# Cross-cutting issues in fusion and fission materials development

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The design of blanket and divertor in Tokamak fusion energy systems needs to enable these components to guarantee sufficient availability under extremely harsh operating conditions in terms of heat flux (up to 20 MW/m2 in the divertor), neutron dose (up to 25 dpa/fpy in the first wall of the blanket) and He accumulation (up to 250 appm He/fpy, also in the first wall of the blanket), as well as chemical environment (water or He as coolants, heavy liquid metals (HLM) as T breeders, all with potentially strong corrosive/erosive effects). Three materials have been selected to sustain these conditions in the European DEMO, namely: (1) Eurofer (reduced-activation ferritic-martensitic steel) as main structural material, supposedly suitable for a 350-550ºC temperature window (its oxide-dispersion strengthened –ODS- version should withstand higher temperature); (2) W alloys for protection against thermal shocks; and (3) Cu alloys to ensure heat evacuation [1]. It seems difficult to find energy generation systems in which materials are expected to sustain harsher conditions.

Yet, if one considers the six fission GenIV systems [2] and accelerator-driven systems (ADS) [3], materials will be subjected to conditions largely comparable with fusion: high temperature, high radiation dose, problems of compatibility with fluids… Examples can be taken from the roadmap towards demonstrators and prototypes of the European Sustainable Nuclear Industrial Initiative (ESNII), namely ASTRID (sodium-cooled fast reactor prototype, now shelved) [3], ALFRED (lead-cooled fast reactor demonstrator) [4,5], ALLEGRO (gas-cooled fast reactor demonstrators) [6] and MYRRHA (ADS) [7]; or from designs proposed by startups for lead-cooled and molten-salt-cooled fast systems [8,9]. Beyond nuclear energy, solar thermal energy (STE) also exposes materials to extreme conditions, for example the receiver is expected to heat fluids well above 500ºC and even round 1000ºC under relevant heat flux, sustaining tremendous temperature fluctuations [10].

There are essentially only three effects that are really specific for fusion, the first two of them affecting only a few centimetres of plasma-near materials/components: (1) High He/dpa ratio, i.e. much higher accumulation of He from transmutation than e.g. in GenIV systems (~10 He appm/dpa in the steel in fusion >> 0.1 He appm/dpa in GenIV) [11]; (2) high heat flux on the order of several MW/m2 [12,13], much higher than in fission, though comparable with STE; (3) large quantities of activated structural materials, without fission equivalent, which imposes stringent needs of using reduced activation materials for fusion [14].

Table 1 summarises the rationale for the identification of commonalities between fission and fusion, as well as nuclear and non-nuclear energy.

TABLE 1. RATIONALE FOR THE IDENTIFICATION OF COMMONALITIES BETWEEN GENIV FISSION AND FUSION MATERIALS / NUCLEAR AND NON-NUCLEAR ENERGY

|  |  |  |  |
| --- | --- | --- | --- |
| GenIV | Fusion | Nuclear | Non-nuclear |
| Doses ~tens of dpa, esp. in the fuel assemblies, irrespective of the system ⇒ radiation resistant materials | First wall receives thermal shocks and tens of dpa ⇒ radiation resistant materials (+ reduced activation constraint, He resistance & thermal shock protection) | Operating temperature in excess of 400ºC for most components, high heat flux (up to 20 MW/m2) in fusion ⇒ temperature resistant materials | In STE, receivers *et alia* experience high temperatures and heat fluxes (>1000ºC, several MW/m2). Molten salts and liquid metals as coolants ⇒ temperature resistant materials, compatibility issues |
| Operating temperature > 400ºC for most components (except in ADS) – some target 800-1000ºC ⇒ temperature resistant materials | In He/water-cooled design, operating temperature of key components in excess of 500ºC ⇒ temperature resistant materials[[1]](#footnote-2) | (In some components/systems the temperature is expected to be in excess of 600ºC or even of 800ºC) | Deep geothermal: drills enter in contact with high temperature supercritical water ⇒ issues of compatibility |
| Use of HLMs, molten salts, He gas, SC water ⇒ compatibility issues, need for protection from environment | Depending on design, He and/or water as coolant, HLM (PbLi) as tritium breeder ⇒ compatibility issues, protection from environment needed + tritium permeation barriers | Use of HLM or He gas in fast systems, but also molten salt and (supercritical) water ⇒ compatibility issues, need for protection against corrosion (and liquid metal embrittlement when relevant) | In bioenergy corrosive fuels used at high temperature, ⇒temperature resistence and compatibility issues. Advanced fuel cells also have issues of compatibility with HLM; high temperatures in hydrogen production and use |

Focusing on the fission/fusion commonalities, four examples are addressed:

* Mitigation of the effects of plastic flow localization under irradiation and cyclic softening through suitable design rules for ferritic/martensitic (F/M) steels;
* Development of high temperature & corrosion resistant F/M steels;
* Compatibility of structural materials with heavy liquid metals in terms of corrosion and also liquid metal embrittlement, which applies to solar thermal energy, too;
* Barriers protecting structural materials from liquid metal corrosion, also investigated as hydrogen isotope barriers in fusion, to avoid tritium permeation;
* Automated materials optimization using modern methods that necessarily include, in the case of irradiation effects, the use of ion irradiation.

Three reasons advise the use of F/M instead of austenitic steels in nuclear systems: better dimensional stability under irradiation (much lower swelling, at least so long as He accumulation is limited), better thermal conductivity and lower thermal expansion. These three points are equally important for fusion and fission, as tolerances can be reduced and heat transfer much improved.[[2]](#footnote-3) But the main reason for fusion to choose F/M steels is that their composition can be tuned to reduce activation and so be hands-on handled after shorter time: this is impossible with austenitic steels because of the presence of Ni. However, using F/M steels poses other problems:

* Design criteria or rules are only partially defined and it is impossible to apply the same as for austenitic steels. New rules are needed to allow correctly for:
  + - * Cyclic softening: the behaviour under cycling load (fatigue) is qualitatively different between F/M and austenitic steels, thus the design rules for the latter are inapplicable and there is a need to understand the underlying processes to elaborate different criteria [15];
      * Plastic flow localisation, or loss of uniform elongation after irradiation: since the existing rules estimate ductility based on uniform elongation and this property goes to zero in F/M steels after a few dpa, steels of this type affected by this problem cannot be currently used to design any structural component. Suitable design rules can be however obtained by understanding the physics of plastic flow localisation: it should be possible to make use of the ductility that these steels still possess in terms of total elongation to release the design criteria without affecting safety [16];
      * Liquid metal corrosion (LMC) and embrittlement (LME): here design rules are more difficult to be derived, as the behaviour should be mapped for a wide range of variables, such as temperature, irradiation, oxygen content in the fluid, fluid velocity, … The main solution that is currently considered is the use of suitable protective ceramic coatings, or changing the composition of the steel to self-produce alumina on the surface (see below), provided that they also protect against LME [17].
* Creep strength and corrosion resistance of F/M steels is not ideal. It should be improved and two routes are followed:
  + - * As shorter term path, compositional tuning and suitable thermo-mechanical treatments (TMT), which is a classical metallurgy approach that may be supported by thermodynamic models [18];
      * Oxide dispersion strengthened (ODS) steels [18], the fabrication of which, based on powder metallurgy, remains, however, costly and not easy to scale to industrial production, so this path is a longer term one.
* In F/M steels protection against corrosion/erosion and LME is needed, generally in the form of coatings [19]:
  + - * In GenIV coatings are specifically needed for HLM-cooled systems. Corrosion/erosion/LME are the key safety factors in these systems.
      * In fusion, in addition to protection from corrosion attack (and LME) in PbLi and He as coolant, it is key to limit the permeation of tritium towards the external environment: reduction of a factor 200 is required for PbLi application and of 10 for He systems. Insulating coatings are thus used for both. They also limit the pressure drop due to interaction with electromagnetic fields in the case of PbLi application.

In Europe corrosion/permeation barriers are created using protective alumina layers [19], which can be applied in different ways: electrochemical processes, pulsed laser deposition or atomic layer deposition. A procedure for coating qualification, however, still needs to be defined. In fusion, an important bottleneck is the enormous surface that needs to be coated (~14,000 m2).

An alternative to coatings, which is valid for fission applications, though not for fusion, because of the reduced activation requirement, is to consider F/M steels with Al added to the bulk composition, so called FeCrAl [20]. In this case, a stable surface alumina layer is spontaneously created in presence of oxygen dissolved in the fluid. These materials are also of use for high temperature STE using liquid Pb as accumulation fluid: overlay welded FeCrAl steel are explored to protect a Ni-alloy substrate with structural functions.

In order to develop new materials solutions such as the one just mentioned for STE, in the case of battery applications and nano-materials so-called materials acceleration platforms (MAPs) are being implemented. These are meant to enable autonomous materials discovery following an iterative process, in which high throughput fabrication and automated exposure and characterization techniques are used to produce large quantities of data on many materials that differ because of composition nuances. These data are subsequently analysed using artificial intelligence and the correlations thereby obtained are used to guide further tuning of compositions and fabrication processes, until an optimal material is identified. In the case of irradiation effects, such as for application to nuclear materials, ion irradiation is an almost unavoidable tool in this context. However to use ions as screening tool there remain transferability issues to neutrons [16]. The spectra are different, the dpa rate as well, the damage penetration is limited, there is a damage gradient, injected species ... these effects need to be minimised trough good practices. These are broadly known, but still need to be established as standard practices [16].

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1. In the water-cooled design the operating temperature is similar to current reactors, so radiation-induced embrittlement is an issue, as well as corrosion. [↑](#footnote-ref-2)
2. He production is roughly the same in both classes of steels. There used to be a price advantage using F/M steels which, however, seems not to exist any longer (moreover one should see which market would exist for RAFM: if small they will anyway cost more). [↑](#footnote-ref-3)