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Organisation of the European Research Community on Nuclear Materials

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Work Package 4 – Interaction with other bodies, initiatives and stake-holders, including infrastructures

Deliverable D4.3

Draft protocol of collaboration of EJP with EUROfusion, including identification of cross-cutting issues and proposed funding policies

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List of abbreviations

ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator
AIM1	Austenitic Improved Material
ATF	Accident Tolerant Fuel
ASME-BPVC	American Society of Mechanical Engineers Boiler and Pressure Vessel Code
CEP	Co-funded European Partnership
DEMO	DEMOnstration Power Plant
EERA-JPNM	Joint Programme on Nuclear Materials of the European Energy Research Alliance
ESNII	European Sustainable Nuclear Industrial Initiative
F/M ODS	Oxide Dispersion Strengthened Ferritic/Martensitic Steel
GFR	Gas-cooled Fast Reactor
HCPB	Helium Cooled Pebble Bed
IASCC	Irradiation Assisted Stress Corrosion Cracking
IFMIF-DONES	International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source
ITER	International Thermonuclear Experimental Reactor
ITER-SDC	ITER Structural Design Criteria
LWR	Light Water Reactor
LFR	Lead Fast Reactor
MTRL	Material Technology Readiness Levels
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
NUGENIA	Nuclear Generation II & III Alliance
RAFM	Reduced Activation Ferritic Martensitic Steel
RCC-MRx	AFNOR Design and Construction Rules for mechanical components of nuclear installations
SFR	Sodium Fast Reactor
RPV	Reactor Pressure Vessel
SRA	Strategic Research Agenda
TAG	Technical Advisory Group
TBM	Test Blanket Module
WP	Work Package
WP BB	Work Package Breeding Blanket
WP MAT	Work Package Materials
WP PRD	Work Package Prospective Research & Development

Summary

This document reports information on the identification of the research items of common interest between EUROfusion and the future Co-funded European Partnership (CEP) on nuclear materials. The ultimate aim is to set up common projects and possibly, identify a framework for collaboration with a shared funding scheme, which may be either external or internal to either partnership.

The document reviews the relevant structure and projects of the EUROfusion programme and the commonalities on materials research with the Strategic Research Agenda of the CEP stemming from ORIENT-NM. The results of the first discussion with the colleagues from fusion on the possible cross cutting activities are reported as well.

Introduction

The aims of the EUROfusion programme are outlined in the 'Roadmap to the Realisation of fusion Energy' and are the preparation of the ITER experiment for technical demonstration of large-scale fusion power and the development of concepts for the future demonstration of the connection of the fusion power plant DEMONstration Power Plant (DEMO) to the electricity grid. The research on innovative materials and materials solutions is part of the Roadmap and plays an important role with focus on the development of low activation structural and functional materials with improved resistance to the harsh environment of the fusion plants.
The identification of a common development programme and protocols of interaction between the Co-Funded European Partnership on nuclear materials and the EUROfusion program is desirable and strongly recommended by EURATOM for the obvious benefits of sharing knowledge and methodologies as well to optimise the use of resources, avoiding duplication of activities. The interaction with EUROfusion will be beneficial also for the design of the CEP on nuclear materials, by taking advantage of the experience accumulated over the years within the EUROfusion CEP, its R&D programme, quality assurance schemes, etc.
The present document summarizes the work performed to date in Task 4.3 to define the interaction of the future CEP on nuclear materials with the EUROfusion programme. The document reviews the relevant structure and projects of the EUROfusion programme and the commonalities between the EUROfusion materials roadmap and the Strategic Research Agenda of the future CEP on nuclear materials, as defined in the roadmap of the supporting organizations. The results of the first discussion with the colleagues from fusion on the possible cross cutting activities are reported, as well.

Research on materials in EUROfusion

The development of materials is the third of the eight strategic missions defined in the European roadmap to the realization of fusion energy [1] and most of the work is carried out within the Work Package Materials (WPMAT). The project is focused on materials with sufficient maturity for application to the DEMO reactor and is divided into 7 sub-projects outlined as below [2]:

- Engineering Design Data and Integration (EDDI). Development of a DEMO Material database, a Material Property Handbook and DEMO specific design rules. Assessment of the Material Technology Readiness Levels based on the DEMO application constraints
- Advanced Steels (Steel Development and Qualification SDQ). Development of Reduced Activation Ferritic Martensitic (RAFM) steels for low and/or high temperature applications.
- High Heat Flux Materials (HHFM). Development of plasma facing and heat sink materials including relevant joining technologies for the divertor and breeding blanket

- Functional Materials (FM). Development of optical and dielectric materials for diagnostics and heat and current drive systems
- Irradiation (IRRAD). Neutron irradiation campaigns for baseline and risk mitigation structural and high heat flux materials. Modelling activities integrate this task, in support of the interpretation of experimental results.
- Test Blanket Module (TBM). Characterization program for qualification of EUROFER97 as structural material for the European TBMs in ITER according to French code RCC-MRx, in non-irradiated and irradiated state (up to 3 dpa).
- Materials Technology (TECH). Industrial large-scale production of 9Cr steels (up to 1000-ton range), Development of welding technologies for 9Cr steels, and defining welding specifications, Characterization of the influence of coatings (corrosion barriers, diffusion barriers) on the mechanical properties of the Eurofer steel.

Part of the work on functional materials like tritium breeders, neutron multipliers, and anti-corrosion/anti-permeation coatings for application to the DEMO reactor, is carried out within the Work Package Breeding Blanket (WPBB), as well as some work on the compatibility of the Eurofer97 steel and coatings with the breeder and the water coolant.

Finally, some of the work on materials with insufficient maturity for application to the DEMO reactor, or considered unnecessary for its realization, is performed in the Work Package Prospective R&D (WPPRD). The relevant PRD subprojects are listed below.

- Advanced ODS Materials and Manufacturing (ADVM). Scale-up of the manufacture of advanced steel and oxide-dispersion strengthened (ODS) steels and further optimisations (composition, heat-treatment) taking into account the advanced manufacturing methods.
- High Heat Flux Materials (HHFM). Development/investigation of perspective plasma facing and heat sink materials including additive manufacturing, innovative alloys and composites.

Technical areas of common interest for the Co-Funded European Partnership (CEP) on nuclear materials with the EUROfusion program

In principle there are many similarities concerning materials science research between fission and fusion technology, especially when fission “core” structural materials are considered. In order to keep the promises of economic sustainability and efficient use of natural resources, both future nuclear fission and fusion reactors will require high-performance structural materials with improved resistance to neutron radiation damage and intense thermomechanical stresses, which should be able to guarantee stable operations at high temperatures, in contact with corrosive environments. However, despite the many commonalities, from the programmatic point of view the nuclear materials research in fission and fusion are usually separated, even if often involving the same institutes and research groups. The early work on fusion materials largely benefited from the LWR and FBR experience that constituted the base knowledge for the development of the first materials for fusion. Successively and until the renewed interest on fast rectors and Gen IV systems, most of the research in nuclear material science has been carried out in fusion followed by a transfer of knowledge in the other direction. Some of the materials developed in fusion have been considered for application to the GenIV systems e.g., SiC_f/SiC composites and vanadium alloys. SiC_f/SiC ceramic composites are still the choice for the realization of the core of the High Temperature Gas-cooled Reactor.

Overview of the materials research in EUROfusion

The requirement of using low activation elements and the progress in the design of fusion reactors led to a streamlined selection of the fusion materials portfolio in EUROfusion. Presently, the materials research for the core materials in EUROfusion is therefore focalized on:

- the RAFM steel Eurofer97 for the components of the in-vessel structures;
- tungsten based materials for the plasma facing components;
- copper alloys (CuCrZr) for the heat sink materials in the divertor .

The full list of materials for in-vessel applications under development in WPMAT within the 2020 DEMO Material Technology Readiness Levels (MTRLs) Classification is shown in Figure 1 below [3].

Figure 1 does not include the anti-permeation and anti-corrosion coatings since, as stated above, their development, including the permeation properties, is carried out in the WPBB.
The realization of the DEMO reactor, ITER and the TBM experiments will need fusion specific design rules for the introduction of new materials and the specific loads envisaged. Major issue in this regards is the lack of data regarding the performance under irradiation, therefore neutron irradiation under DEMO loading conditions are planned for the determination of material properties in support of the design of the components [4]. 14.1 MeV neutron sources adequate for fusion materials testing are lacking as well as fast fission neutron facilities, so the neutron irradiation presently are carried out in the light water reactors cores that, although providing useful information, not completely fit for purpose. The realization of a 14MeV neutron source, the International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source (IFMIF-DONES), is part of the program.
The amount of data that will be produced in the present and planned irradiation campaigns (fission reactors and future 14Mev irradiation facilities) will not be sufficient, per se, to guarantee a safe design. Therefore, there is the need to put in place accelerated development programs based on the management of incomplete and sparse data set. In addition, efforts must be spent to develop reliable atomistic and multiscale computational modelling approaches that can integrate the irradiation data in support their interpretation. Finally, the need to maximize the space available in in pile irradiation and the limited volumes for testing in the future neutron sources makes indispensable the development of standards for the use of small specimen test techniques [5, 6].

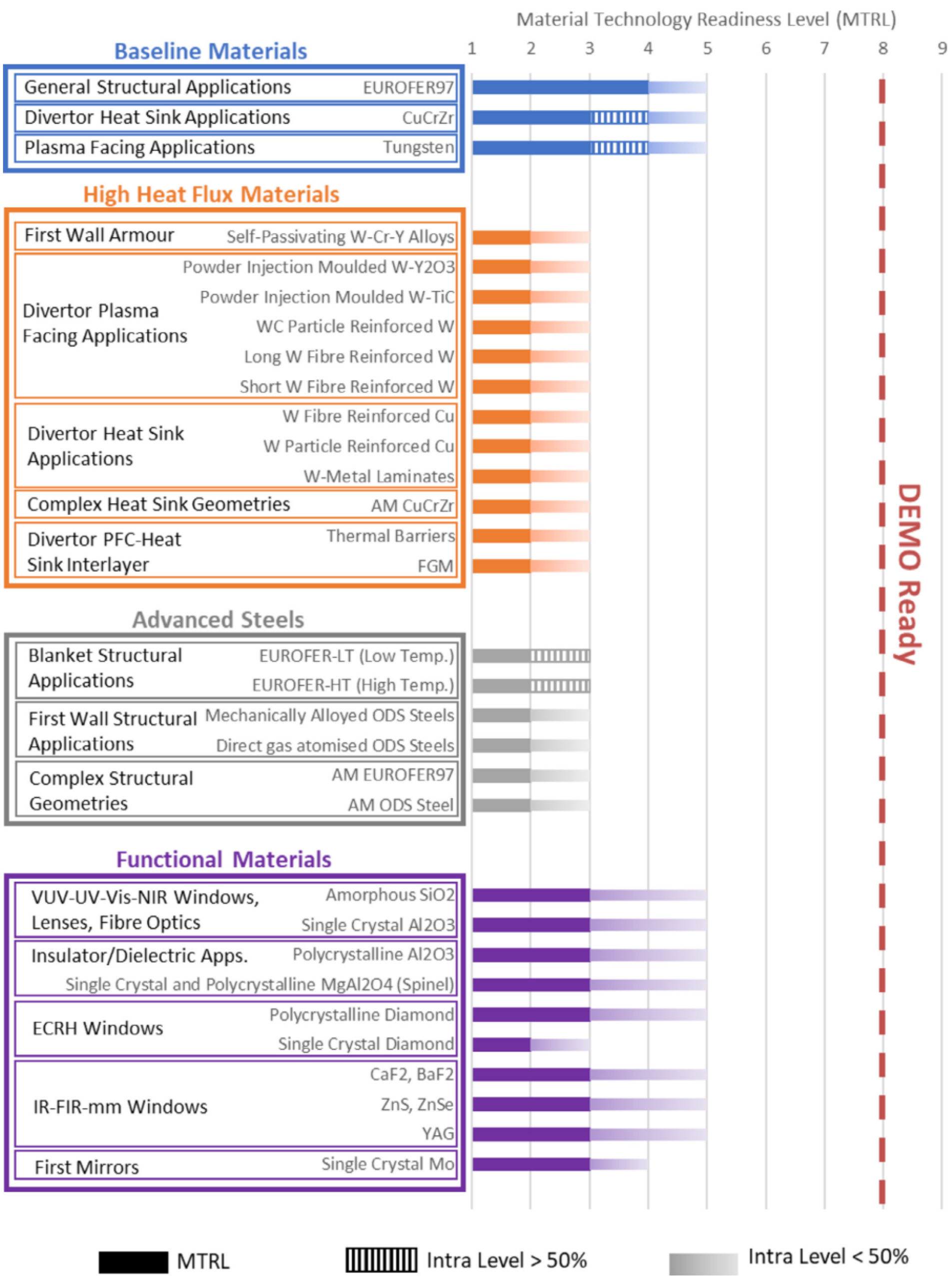

Figure 1. 2020 DEMO Material Technology Readiness Levels (MTRLs) Classification of WPMAT materials for in-vessel applications. Solid colour illustrates current MTRL, dashed lines indicate intra-level progress over 50% and shaded lines indicate intra-level progress below 50% [3].

The materials research in the CEP stemming from ORIENT-NM

The materials research in the future CEP on nuclear materials is the outcome of the Work Package 2 of the ORIENT NM project. The Strategic Research Agenda (SRA) is elaborated based on advice from the experts in the Technical Advisory Group, which produced the materials identity cards, where the main issues concerning a wide spectrum of nuclear materials have been identified. It aggregates the inputs coming from the Joint Programme on Nuclear Materials of the European Energy Research Alliance (EERA-JPNM) and the Sustainable Nuclear Energy Technology Platform (SNETP), especially relative to the European Sustainable Nuclear Industrial Initiative (ESNII) Gen IV systems, and the Nuclear Generation II & III Alliance (NUGENIA), relative to the light water reactors (LWR). The ambition of this SRA is to be of validity for any nuclear reactor system and material class. This goal is reached by elaborating it based on methodological, rather than strictly technical, considerations, with emphasis on fostering and boosting innovation through the use of modern digital technologies. This is fully consistent with the approach put forward in the recent Advanced Materials 2030 Manifesto, which has been elaborated for as many as 9 materials markets [7].

The materials research for the EERA JPNM community has been delineated in the Strategic Research agenda [8] and covers the materials needs for the Gen IV systems of the European Sustainable Nuclear Industrial Initiative (ESNII), namely:

- the Sodium Fast Reactor (SFR)
- the ALLEGRO Gas-cooled Fast Reactor (GFR).
- the flexible fast spectrum irradiation facility MYRRHA
- the ALFRED demonstrator for Lead-cooled Fast Reactor (LFR).

The SFR is the most mature technology among the Gen IV systems, for which there is considerable experience regarding both materials and design. Several sodium cooled fast reactors have been realized and operated worldwide, allowing performance data throughout thousands hours exercise to be accumulated. The SFR's design relies on steels of the class 300 for the structures, the 15-15Ti steel (Austenitic Improved Material 1, AIM1) for the cladding and the EM10 martensitic steel for the hexagonal cans. The molten sodium is mild to the FeCr steels and the SFR material issues are mainly related to the SFR cost-effectiveness and concerns the need to:

- increase the fuel burnup,
- increase the operating temperature,
- increase the lifetime of the plants to 60 years [9].

The material research for the SFR share with fusion the interest for the oxide dispersion strengthened ferritic/martensitic steels (F/M ODS). The F/M steels, given their superior resistance to neutron swelling, are considered by many the only available option to increase fuel burnup. The main limitations to their use for the steel cladding are the poor mechanical properties at high temperatures and creep resistance. For this reason, F/M alloys hardened by dispersion of oxides are under development for the SFR, identically to the low activation alloys for the breeding blanket of the HCPB DEMO [10].

The roadmap for the gas-cooled fast reactor (GFR) system foresees a staged approach and the first core of the reactor will rely on the materials already developed for the French sodium reactors. The machine will serve for the development of the materials for its definitive version made of a ceramic assembly of hexagonal fuel elements, consisting of ceramic hexagonal wrappers containing ceramic fuel cladding tubes. The present material choice for the high temperature core components is the SiC_f/SiC composite [11].

The design of the lead fast reactor (LFR) also relies on the materials developed for the SFR. The main issue is the corrosion of the steels of the 300 series by the molten lead alloys. Recent results from the Euratom-funded. GEMMA (Generation IV Materials Maturity) project [12] demonstrate inacceptable corrosion of the FeCrNi austenitics at temperatures above 470°C. The development of materials resistant to lead corrosion at high temperature is thus an open issue and surface treatment (e.g., aluminization, ceramic coatings) are proposed as an effective way to protect them. As a matter of fact, the full exploitation of the potential of lead as a coolant lies in the possibility of extending the operating temperature well beyond the temperatures imposed by corrosion by using refractory materials [13]. The present LFR design foresees a step-by-step approach starting from a reactor operated at low temperature, where lead corrosion is negligible using the FeCrNi alloys developed for the SFR. This low temperature machine will then be used as irradiation facility to develop core materials resistant to the lead corrosion at higher temperature.

The brief review above outlines the main issues addressed within the EERA JPNM community. Nevertheless, the number of systems under consideration and the different designs make the list of materials under study for the realization of ESNII systems much wider and for complete information we refer to the EERA JPNM SRA [7].

The LWRs have clearly the highest level of maturity. The focus of materials research is mainly on strategies to manage the ageing of materials and components, in connection with plant life extension, including repair and replacement, also using advanced manufacturing techniques. Several countries and nuclear energy companies in Europe have already extended are the extension of their nuclear reactors' operation beyond the design lifetime (generally 40 years), up to 60 years. This decision is driven by obvious economic reasons and is consistent with an increasing need for atomic power as a solution to the ongoing squeeze on energy supply. Life extension is clearly related to the performance of materials after prolonged exposure in the LWR environment. Radiation-induced embrittlement of reactor pressure vessels (RPV) is a major issue since the RPV is a plant component for which a duplicate or redundant backup system does not exist. It is therefore necessary to understand the microstructure evolution behind embrittlement to prevent possible integrity issues and evaluate the status of the RPV steels [14]. Irradiation assisted stress corrosion cracking (IASCC) of austenitic stainless steels and nickel-base alloys is also a significant problem, in connection with the integrity of LWR core components. IASCC is strongly dependent on the neutron dose, i.e., materials exposed to neutron radiation become more susceptible to stress corrosion cracking. Here, too, a better understanding of the evolution of localized

deformation in the irradiation damage microstructure is required to ensure the structural integrity of core components.
The nuclear accident at the Fukushima Daiichi Nuclear Power Plant in 2011 demonstrated the need to enhance the safety of nuclear fuel during accident scenarios, so giving new impulse for the development of materials for LWR's cladding. The Fukushima-Daiichi event demonstrated that the zirconium fuel claddings have the significant safety risk of hydrogen detonation due to the strong oxidation and hydrogen release during the design basis accidents (DBA) and beyond design basis accidents (BDBA). Therefore, research and development of accident tolerant fuel (ATF) concepts aiming to improve nuclear fuel safety during normal operation, operational transients and possible accident scenarios have been boosted. Deposition of protective coatings on Zircaloy cladding tubes, FeCrAl ODS alloys, Coated ODS molybdenum and SiC/SiC-composite cladding are being considered as solution of enhanced ATF cladding [15].

Outcomes of the first interaction between the fission and fusion materials communities

The first interaction between the fission and fusion materials communities took place in the context of the “Technical Meeting on Synergies in Technology Development between Nuclear Fission and Fusion for Energy Production” organized by the International Atomic Energy Agency in Vienna in 6-10 June 2022. Moreover, the perimeter of the activities of common interest was better defined in valuable discussions with dr. Giacomo Aiello Senior Materials and C&S Engineer EUROfusion - Program Management Unit, and summarized in the following bullet list:

- **Neutron irradiation resistant (ferritic/martensitic) steels**, in low and high temperature versions, are foreseen for the cladding of the future Gen IV reactors due their outstanding resistance to the neutron irradiation. A better understanding of the mechanism of embrittlement under irradiation at low temperature can benefit from the development of models for Reactor Pressure Vessel steels [14]. In addition, component design rules for irradiation conditions are currently largely incomplete for this class of materials: they are equally needed for fission and fusion applications and in both cases, their development has the common problem of different inherent features with respect austentic steels, for which rules exist, but cannot be simply extended to F/M steels (e.g., cyclic softening).
- **Multiscale materials modelling and behavioural predictive tools** are indispensable for the accelerated development of materials and for interpretation of experimental data. In particular, the fundamental mechanisms that drive the microstructure evolution under irradiation and its effect on mechanical properties are essentially the same in low alloy bainitic steels for reactor pressure vessels of current LWRs and in F/M alloys and steels, thus at this level both approaches and results have a lot in common. In addition, the use of ions for irradiation experiments, which bears a strong ink with modelling activities, requires the

identification of common good practices in order to be usefully and correctly transferred to neutron irradiation.

- **Multidimensional material properties databases and data mining tools** are also indispensable for the accelerated development of materials and improved use of experimental data.
- **The establishment of standards for the use of small specimen test techniques** is a must for the development of neutron resistant materials. This is a common issue of the fission and fusion community, due to the limited space for irradiation in the reactor cores, as foreseen in the future 14MeV irradiation facilities. Such testing techniques are also required for the accelerated development of materials to get meaningful data from small batches of experimental steels and alloys.
- **The development of coatings** is necessary for the management of tritium in the nuclear power plants, as well as for protection against corrosion. Tritium is produced in all nuclear facilities, such as pressurized water reactors, fast reactors, irradiated fuel and recycling plants and tritium production plants under normal operation and accident conditions. The development of efficient and durable coatings to realize tritium barriers, even if with different objectives depending on the system, is an urgent need. Likewise, both in fusion and in fission systems the use of corrosive fluids obliges specific components to be protected against it, e.g., for the protection from high temperature heavy liquid metals in the LFR and in some fusion breeding blanket designs that make use of liquid lead-lithium alloys. Finally, coatings are under development also for the realization of accident tolerant LWR's fuel cladding.

Conclusions and future work

The technical framework identified in this deliverable will serve as starting point in setting up the collaboration between the fission and fusion materials science communities.

Considering the above, it is clear that the EUROfusion consortium is potentially a key partner of the CEP stemming from ORIENT-NM and a collaboration scheme would be beneficial to both organisations. Regarding the funding, it should be underlined that the EUROfusion funds are assigned to the institutions member of the EUROfusion consortium and allocated for the execution of the project activities, therefore not available for the support of crosscutting activities. Likewise, the funds allocated to the nuclear materials CEP will have to be used to fund the relevant research lines, thereby calling for bespoke funding dedicated to cross-cutting activities.

A formal legal agreement between the CEP stemming from ORIENT-NM and the EUROfusion consortium is possible and desirable and the definition of a scheme of cooperation must necessarily pass through the involvement of appropriate representatives of the two entities. Further work in the next few months will be committed to discuss deeper on the formalization of the collaboration.

Con formato: Inglés (Reino Unido)

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