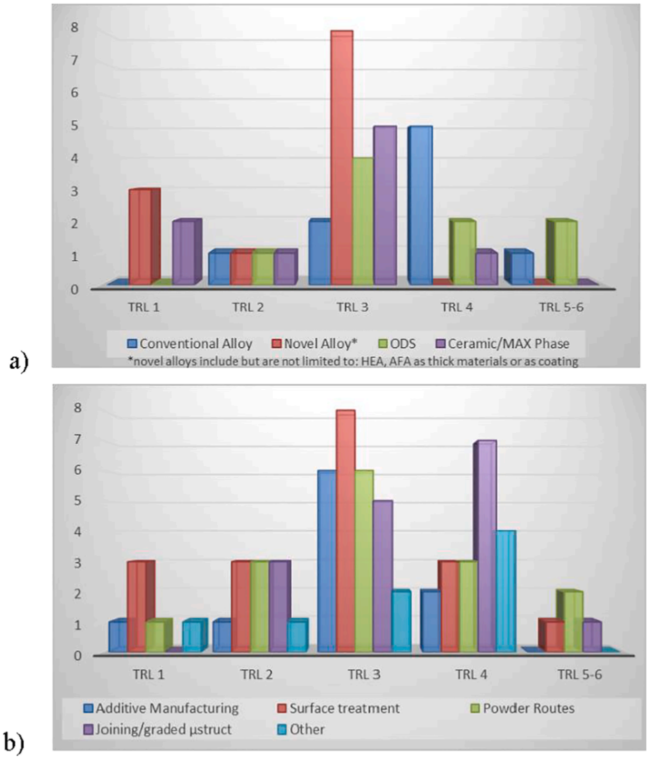


Fig. 3. Number of projects reaching the specified TRL (a) by materials family; (b) by process category [Data and graphs presented in this paper are only based on outputs of the survey carried out within the EGISM. They do not reflect all activities performed in OECD countries.]

steps again lowers the materials-solution readiness with FM ODS by direct melting at TRL-4 and by AM (SLM) at TRL-2. EATF are being studied and developed as a more tolerant alternative to commercial zirconium alloys tube cladding for light water reactors since 2011 [34]. With the today's commercial Zr-alloy clad at TRL-9, the most mature EATF solution namely Cr-coated Zr-alloy tube has reached TRL-5. More advanced solutions like the use of an inner-coating at a TRL-2 or the design of an advanced coating based on MAX-Phase at a TRL-1 will need large R&D efforts to move up the TRL scale.

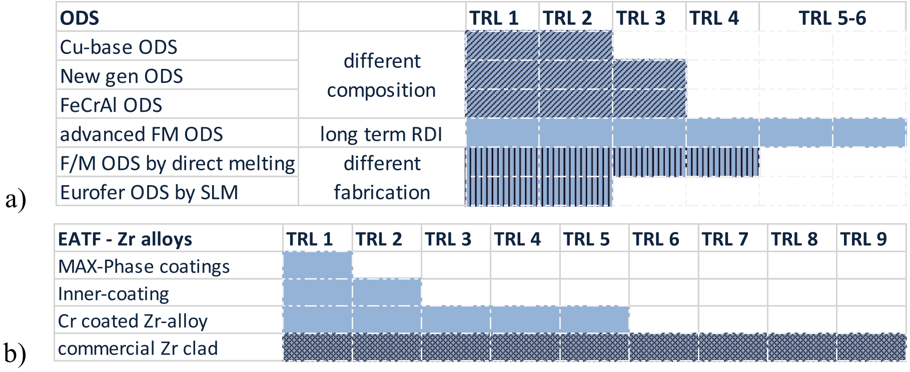
5. Examples taken from the cases reported within the group

In the following paragraph, selected examples are detailed in order to illustrate how project readiness can be assessed with the proposed TRL scale. These case studies were chosen with a range of TRL's, between 1 and 6, in order to exemplify the time needed to reach a given TRL, elements that have accelerated climbing the TRLs as well as hurdles, which impair the ability to move toward a higher TRL.

5.1. Example of materials at a TRL-1 - development of alumina forming HEAs

The development of alumina forming HEAs at Karlsruhe Institute of Technology (KIT) aims for corrosion resistant and irradiation tolerant materials exposed to extreme environments like liquid metals or high temperature steam.

In the original HEA concept, it was considered that the single-phase solid-solution could be stabilized by achieving the highest configurational entropy using equiatomic ratios of multiple principal elements [42]. However, this classical HEA concept has limited application for the design of alloys with sufficient mechanical properties, since it involves only one principal strengthening mechanism, namely the solid solution strengthening [43]. Hence, by shifting from "classical" single-phase



a)

ODS		TRL 1	TRL 2	TRL 3	TRL 4	TRL 5-6
Cu-base ODS	different composition	▨	▨			
New gen ODS		▨	▨	▨		
FeCrAl ODS		▨	▨	▨		
advanced FM ODS	long term RDI	■	■	■	■	■
F/M ODS by direct melting	different fabrication	▥	▥	▥	▥	
Eurofer ODS by SLM		▥	▥			

b)

EATF - Zr alloys	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
MAX-Phase coatings	■								
Inner-coating	■	■							
Cr coated Zr-alloy	■	■	■	■	■				
commercial Zr clad	▩	▩	▩	▩	▩	▩	▩	▩	▩

Fig. 4. In-depth look at specific categories: a) selected projects on ODS alloys and b) EATF (Zr alloys) [Data and graphs presented in this paper are only based on outputs of the survey carried out within the EGISM. They do not reflect all activities performed in OECD countries.]

equiatomic alloys to dual- or multiphase non-equiatomic compositions, it is possible to produce HEAs with fine-tuned strength-ductility combinations [44]. Considering this new approach, single-phase and multiphase HEAs with non-equiatomic compositions were designed at KIT with respect to using empirical parameters that have been applied to predict the formation of solid solution and intermetallic compounds; the enthalpy of mixing (ΔH_{mix}), the difference in atomic radii (δr), the parameter $\Omega = \frac{\sum_i^n c_i Tm_i \cdot \Delta Smix}{|\Delta Hmix|}$, and the valence electron concentration (VEC). The CALPHAD approach is employed in a second step to analyze their stability with respect to the temperature. Six quaternary Al-Cr- Fe-Ni-based and three quinary Al-Cr-Fe-Ni-(Nb, Ti, Cu)-based HEAs were prepared by arc-melting. These HEAs were exposed in as-cast state to liquid Pb at temperatures of up to 650 °C for 2000 h to investigate the corrosion resistance and the structural stability. All of the alloys exhibit good corrosion resistance (Fig. 5), while the majority of them displayed phase stability. A selection of these HEAs tested in steam at 1200 °C showed as well good corrosion resistance [45,46]. As all work is performed on model alloys produced in small quantities with a Lab scale arc-melter, so far no mechanical properties have been measured, thus the TRL is between 1 and 2.

To speed up the increase of the TRL and widen the development of HEAs in Europe, the pilot project HEAFNA was launched in the framework of EERA-JPNM, based on in-kind contributions by its members. KIT coordinates this pilot project in which participants from more than 23 European associations work together for a wider exploration of HEAs.

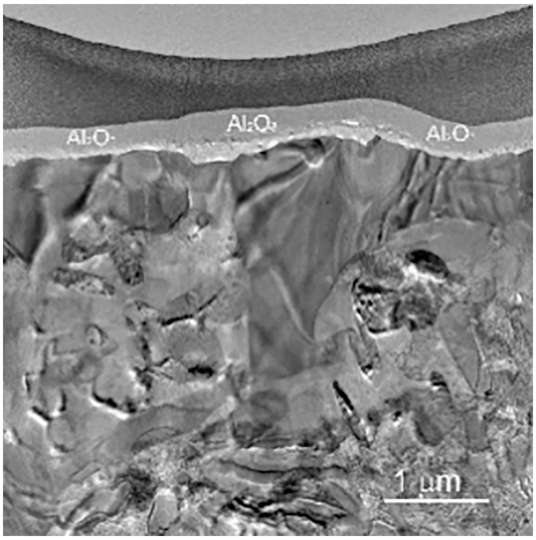


Fig. 5. HEA, exposed to oxygen-containing molten lead for 2000 h at 600 °C, is passivated by an alumina scale with the thickness of 300 nm.

The work is divided into 5 work packages that cover all aspects of material development, from material production over material compatibility to mechanical properties and finally irradiation experiments all of them accompanied by related modelling activities. Work package 1 “Modelling, design, production and basic characterization (microstructure & mechanic properties)” has started the work already under the guidance of CENIM in Spain focusing on the pre-selection of potential material compositions by several modelling approaches. In a first step, a pre-selection of candidate alloy compositions is done using the approach of empirical parameters as described above while considering the approximation of the solid solution hardening effect to select, from the possible HEAs, those with good expected mechanical properties. To further down select the number of potential stable HEAs CALPHAD approaches using simulation tools like THERMOCALC will be applied to the pre-selected compositions. In 4 years, all activities should have produced results to reach TRL-3. This step forward, however, will crucially depend on whether or not funds supporting the research is made available in Europe.

5.2. Example of materials and associated fabrication processes at a TRL-3/4 - innovative metallic materials for high and low temperature

The FERRONESS and the Advanced Steels projects have similar objectives, but target different applications and follow somewhat different methodologies.

FERRONESS is a Spanish national project that aims to develop nanostructured steels to mitigate materials degradation and enhance operational performance under combined corrosive, high temperature and high dose irradiation environments. The reference material is the T91 FM steel: without changing the composition, but applying specifically studied thermomechanical treatments, the idea is to create a microstructure that provides higher creep strength, trying to maintain reasonable fracture toughness and corrosion resistance, particularly in contact with HLM. The project includes a wide range of mechanical and microstructural studies, aimed at verifying the correlation between fast screening (small punch and tensile tests) and full qualification (creep tests), as well as at investigating in detail, by electron microscopy, the microstructural modifications that are responsible for the changes in the mechanical and corrosion properties, including under deformation and during and after thermal ageing. The mechanical characterization is essentially complete [47] and the corrosion tests are well advanced, while the microstructural characterization is still in course. For the moment the materials have not been irradiated, the results show that the creep strength is significantly improved, with little detriment of the fracture toughness, see Fig. 6. Interestingly, however, the corrosion properties seem to be somehow compromised. A step towards the industrial upscale of the thermo-mechanical treatment has been taken, with the subsequent realization of a semi-industrial production.

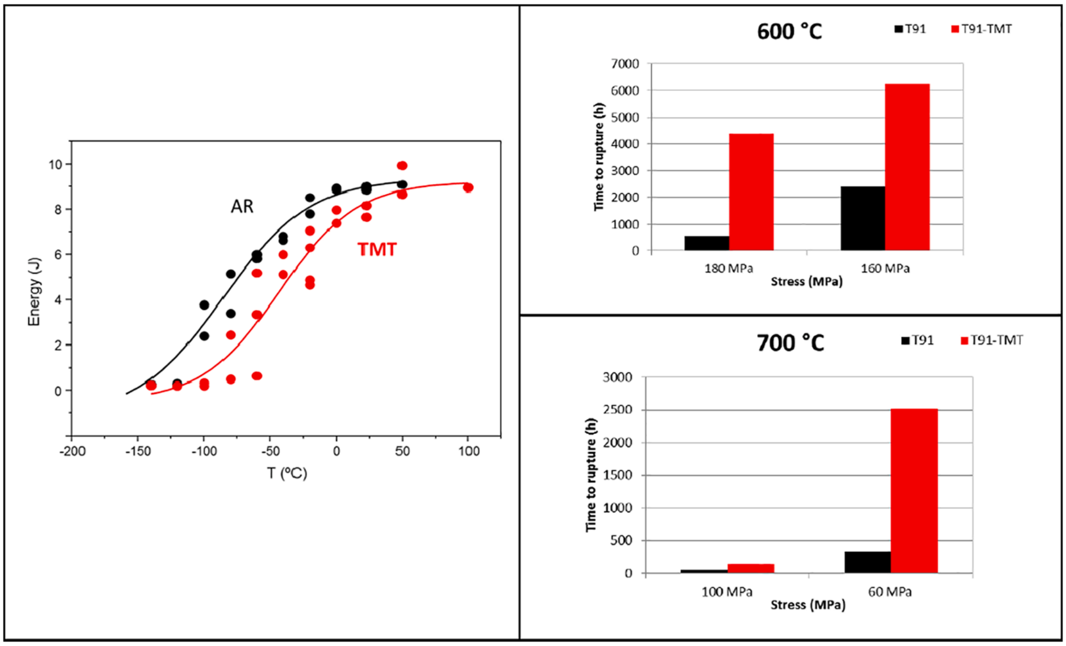
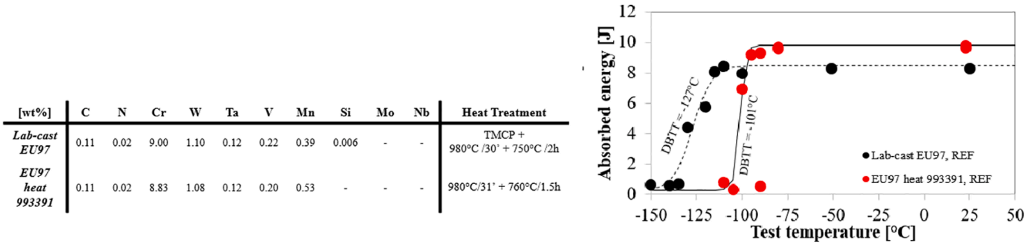


Fig. 6. Left: Toughness of as-received (AR) and thermo-mechanically treated (TMT) T91 from Charpy testing. Right: Time to rupture from creep tests at 600 and 700 °C: the TMT material exhibits systematically a larger time-to-rupture under the four conditions of temperature and stress that have been considered.

Within the Advanced Steel project (part of the EUROfusion programme [48]), SCK-CEN and Ocas Nv, pursue the ultimate goal of extending the operational temperature window for the structural steels of the DEMO fusion reactor [49], by increasing the creep strength so as to push the operational temperature limit to 650 °C (see Fig. 7a and b illustrating development of lab-casted E97 by OCAS). In parallel, the mechanical performance around 300 °C after neutron irradiation is improved, to limit fracture toughness degradation after neutron irradiation. Eurofer97 is the reference material. The basic ideas behind these developments consist of (i) modification of the chemical composition with respect to elements responsible for the formation of carbides and carbo-nitrides; (ii) followed by advanced thermo-mechanical treatments (TMT); (iii) modification of the chemical composition to suppress or exclude the chemical elements that are known to exhibit strong coupling with irradiation defects, thereby reducing the ability of the material for uniform/homogeneous ductile deformation. Thermodynamic modelling was used and detailed microstructural investigation was the first step in the down-selection of perspective TMTs for upscaling and detailed mechanical characterization [50,51]. The casts processed by advanced TMT are produced in plates with a thickness of 10–15 mm with a weight up to 60 kg. Up to now, the mechanical characterization was essentially limited to tensile and bending testing in a wide temperature range (from DBTT up to 650 °C). Some early down selected casts were thermally aged for long times, while some were irradiated with ions and also with neutrons [52]. No evaluation of corrosion properties is currently planned.

The materials developed within both above-mentioned projects moved between TRL-3 and 4, with an intention to set a foot on TRL-5, although neither of them really succeeds in this. The validation of the proof of concept was achieved without going through TRL-1 and 2, because the concept did not need to be developed, only verified in the specific case of application. Laboratory scale experiments were performed, material properties were measured and the microstructural characterisation was carried out. Thus TRL–3 is reached. Experimental testing in relevant operational conditions was performed (high temperature, irradiation, corrosion, creep experiments…), thus TRL-4 is also under evaluation. However, in neither case can the conditions of exposure be counted as fully representative of the target operational environment. Bridging towards higher TRL would require scaling up towards industrial production, performing first neutron irradiation, compiling basic performance property data with a view to qualification. Assuming this happens, in both cases considerable resources will be needed to move to TRL-6, because of the lack, currently, of a model or prototype system where the relevant environment is reproduced, be it Gen. IV or fusion.



[wt%]	C	N	Cr	W	Ta	V	Mn	Si	Mo	Nb	Heat Treatment
Lab-cast EU97	0.11	0.02	9.00	1.10	0.12	0.22	0.39	0.006	-	-	TMCP + 980°C /30' + 750°C /2h
EU97 heat 993391	0.11	0.02	8.83	1.08	0.12	0.20	0.53	-	-	-	980°C/31' + 760°C/1.5h

(a) (b)

Fig. 7. Comparison of the reference E97 (grade 2, heat 993391) and optimized lab-casted E97 fabricated by OCAS. The main difference comes in the additional hot rolling step applied at 850 °C, which generates some improvement in DBTT, a different initial precipitation state, somewhat lower strength at RT which however becomes comparable to that of ref. E97 at higher temperature. The figure summarizes chemical composition (a) and absorbed energy vs. test temperature (b).

5.3. Example of fabrication process at a TRL-3 - laser additive manufacturing of grade 91 steel

In a recent laboratory funded research and development project at Los Alamos National Laboratory (Los Alamos, NM USA), grade 91 steel has been produced using the laser powder-based fabrication (L-PBF) AM technique for nuclear materials applications [53]. In detail, powders of grade 91 steel were obtained from a commercial vendor and coupons and a small component were produced with a laser powder-bed Electro-Optical Systems (EOS) M280 powder-bed machine. It is interesting to note that even though grade 91 has extensive experience for use in the fossil energy and nuclear energy systems in the wrought normalized and tempered form and is available commercially as tubes and plates, it is only at a TRL-3 when produced by additive manufacturing as AM significantly changes the microstructure produced in the parts during processing. Research is underway to test and qualify this material and there are many preliminary results worth noting and described in more detail in [54]:

1. Additive manufacturing processing conditions using L-PBF were developed for production of samples without porosity without any post processing needed.
2. Samples that were normalized and tempered (1040 °C for 30 min and air cooled followed by 760 °C for 1 h and air cooled) after deposition were mechanically tested in tension at room temperature, 300° and 600 °C and showed that the mechanical properties were very similar to those measured on wrought processed T91 in the same normalized and tempered condition.
3. Tensile tests performed on the AM L-PBF produced grade 91 material in the as deposited condition showed improved tensile strength and ductility over wrought processed material at room temperature and up to 600 °C. The yield stress measured at 600 °C was a factor of 2 higher than that measured on wrought material.
4. The microstructure measured on the AM L-PBF produced grade 91 material in the as-deposited form is significantly different from that observed for wrought grade 91 in the normalized and tempered form. The AM produced grade 91 material exhibits a heterogeneous microstructure composed of large ferrite grains with some areas containing martensite, carbides and some platelet like features consistent with lower bainite.

Research continues on this material to qualify it for nuclear applications including long-term creep tests and long term environmental exposure testing, but it is a good example of how a change in fabrication method can significantly affect the TRL level for a material system.

5.4. Example of materials and associated fabrication processes at a high TRL – Development of ODS cladding tubes

The development of high burn-up fuel for fast reactors can contribute to the reduction of the environmental load by transmutation of minor actinides, while reducing reactor operating costs. For the fuel cladding tube of sodium-cooled fast reactors (SFR), the Japan atomic energy agency (JAEA) has developed oxide dispersion strengthened tempered martensitic steels (ODS TMS) [35,36] while their full-scale implementation in the reactors is still pending. Fig. 8 shows the schematic view showing the current status of development. Developmental tasks can be divided into two areas, i.e. fabrication technology and demonstration of in-reactor performance leading to qualification.

The fabrication technology of an ODS alloy based on powder metallurgy has already been commercialized in non-nuclear industries. In JAEA, the fabrication process for fast reactor application has been developed since the late 1980 s, e.g. for roughly 30 years, to satisfy the high quality requirements for fuel cladding tube (high-temperature strength, radiation resistance, workability and quality stability). For ODS TMS, the bench-scale fabrication technology is already established (TRL-5); the batch size of mechanical alloying is 10 kg/batch; the tube size is 18 mm in outer diameter (OD), 3 mm in wall-thickness (WT) and 200 mm in length (L) for the mother tube; 6.9–8.5 mm OD, 0.4–0.5 mm WT and 2000 mm L for the cladding tube. A drawback of ODS steels is their weldability. The application of the fusion welding process ruins the elaborately controlled nano-scale structure, resulting in a significant decrease of mechanical strength. A pressure resistance welding technique has been established in bench-scale for the solid-state bonding of cladding tube and end-plug both made of ODS steel (TRL-5) [37]. The basic technology for large scale manufacturing (scaling up mechanical alloying system and size of mother tube) is under development for reduction of fabrication costs (TRL-5/6) [38]. The critical point here is the quality assurance as well as nano-scale structure control ensuring the excellent mechanical strength and radiation resistance in ODS steels [39].

The in-reactor performance of 9Cr-ODS TMS cladding tube has been confirmed by material irradiations using the experimental fast reactor Joyo (TRL-4) and fuel pin irradiations up to the peak burn up of approximately 112 GWd/t using BOR-60 (TRL-5) [40]. The accumulation of out-of-pile mechanical properties data has proved the excellent high-temperature and very long term creep strength of 9Cr and 11Cr-ODS TMS cladding tube compared with conventional ferritic steels and austenitic steels developed for high-temperature application [41]. JAEA has already obtained agreement for a fuel pin irradiation test of ODS steel cladding tube in Joyo up to the peak burn up higher than 200 GWd/t. For the licensing of the full-scale implementation, not only fuel pin irradiation tests but also fuel bundle irradiation tests up to target

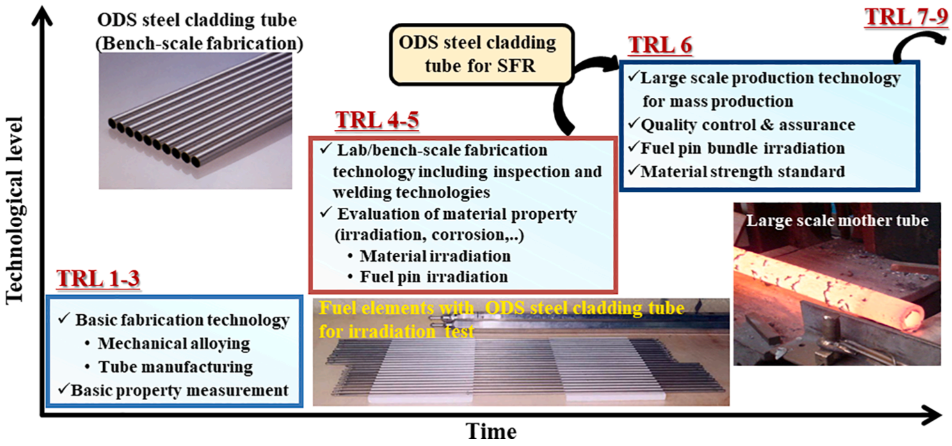


Fig. 8. Development of oxide dispersion strengthened tempered martensitic steel for high burn-up fuel cladding tube of sodium-cooled fast reactor.

burn up will be required. For achieving these tasks, which is based on conventional and proven procedure, fast neutron irradiation facilities such Joyo should play a key role.

The conventional fabrication route is composed of several processes (mechanical alloying, powder consolidation, machining, cold-rolling and heat treatment for thin-walled tubing, etc). For acceleration towards the establishment of a mass production process, additive manufacturing (AM) is envisioned [55]. This innovative process consists of preparing metallic and oxide powder mixture and component production through extremely rapid heating to solidification by selective laser irradiation, thus having the advantage of process simplification. In addition, the AM could produce the joining-free component, thus having the potential for making it easier to assure the quality of component.

6. Discussion

Today, in all fields of industry, new ways of designing materials and new processes to fabricate them considerably accelerate the pace of materials discovery. In this framework, the fast development of data analysis including machine learning and artificial intelligence associated with combinatorial materials fabrication processes, automated characterization techniques and materials simulation are expected to allow rapid synthesis and qualification of materials, closing the loop from design/fabrication/qualification and paving the way towards “inverse design” of materials [8].

These developments require, however, a sufficiently large quantity of “qualified” data; this can indeed be a first hurdle for increasing the TRL level of new materials solutions, specifically in the nuclear field, where materials data remain scarce, especially irradiation data. Opportunities are numerous but the ability to collaborate and share, beyond the nuclear field when pertinent, will be crucial to go faster.

Taking the example of high entropy alloys, numerous initiatives and developments are ongoing for nuclear and also non-nuclear applications on the design and optimisation of composition of these materials, for reaching better mechanical properties or better irradiation tolerance. These developments require fundamental data, atomic and electronic modelling, thermodynamic calculations, use of data mining/machine learning [7,19], combinatorial fabrication processes as well as characterization techniques.

All the projects concerning HEAs, identified among the EGISM members, which represent 14% of all the projects, are at TRLs between 1 and 3. Collaborating in this field by selecting common HEA families, sharing data and models, benchmarking the fabrication processes and the materials qualification could allow the acceleration of the development of such materials. In this field, sharing also when possible with the non-nuclear field is an opportunity.

The need for qualified data is critical. With this objective in mind, it is essential to develop common databases with shared structures and formats of data with a specified methodology to guarantee the validity/level of uncertainty of the data incorporated. Moreover, with the rapid development of new fabrication processes as well as coated systems, data on the processes have also to be included in the database, which will have to include the type of process, the nature of the equipment, the process parameters, the associated generated microstructures and the fabricated specimen properties. In this framework, the database design and the data format definition are challenges in themselves.

Concerning emerging fabrication processes, additive manufacturing but also advanced coating technologies, nano-manufacturing, as well as hybrid processes, are opportunities for fast development of high performance materials [10]. The development of high-speed cameras and/or in situ instrumentation will help produce a large amount of in situ process data. As said already, databases on both materials and processes are key issues to progress fast, combined to data analysis using artificial intelligence and numerical simulation. These activities should also benefit from the feedback of the non-nuclear field.

Combinatorial synthesis to accelerate materials or coatings developments coupled to automated characterization techniques and process optimization assisted by artificial intelligence allow very fast elaboration and characterization of coatings or materials. However, the specifications and the expected properties have to be clearly defined regarding the final application of the material/component. For structural materials, understanding the link between the process parameters and the obtained microstructures is essential to progress fast and reach these specifications. In addition, structural materials are especially challenging in a MAP framework because, even if high throughput fabrication is certainly possible, high throughput characterisation of properties that are representative of in-service behavior is highly challenging.

On these aspects, finding ways to collaborate on process understanding and modelling, benchmarking between the available technologies and working closely with the industry will also allow time to be gained in the down selection of processes and in the optimization of operating parameters. For this purpose, however, adequately public support is also needed. Another field for collaboration should be the access to large test facilities in representative environment, first of all irradiation facilities with the right neutron spectrum [6]. Many projects in the EGISM template have climbed up to TRL-3 but materials solutions will need to be evaluated for their radiation resistance in a MTR, an experimental fast reactor or IFMIF like facility, to move forward. As shown in the example of ODS cladding tubes, irradiation in representative conditions is then the crucial hurdle along the scale to move from TRL-6 to proof of performance.

Regarding the specificities of the nuclear industry, and taking into account the very long process of qualification of new materials solutions, working on removable components can be a first step to develop new materials solutions. As we can observe in the TRL evaluation of the EGISM projects, the highest TRLs are for clads (including developments on EATF), that are not *stricto sensu* structural materials. Indeed, we have to observe that, for the clad, developments of new materials solutions can go up to TRL-5 and maybe 6 in the next years, both in the case of advanced materials (ODS – TRL-5; SiC_f/SiC – TRL-4) and advanced coating technologies (Cr coated Zr – TRL-5). The developments performed on nuclear components with less stringent requirements could be a bridge towards developments on structural materials.

Moreover, regarding the development of new concepts of reactors, such as Small Modular Reactors or Molten Salt Reactors, which will be smaller, with potentially shorter life duration, new ways of designing, building, qualifying and inspecting have to be found and this will have to be performed in close collaboration with regulators.

Finally, the rapid development of advanced fabrication technologies with laser based additive manufacturing introduces both opportunities and challenges. While the benefit of AM is well understood, the long-term thermal and radiation stability under service conditions relevant to both current and more advanced reactor systems are largely unknown. It is well understood that microstructural control is essential to the materials performance and special care needs to be taken for welds due to the undesired microstructural changes because of the joining process. AM is basically a computer-assisted laser welding process of 3D object which can develop highly heterogeneous microstructure significantly different from that of conventional material with the same composition [56–58]. The option of microstructural optimization for both AM process parameters and post AM thermo-mechanical heat treatment is quite limited comparing to that of conventional materials, due to the near final shape constrain. The radiation performance of AM materials is also largely unknown and significant effort and resources are required to fill the knowledge gap on the impact of heterogeneous microstructure on radiation stability. Tremendous effort in the materials development for improved radiation tolerance is on the microstructure and microchemistry optimization and control [59]. While ion irradiation may be used for quick screening, the neutron irradiation effects on microstructure, corrosion behaviour, mechanical property and dimensional stability is critical before the parts or components made by AM can be considered for reactor in-core application.

The use of ion and neutron irradiations [17] is in fact essential to down select and evaluate innovative structural materials for nuclear components. Ion and neutron irradiations offer complementary capabilities, the former potentially being part of a strategy for accelerating the development and qualification of new high performance structural materials. However, complete “emulation” of neutron irradiation effects by ions is problematic (or impossible) due to dose rate difference, transmutation and PKA spectrum effects, as well as potential artefacts due to surface proximity, damage gradients and injected species in the case of self-ion or heavy-ion irradiation. Yet, ion irradiations are an indispensable scientific tool to help guide and validate the development of physics-based comprehensive models of radiation effects, thanks to better control on irradiation temperature, damage rate and total irradiation dose in dpa. This is why ion irradiation is one of the accelerated tools to enhance materials solutions readiness for the proof of concept, provided that established and agreed upon methodologies to design and interpret ion irradiation experiments are put in place.

For higher TRL, licensing crucially enters into play. For nuclear structural materials, this requires access to large and validated databases for properties and joining as well as a code and standard approach adapted for the component/system. For innovative materials solutions, it is necessary to involve regulators when the TRL is still low, to accelerate the process at higher TRL and to avoid deadlock or standstill due to licensing.

7. Conclusion

The development of advanced materials solutions including advanced materials and processes is moving much faster than the actual ability of the nuclear industry to introduce them into design codes. Indeed, getting new materials and new fabrication processes into nuclear market requires decades of research, development, qualification and licensing.

If the nuclear industry wants to get these innovations into market for the building of advanced reactors, issues of qualification and licensing have to be addressed. New frameworks of development and licensing have to be imagined and international collaboration has to be reinforced to work on the establishment of common data platforms for validation and qualification for these new materials and processes. Adequate public support is also necessary to foster implementation of new materials solutions. The link with the regulators has also to be reinvented for more association and collaboration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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