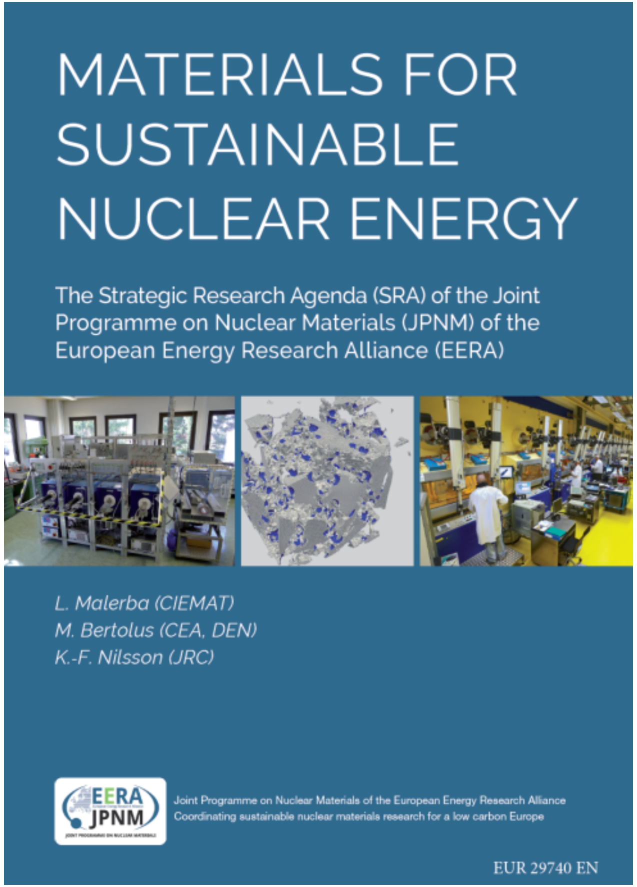
Group Discussion I:
Outstanding Research Challenges

The European Commission's science and knowledge service

Joint Research Centre

IAEA Technical Meeting on Structural Materials for Heavy Liquid Metal Cooled Fast Reactors, Vienna, Austria, 15-17 October 2019

European Commission



MATERIALS FOR SUSTAINABLE NUCLEAR ENERGY

The Strategic Research Agenda (SRA) of the Joint Programme on Nuclear Materials (JPNM) of the European Energy Research Alliance (EERA)

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Joint Programme on Nuclear Materials of the European Energy Research Alliance
Coordinating sustainable nuclear materials research for a low carbon Europe

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Joint Programme on Nuclear Materials (JPNM) of the European Energy Research Alliance (EERA) is coordinating sustainable nuclear materials research for a low-carbon Europe

Strategic Research Agenda (SRA) entitled **Materials for Sustainable Nuclear Energy** published in 2019

Available at: https://www.eera-set.eu/wp-content/uploads/Materials-for-Sustainable-Nuclear-Energy-SRA-of-the-EERA-JPNM-web-Identif.pdf

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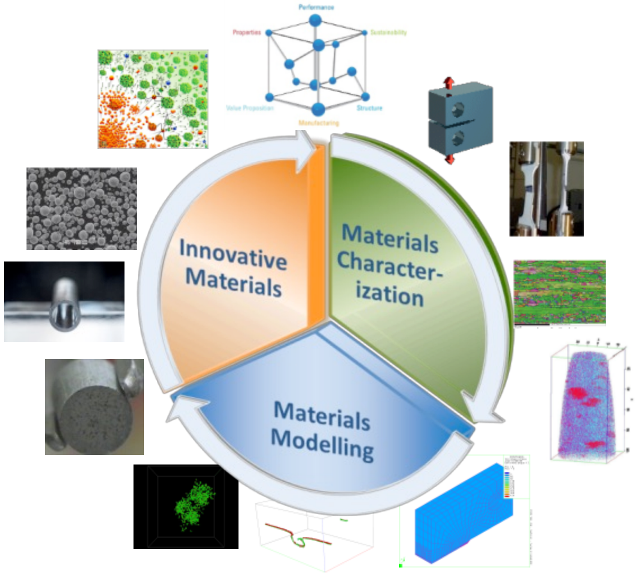
EERA JPNM: Research Approach and Strategy Pillars



- **Grand Challenge 1: Elaboration of design correlations, assessment and test procedures for the structural and fuel materials that have been selected for the demonstrators, under the service conditions expected.** This involves deployment of infrastructures for exposure to ageing environments, testing of materials and production of data and knowledge.
- **Grand Challenge 2: Development of physical models coupled to advanced microstructural characterization to achieve high-level understanding and predictive capability**. These are essential assets, given the scarcity of experimental data and the difficulty and cost of obtaining them.
- **Grand Challenge 3: Development of innovative structural and fuel material solutions and fabrication processes**, in partnership with industry, to achieve superior thermo-mechanical properties, better compatibility with coolants and improved radiation-resistance, so as to increase safety and improve efficiency and economy.

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EERA JPNM: Main structural materials expected to be used in the different ESNII Gen-IV systems (SFR, LFR, GFR, MYRRHA)

PHASES → SYSTEMS ↓		ESNII demonstrator		FOAK (prototype)	Commercial deployment
		As licensed (phase I)	Evolving (phase II)		
ADS (MYRRHA)	Periodically Replaced Components	Cladding: 1.4970; structures: 316L(N)	Coated 15-15Ti (FeAl, FeCrSi, FeTa, MAX phases, …) or AFA	N/A	
	Permanent Structural Components	316L(N)			
LFR (ALFRED)	Periodically Replaced Components	Cladding and structures: (Al_2O_3 coated) 15-15Ti (AIM1)	Cladding and structures: Al_2O_3 Coated 15-15Ti or AFA	Cladding: AFA or FeCrAl ODS Structures: AFA	AFA or FeCrAl ODS, or (coated) Mo-ODS, or SiC_f/SIC
	Permanent Structural Components	316L(N)		AFA or ferritic steel lined with AFA	

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Sustainable Nuclear Energy Technology Platform

ESNII
European Sustainable Nuclear Industrial Initiative

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EERA JPNM: Main issues concerning pre-normative R&D-materials qualification, design rules, assessment & test procedures (1/4)

Main issue	Breakdown in sub-issues	Materials concerned	Techniques/Methods
High temperature behaviour and degradation of metals	Creep, relaxation and cyclic deformation	Austenitic steels (316L), F/M steels (Grade91)	<u>Experiments</u>: For *long-term operation*: Mechanical tests of in-service material, long-term tests, accelerated tests. Basic tests for *model calibration*: creep, low-cycle fatigue, crack propagation tests. Special emphasis on long hold times. Microstructural analysis to link mechanism-based models to experiments are needed. <u>Models</u>: For creep, relaxation and cyclic deformation, emphasis on unified visco-plastic continuum models, mechanistic models for different creep mechanism and damage crack propagation fracture mechanics Models need to be translated into Design Rules or Assessment Procedures.
	Creep and creep-fatigue damage and crack propagation		
	Thermal ageing		
Environmental compatibility between coolant and structural materials	Liquid Metal Corrosion and erosion (LMC)	Austenitic steels:316L, 15-15Ti and 15-15Ti with alumina surface protection	<u>Mechanical tests</u>: slow-strain rate tensile; fracture, fatigue, and creep-fatigue in flowing and stagnant conditions; <u>Corrosion tests</u>: Erosion and corrosion (oxidation and solution tests) in flowing conditions <u>Qualification tests</u> (mechanical and corrosion) for 316SS and welded components. <u>Accelerated tests</u> to map bounding conditions. Emphasis on <u>long-term tests</u>; A very careful documented control and monitoring of the test conditions (in particular oxygen control) is required for all tests. Tests to be complemented by detailed microstructural analysis (e.g. SEM, EBSD, XRD, TEM); <u>Engineering related approaches need to be developed</u> Coupling with models.
	Liquid Metal Embrittlement in HLM (LME)		
	Weld procedures		
	Degradation modes and defect assessment		
	Compatibility with HLM		

EERA JPNM: Main issues concerning pre-normative R&D- materials qualification, design rules, assessment & test procedures (2/4)

Main issue	**Breakdown in sub-issues**	**Materials concerned**	**Techniques/Methods**
Radiation effects	Low temperature embrittlement & plastic flow localisation	Austenitic and F/M steels (irreplaceable & structural components)	Exposure to irradiation, also including coolant environment. Standard mechanical test in hot cells of neutron irradiated materials (irradiated in test reactors or in-service exposed) and complementary ion/proton irradiation. These tests need to be supported by irradiation models Transfer the data into reduction factors for material properties.
	Long-term/low dose irradiation in environment		
	High dose irradiation swelling and creep	Fuel cladding materials: 15-15-Ti austenitic steel	
Assessment of complex loadings	Non-isothermal thermo-mechanical loads	All	Experiments: Component or specimen tests that simulate thermo-mechanical loads (e.g. thermal shocks), variable amplitude tests for fatigue; tensile high strain rate tests, multi-axial tests, e.g. cruciform specimen for biaxial loading. Modelling: Finite element models of complex load cases and simplification to translate into design rule load cases.
	Complex stress distributions		
	Load transients and beyond design conditions		
	Weld procedures		
	Degradation modes and defect assessment		
	Compatibility with HLM		

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EERA JPNM: Main issues concerning pre-normative R&D - materials qualification, design rules, assessment & test procedures (3/4)

Main issue	**Breakdown in sub-issues**	**Materials concerned**	**Techniques/Methods**
Integrity and qualification of weldments and welded components	Residual stresses Weld procedures Degradation modes and defect assessment Compatibility with HLM	All welds: austenitic, F/M; Ni-based alloys and dissimilar metal welds	Modelling: Simulation of weld process and post-weld heat treatment for residual stresses; Structural integrity assessment (defect assessment crack propagation, damage) of welded specimens and components by FEM. Translation of structural analysis assessment into Design Rules.

EERA JPNM: Main issues concerning pre-normative R&D - materials qualification, design rules, assessment & test procedures (4/4)

Main issue	Breakdown in sub-issues	Materials concerned	Techniques/Methods
Sub-size and miniature specimen test standardization	Sub-sized/ miniaturised specimens for mechanical property	Fuel cladding material, 15-15Ti	Experiments: Various fuel cladding tests (internal pressure, ring-compression, small-punch, cone mandrel) with emphasis on hot-cell tests; Small-punch test for tensile and creep properties; Nano-indentation, micro-pillar tests for tensile properties; miniature specimen fracture and fatigue tests. Modelling: Test to be complemented with finite element analyses, and meso-scale models (dislocation dynamics and crystal plasticity)
	Thin-walled cladding tubes		
	Small Punch test	All	
	Micro-pillar tests and nano-indentation	All	
Component and material health monitoring		All	Patterns of response of material to NDE techniques as part of codification; Exploration of possibility of lifetime estimation based on NDE in view of online monitoring

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EERA JPNM: Summary of issues relevant to the different structural material classes and types (1/4)

Type of related issues ***Materials***		***Pre-normative research***	***Modelling***	***Advanced materials' solutions***
Austenitic steels	*316L(N)* *(prototype irreplaceable components)*	*Thermal ageing, thermal creep, compatibility with heavy liquid metals (HLM): increased database (including welds), accelerated testing, models describing micro/macro evolution → refinement of existing, or elaboration of new, design rules*		*Improve compatibility with coolants, apply high temperature protective barriers*
	15-15Ti (cladding)	*Irradiation creep and swelling, thermal creep, compatibility with coolants & fuel: increased database, models describing micro/macro evolution → refinement of existing, or elaboration of new, design rules*		Improve swelling resistance and compatibility with coolants (apply high temperature protective barriers).
	Alumina forming austenitic (AFA) steels	*Exposure needed for screening between candidates*	*Thermodynamic models for composition optimisation, microstructure evolution models*	*Addition of Al increases compatibility with coolants (protective alumina layer), but causes embrittlement at low T, although improves high T creep strength (NiAl precipitates): compromise searched*

EERA JPNM: Summary of issues relevant to the different structural material classes and types (2/4)

Type of related issues ***Materials***		***Pre-normative research***	***Modelling***	***Advanced materials' solutions***
Ferritic / Martensitic (F/M) steels *(cladding and core)*	*9-14 %Cr*	*Low temperature irradiation embrittlement, irradiation creep, thermal ageing/creep, creep-fatigue (cyclic operation softening) compatibility with coolants, liquid metal embrittlement: increase database (including welds), models → define design rules and develop models in support*		*Need solution to minimize embrittlement, improve creep resistance (e.g. by thermomechanical treatment) and improve compatibility with coolants*
	Oxide dispersion strengthened (ODS)	*Exposure needed for screening between candidates, suitable treatments for recrystallization to eliminate anisotropy after powder metallurgy production of bars and tubes by extrusion.*	*Oxide formation/stability, microstructure evolution, modes of deformation*	*ODS steels (tubes) have better creep resistance, but manufacturing and joining are issues (optimization needed); toughness and compatibility are also issues*
	FeCrAl alloys (also ODS)		*Thermodynamic models for composition optimisation, microstructure evolution models*	*Addition of Al increases compatibility with coolants (protective alumina layer), but worsens mechanical behaviour: compromise searched*

EERA JPNM: Summary of issues relevant to the different structural material classes and types (3/4)

Type of related issues ***Materials***		***Pre-normative research***	***Modelling***	***Advanced materials' solutions***
Refractory metallic alloys *(cladding and core)*	*Molybdenum alloys (including ODS)*	*Exposure needed for screening between candidates. Irradiation creep and swelling, thermal creep, compatibility with coolants & fuel: increase database, models describing micro/macro evolution → refinement of existing, or elaboration of new, design rules, supported by models*		*Prospective materials, mainly for cladding, studied also in the past, with problems of manufacturing, compatibility with coolant and mechanical behaviour*
	Vanadium alloys			
	High Entropy Alloys	*Prospective metallic materials with potentially excellent mechanical properties, coolant & radiation resistance, need extensive investigation for screening, including understanding of origin of properties through modelling, before applications are identified.*		

EERA JPNM: Summary of issues relevant to the different structural material classes and types (4/4)

Type of related issues ***Materials***		***Pre-normative research***	***Modelling***	***Advanced materials' solutions***
Ceramics *(cladding and coating)*	*SiC/SiC (also C/C) composites (cladding)*	*Mechanical test standardization, radiation resistance (thermal conductivity, hermeticity, swelling, ...) and corrosion resistance → define design rules*	*Microstructure evolution models under irradiation, finite element models for composite architectures, X-ray tomography techniques*	*Liners to guarantee hermeticity of cladding, or other techniques to guarantee hermeticity. Limit thermal conductivity degradation under irradiation.*
	Non-metallic core support structures (ad hoc ceramics)	*Screening of candidates. Test standardization (mechanical & thermophysical properties)*	*Microstructure evolution models under irradiation*	*Protection against oxidation*
	Al_2O_3 coatings	*Applied with different techniques on different substrates to protect against coolant attack and temperature: exposure for screening and qualification*		
	Max phases	*Prospective ceramic materials with excellent mechanical properties (for ceramics), coolant and radiation resistant, though stability to high temperature needs to be verified case by case. Need extensive investigation for screening, including understanding of origin of properties, before applications are identified. Usable as coatings.*		

Objectives of the Technical Meeting

- **Discuss and identify R&D needs and gaps** to assess the future requirements in the field, which should eventually lead to efforts being **concentrated in the key lacking areas**

- **Enable the integration of research on materials in Member States** (e.g. development of materials for operating in corrosive/severe environments, study of physics and chemistry of the process, design of dedicated experimental facilities and development of computational tools for material characterizations etc.) to **support the development of new technologies that have a higher level of technological readiness**

- **Provide recommendations to the IAEA for future joint efforts and coordinated research activities (if required) in the field**

Possible discussion topics

- **Discuss update / complementation of R&D needs**
- **Attempt prioritization of R&D needs to support deployment of HLM-cooled reactors**
- **Provide possible recommendations to IAEA for possible future joint efforts**
  - **Proposal of the GIF LFR System Steering Committee (SSC) discussed at the meeting on 8-10 Oct 2019** to establish an expert team (group) to develop **start-of-the-art evaluations of available corrosion resistance data** of candidate structural materials for HLM-cooled concepts
  - Provide **authoritative recommendations to designers and safety authorities in support to licensing**
  - **Format:** to be discussed (should be peer-reviewed)