

## Reduced activation structural materials for fusion power plants – the European Union program

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**Abstract.** The competition of fusion power plants with the renewable energy sources in the second half of the 21<sup>st</sup> century requires structural materials operating at high temperatures, and sufficient radiation resistance to ensure high plant efficiency and availability. The reduced activation materials development in the EU counts several steps regarding the radiation damage resistance: 75 dpa for DEMO and 150 dpa and beyond for power plants. The maximum operating temperature development line ranges from the present day from the present day feasible 600 K up to 1300- K in advanced power plants. The reduced activation steel, RAS, forms the reference for the development efforts. EUROFER has been manufactured in the EU on industrial scale with specified purity and mechanical properties up to 825 K. The oxide dispersion strengthened , ODS, variety of RAS should reach the 925 K operation limit. The EU has selected silicon carbide ceramic composite as the primary high temperature, 1300 K, goal. On a small scale the potential of tungsten alloys for higher temperatures is investigated. The present test environments for radiation resistance are insufficient to provide data for DEMO. Hence the support of the EU for the International Fusion Materials Irradiation facility. The computational modelling is expected to guide the materials development and the design of near plasma components. The EU co-operates closely with Japan, the RF and US in IEA and IAEA co-ordinated agreements, which are highly beneficial for the fusion structural materials development.

### 1. Introduction

Fusion power plants have the promise to make up for a large fraction of the electricity to be generated in highly populated areas with a high level of commercial activity such as the EU [1]. Their properties such as high power plant efficiency, availability and reliability are of supreme importance. For the competition with renewable options these aspects are a pre-requisite to the environmental impact of fusion power plants.

Structural materials play a crucial role in meeting these requirements. Fabrication technology has considerable influence on the reliability and maintainability of the crucial components in the utility. The operating temperature of materials determines principally the plant efficiency. The resistance of structural materials against the effects of the main energy generating process, fusion of nuclei under emission of highly energetic neutrons, determines the primary components useful lifetime and availability.

The highly energetic neutrons transport heat to the surrounding components to be extracted by a coolant to the power generating components. At the same time the neutrons interact with the nuclei of the structural materials' atoms. The selection and industrial control of the structural materials composition can accomplish strong reductions of their activation. The reduction in activated waste should allow fusion power production to compete with renewable sources in the field of environmental impact.

This paper presents the materials development program of the European Union, as carried out by EFDA. This program is not isolated. In the IEA framework and under IAEA agreements the co-operation with Japan, the RF and the US is organised [2,3]. The different stages of the program and the choices for directions will be highlighted.

## 2. Primary components in Fusion Power Plants

### 2.1 Blankets

In the EU the Helium Cooled Pebble Bed, HCPB, and the Dual Coolant Lithium Lead, DCLL, concepts are under development for breeding blanket [4]. The concepts are aiming for application in DEMO for an anticipated lifetime exposure of 75 dpa. Later developments should allow utilisation up to 150 dpa with the ultimate goal at 750 in advanced power plants. The first demonstration of the blanket performance is foreseen in ITER for a limited damage level. The major structural material is EUROFER a reduced activation steel, RAS, with main alloying elements 9 % Cr and 1 % W. To reduce the activation to recycling levels, the impurity level has to be controlled in the ppm range. This can be accomplished on industrial scale, provided production lines for low impurity steels are available. The potential for an operating temperature increase of 100-150 K lies here in the use of Oxide Dispersion Strengthening, ODS, for the steel. The potential net efficiency would be about 37 %. The application of silicon carbide composite ceramics, SiCcc, inserts in a steel structure increases the maximum temperature another 150 K resulting in about 44 % efficiency.

### 2.2 Heat heat flux components

The main divertor concepts in the EU power plant studies, shown in figure 1, use a limited set of structural materials.

Higher coolant temperatures allow higher armour (tungsten) temperatures.

Tungsten is practically not produced as a reduced activation alloy. The only way to make reduced activation is elemental tailoring, which is at present prohibitively expensive.

From these considerations it can be concluded that RAS, including the ODS variety, SiCcc and tungsten will form the core of the EU materials development program for structural steels.




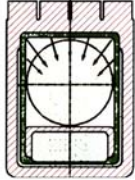
Coolant	Water	He (classic)	Pb-17Li	LM (Na)
Structural Mat	RAFM	W	SiC/SiC	W
Elementary cell design				
Details	Swirl, monoblock	Bi-directional, multi-section	Joint SiC-SiC / W tiles	Evaporation, capillarity
Coolant P & v	15.5 MPa - 15 m/s	14 MPa - 280 m/s	0.3 MPa - 2.5 m/s	0.15 MPa - 230 m/s
Coolant in/out T (°C)	300 / 315	500 / 551	300 / 810	830/850 (Na)
Max heat flux	~7 MW/m <sup>2</sup>	~5 MW/m <sup>2</sup>	~5 MW/m <sup>2</sup>	~5 MW/m <sup>2</sup>
Max T armor (°C)	1061	968	1126	1400

Figure 1. Several divertor concepts proposed for EU power plant studies, from [4].

## 3. Evaluation of candidates potential

Nuclear data analyses and experiments are integral part of the materials development program to validate the selections and choices concerning low impurity levels, low activation and after-heat.

Shortly the structural materials for blankets and high heat flux components under development in the EU are evaluated. Some other materials are included. They are studied at a lower intensity level, because of their limited promise for application in fusion power plants.

### 3.1 Steels

The RAS composition can be controlled on an industrial scale that recycling of the steel within 100 years seems likely. The main concern with the RAS steels is their lower operating temperature controlled by the toughness. After irradiation the ductile brittle transition might be over 400 K. The reduction of the post-irradiation transition temperature is pursued applying microstructure refinement and heat treatments. The manufacturing demonstrations, in the EU with EUROFER, have proven that it provides designers with a wide range of fusion and diffusion joining techniques and shaping with hot iso-static pressing of powdered and solid steel [5]. Compatibility with coolants seems to be well under control. The hydrogen effects at lower temperatures are addressed.

The upper application temperature amounts to about 825 K. Using ODS might increase the upper application temperature to 925 K. This does not mean that complete near plasma structures have to be built from ODS steel. The application could also be limited to those parts of the component that are exposed to that temperature range. In the EU EUROFER with ODS is presently investigated for its potential to be applied in blankets and divertors.

### 3.2 Ceramics

The low activation and high temperature mechanical properties form a main asset of silicon carbide composite ceramics, SiCcc. The radiation resistance and thermal conductivity are being addressed in the EU materials development in co-operation with the international IEA partners. The fibre development specifically for applications in strong neutron fields is mainly taking place in Japan and the US. The EU concentrates on the multi-dimensional textures fabrication, joining and their characterisation in-pile [6]. The development of SiCcc has a long road to go before the assertion that it is a reliable structural material is there.

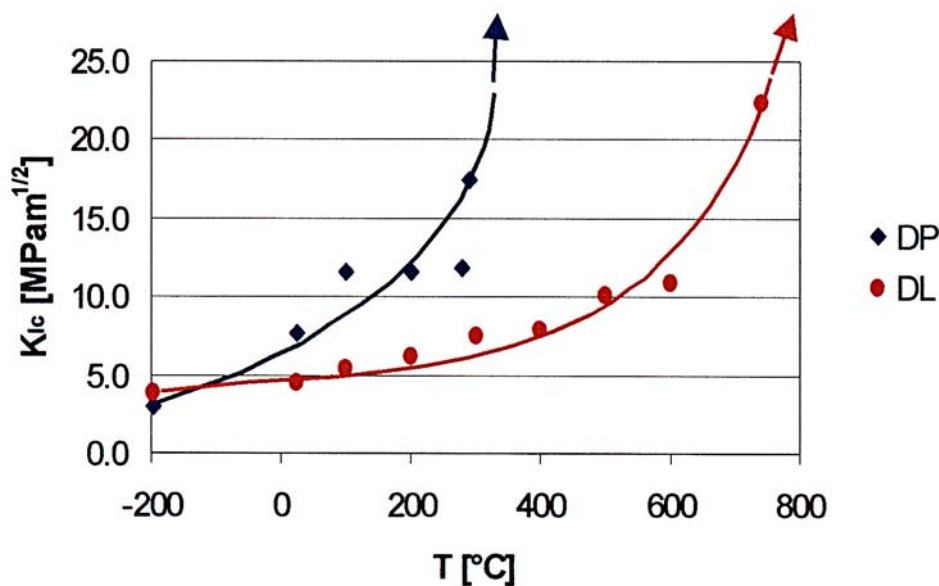


Figure 2. Dependence of fracture toughness on temperature of two chromium qualities: DUCROPUR and DUCROLLOY, from [7].

### 3.3 Refractory alloys

Mo, Nb and Ta suffer from high activation and their physical-mechanical properties do not pose an attractive alternative for the other refractory alloys.

The EU has terminated the effort on vanadium alloy development, irrespective of its low activation properties, because of the limited potential of the alloy in lithium-cooled blankets.

Chromium based alloys have been studied in the EU, because of their attractively low activation and high temperature mechanical properties. It turned out that the lower application temperature limit seems to remain over 600 K, because of embrittlement figure 2. Efforts to improve the toughness of chromium at lower temperatures, [7], by micro-structural refining seem promising, but in the EU the main effort on structural applications will be devoted to tungsten and its alloys. The chromium experience will be used for the improvement of the tungsten alloys, which also show poor toughness values below 900 K.

## 4. Development paths

### 4.1 Test reactors and IFMIF

The ultimate goal for near plasma components is to serve the full power plant lifetime. For 30 years of service and a neutron output from the plasma of about 2.5 MW.m<sup>-2</sup>. this means an end of life radiation damage in structural materials near the plasma of about 750 dpa [4].

The materials development in the EU depends for the near future on materials test reactors. The mixed spectrum reactors provide up to 15 dpa in a reasonable, less than 3 years time. Fast reactors can generate 70 dpa under 3 years, but at present with a minimum irradiation temperature in excess of 600 K [8]. These fission reactors do not provide the transmutation product range in structural materials to be encountered near a fusion plasma. The main fusion neutron transmutation products, helium and hydrogen, are expected to affect the materials properties considerably. The International Fusion Materials Irradiation Facility, IFMIF, could produce a fusion relevant neutron spectrum and a flux sufficient to reach 150 dpa in a few years [9]. The irradiation volume is a restriction that can be eliminated using small specimen sizes and proven scaling laws.

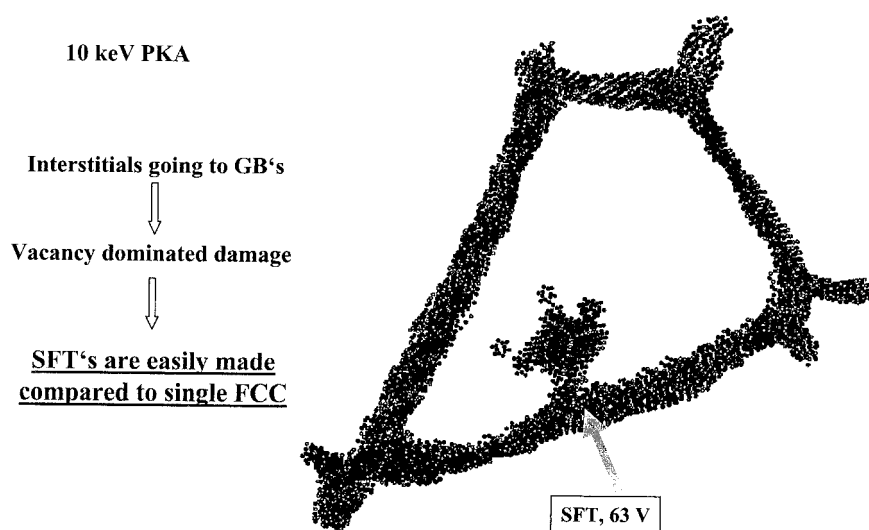


Figure 3. Modelling grain boundaries as sink for interstitial vacancy dominated radiation damage from [10].

## 4.2 Modelling

The modelling efforts will greatly depend on computational approaches based on first principles [10]. Computational power increases for the next ten years are expected to follow the trends previously observed. This would allow analysis in acceptably short time the effects of displacement damage, and helium and hydrogen transmutation production on the macroscopic behaviour of the structural materials, figure 3. The analyses could be verified with the results from IFMIF experiments later on. These would provide the basis for the development of materials resistant to damage into the era of fusion power plants with components to be replaced only after hundreds of dpa accumulated in-service.

## 5. Conclusion

Ongoing research shows that the reduced activation steels have the potential to reach the operating temperature level of 825 K up to 925 with oxide dispersion strengthening. The use of silicon carbide composites might allow operating temperatures to rise as high as 1300 K, but several principle hurdles have to be taken. Tungsten alloys have attractive high temperature properties similar to SiCcc, but have no inherent reduced activation properties. For the DEMO plant the International Fusion Materials Irradiation Facility, IFMIF, is indispensable for the relevant confirmation of the intended behaviour of materials and component cutouts. The modelling activities, based on computational approaches with increasing speed, will guide both design and materials development in the meantime.

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