SELECTION CRITERIA FOR FUSION REACTOR STRUCTURES

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ABSTRACT

Fusion energy is the ultimate energy to cover Mankind's energy needs forever. However, taming the fusion energy is the greatest technological challenge the humanity is facing. Development of structural materials to withstand against the extreme conditions in the course of fusion power plant operation is one of the toughest nuts to be cracked. A great number of structural materials have been investigated for fusion reactor applications, such as steels (austenitic stainless steels and ferritic/martensitic steels), vanadium alloys, refractory metals and alloys (niobium alloys, tantalum alloys, chromium and chromium alloys, molybdenum alloys, tungsten and tungsten alloys), and composites (SiC_f/SiC and Carbon Fibre Composite CFC composites).

Steels have extensive technological data base and significantly lower cost compared to other refractory metals and alloys. Ferritic steels and modified austenitic stainless (Ni and Mo free) have relatively low residual radioactivity. However, steels cannot withstand high neutron wall loads to build an economically competitive fusion reactor. Some refractory metals and alloys (niobium alloys, tantalum alloys, molybdenum alloys, tungsten and tungsten alloys) can withstand high neutron wall loads. But, in addition to their very limited technological data base, they have high residual radioactivity and prohibitively high production costs.

A protective, flowing liquid zone to protect the first wall of a fusion reactor from direct exposure to the fusion reaction products could extend the lifetime of the first wall to the expected lifetime of the fusion reactor. In that context, a fusion-fission (hybrid) with a multi-layered spherical blanket has been investigated, which is composed of a first wall made of oxide dispersed steel (ODS, 2 cm); neutron multiplier and coolant zone made of LiPb; ODS-separator (2 cm); a molten salt FLIBE coolant and fission zone; ODS-separator (2 cm); graphite reflector. Calculations are conducted for a liquid wall with variable thickness, containing Flibe + heavy metal salt (UF_4 or ThF_4) is used for first wall protection. The content of heavy metal salt is chosen as 4 and 12 mol%. A flowing wall with a thickness of ~ 60 cm can extend the lifetime of the solid first wall structure to a plant lifetime of 30 years for 9Cr–2WVTa and V–4Cr–4Ti, whereas the SiC_f/SiC composite as first wall needs a flowing wall with a thickness of ~ 85 cm to maintain the radiation damage limit.

INTRODUCTION

Controlled fusion energy appears to have potential in providing unlimited energy for mankind. A fusion energy system has attributes of an attractive product with respect to safety and environmental advantages compared to other energy sources and it has clear safety and environmental advantages over fission energy. Fusion fuels are abundantly available in the nature, contrary to relatively scarce fission fuel resources. Hence, growing efforts have been invested in fusion energy research in the past 40 years. Figure 1 shows a cross sectional view of a magnetic fusion reactor [1]. Strong superconducting magnets provide compression forces to confine plasma at temperatures > 10^8 °K in the plasma chamber. Fusion neutrons generated in the plasma penetrate through the first wall and deliver their kinetic energy in the surrounding blanket.

In a fusion reactor, first wall around the fusion chamber must withstand to high energetic charged particle fluxes, Bremsstrahlung and gamma-ray radiation, and most importantly to unconventionally high energetic intense neutron fluxes with a mean energy ~ 14 MeV. The latter are expected to lead to much higher material damage than observed by fission reactors, not only due to higher neutron kinetic energy, but also, and even more important due to detrimental threshold reactions for structural materials in MeV range. *Any maintenance and repair work on fusion chamber first wall will cause a long-term plant shutdown and will be very costly.* The highest material damage will occur in the first wall as it will be exposed to the highest neutron, gamma ray and charged particle currents, which are produced in the fusion chamber.
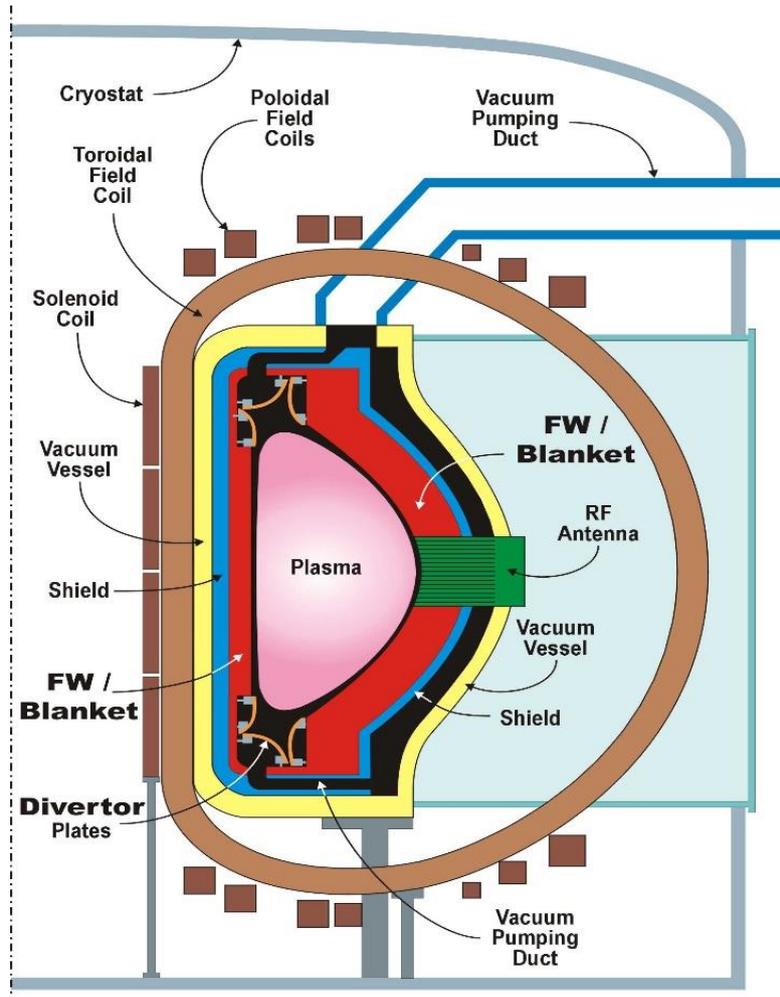
Figure 1. Cross sectional view of a magnetic fusion reactor

Selection of structural materials plays a key role in enhancing the economic competitiveness of fusion reactors. Structural materials for fusion reactors are subjected to thermal, mechanical, chemical and radiation loads. A selection study for candidate materials may be extrapolated based on the experiences gained from fission reactors only to a very limited degree. The expected conventional loads appear higher for economically competitive fusion reactors. This includes ① higher operating temperatures, ② chemically aggressive coolants as energy carrier, such as molten salts, liquid lithium metal or eutectic lithium-lead, lithium-tin, and ③ furthermore magneto-hydro-dynamic effects. In addition to that, nuclear radiation loads for fusion reactors differ greatly from fission reactors. The latter are subjected to fission neutron flux with an average energy ~ 2 MeV and to gamma-ray radiation.

Structural materials of fusion reactors are subjected to unconventional loads, such as higher operating temperatures, chemically aggressive coolants, such as molten salts, liquid lithium metal or eutectic lithium–lead, lithium–tin, and magneto-hydro-dynamic effects. Furthermore, nuclear radiation loads for fusion reactors differ greatly from fission reactors. Especially at the first wall around the fusion chamber must withstand high energetic charged particle fluxes, Bremsstrahlung and gamma-ray radiation, and most importantly high energetic intense neutron fluxes of 14 MeV. Moreover, the structure should be compatible with lithium bearing coolants, such as natural lithium, $Li_{17}Pb_{83}$, $Li_{25}Sn_{75}$, Li_2BeF_4, $NaF \bullet LiF \bullet BeF_2$, $Li_2BeF_4 + UF_4$ and $Li_2BeF_4 + ThF_4$.

It is trivial that fusion reactor structures must be made of refractory materials. At modest neutron wall loads (NWL) ~5 MW/m² and wall temperatures <500 ℃, high level steel alloys can be considered. ODS and vanadium alloys tolerate higher temperatures up to ~600 ℃. Economically competitive fusion reactors must run with high NMW loads, where refractory metals, such as Nb1Zr a niobium-zirconium alloy (with 1% Zr), tantalum-tungsten-hafnium alloy T111 (with 8% W, 2% Hf) or the Titanium-Zirconium-Molybdenum alloy *TZM* (containing 0.5% Ti and 0.08% of Zr) must be considered. For extreme NWL (>30 MW/m²) and wall

temperatures (~1200 ºC) tungsten must be used. The higher the quality of the refractory materials is the higher will be the cost and the harder to machine with increasing order from Nb1Zr, T111, TZM and W being the costliest and hardest to machine.

A protective flowing liquid wall between plasma and solid first wall in these reactors can relax to a great degree the material selection. In this work, the nuclear waste actinide transformation, breeding capability of fusion hybrids, different structural materials and the effects of a protective flowing liquid wall are subject of investigations.

STRUCTURAL MATERIALS

Structural materials of fusion reactors are subjected to thermal, mechanical, chemical and radiation loads during reactor operation. Information and experiences coming from fission reactors related to the performance of structural materials can only be used at a very limited degree in material selection for fusion reactors as the expected loads will be higher for fusion reactors. This involves higher operating temperatures, chemically aggressive coolants, such as molten salts, liquid lithium metal or eutectic lithium–lead, lithium–tin, and magneto-hydro-dynamic effects. Furthermore, nuclear radiation loads for fusion reactors differ greatly from fission reactors. The latter are subjected to fission neutron flux with an average energy of ~2 MeV and to gamma-ray radiation. However, structural material of fusion reactor, especially at the first wall around the fusion chamber must withstand high energetic charged particle fluxes, Bremsstrahlung and gamma-ray radiation, and most importantly high energetic intense neutron fluxes with a mean energy of 14 MeV, which are expected to lead to much higher material damage than observed by fission reactors, not only due to higher neutron kinetic energy, but also, and even more important due to detrimental threshold reactions for structural materials in MeV range. Moreover, the structure should be compatible with lithium bearing coolants; natural lithium, $Li_{17}Pb_{83}$, $Li_{25}Sn_{75}$, Li_2BeF_4, $NaF \bullet LiF \bullet BeF_2$, $Li_2BeF_4 + UF_4$ and $Li_2BeF_4 + ThF_4$. In addition to those, the structural material should have the properties given briefly as below:

1) Attractive high temperature physical and mechanical properties, i.e., tensile strength, creep strength, impact toughness, and fatigue.
2) Reliable, predictable behavior for low rate deterioration of materials properties (ageing, corrosion), and tolerance for overloads.
3) Short repair and replacement periods.
4) Stability and recirculation for renewed application.
5) Suitability for shallow burial. Compatibility of the Activation criteria with 10CFR61 regulations
6) Broad compatibility with cooling fluids and gases.
7) Low neutron absorption cross sections.
8) Easy fabrication with multiple processes.
9) Acceptable inspectability of components.
10) Resistant to 14 MeV neutrons induced displacement damage (strength, ductility and toughness).
11) High heat conductivity, independent of radiation damage level.
12) Low swelling or void formation, dimensional stability.
13) Adequate mechanical properties before and after irradiation.
14) Operation at a wide temperature window.
15) Working at high temperatures.
16) Resistant to atomic displacement and helium generation damage.
17) Low activation property under 14 MeV neutrons.

Various engineering materials; austenitic stainless steels, ferritic/martensitic steels, vanadium alloys, refractory metals and composites have been suggested as candidate structural materials for nuclear fusion reactors. Among these structural materials, austenitic steels have an advantage of extensive technological database and lower cost compared to other non-ferrous candidates. Furthermore, they have also advantages of very good mechanical properties and fission operation experience. Moreover, modified austenitic stainless (Ni and Mo free) have relatively low residual radioactivity. Nevertheless, they can't withstand high neutron wall load which is required to get high power density in fusion reactors. On the other hand, a protective flowing liquid wall between plasma and solid first wall in these reactors can eliminate this restriction.

MATERIAL DAMAGE UNDER NEUTRON IRRADIATION

Material damage types under neutron irradiation can be classified under the main catagories of microscopic and macroscopic damage.

Microscopic Radiation Damage Effects
1. Atomic Displacement under Neutron Irradiation (DPA)

The displacement of an atom from its lattice position results from transferring to another position. The threshold energy is typically of the order of few dozens of electron volts. The displacement per atom (DPA) cross-section is the integral effect of displacements induced directly, by the neutron-nuclei interaction and, indirectly, via the interaction between high energy knocks on atoms and the target atoms in a cascade type process. Figure 2 shows DPA cross-sections for typical structural candidates as a function of neutron energy, evaluated from the CLAW-IV data library [1]. At lower neutron energies, DPA is relatively low and increase rapidly to higher values in MeV range. Fusion neutrons are generated by 14 MeV and the neutron spectrum in a fast breeder reactor (FBR) is around 400 to 500 keV. Hence atomic displacement damage in fusion reactors will be substantially higher than in FBRs. DPA in fusion reactor structure is expected to be at least 100 times higher than in FBRs.
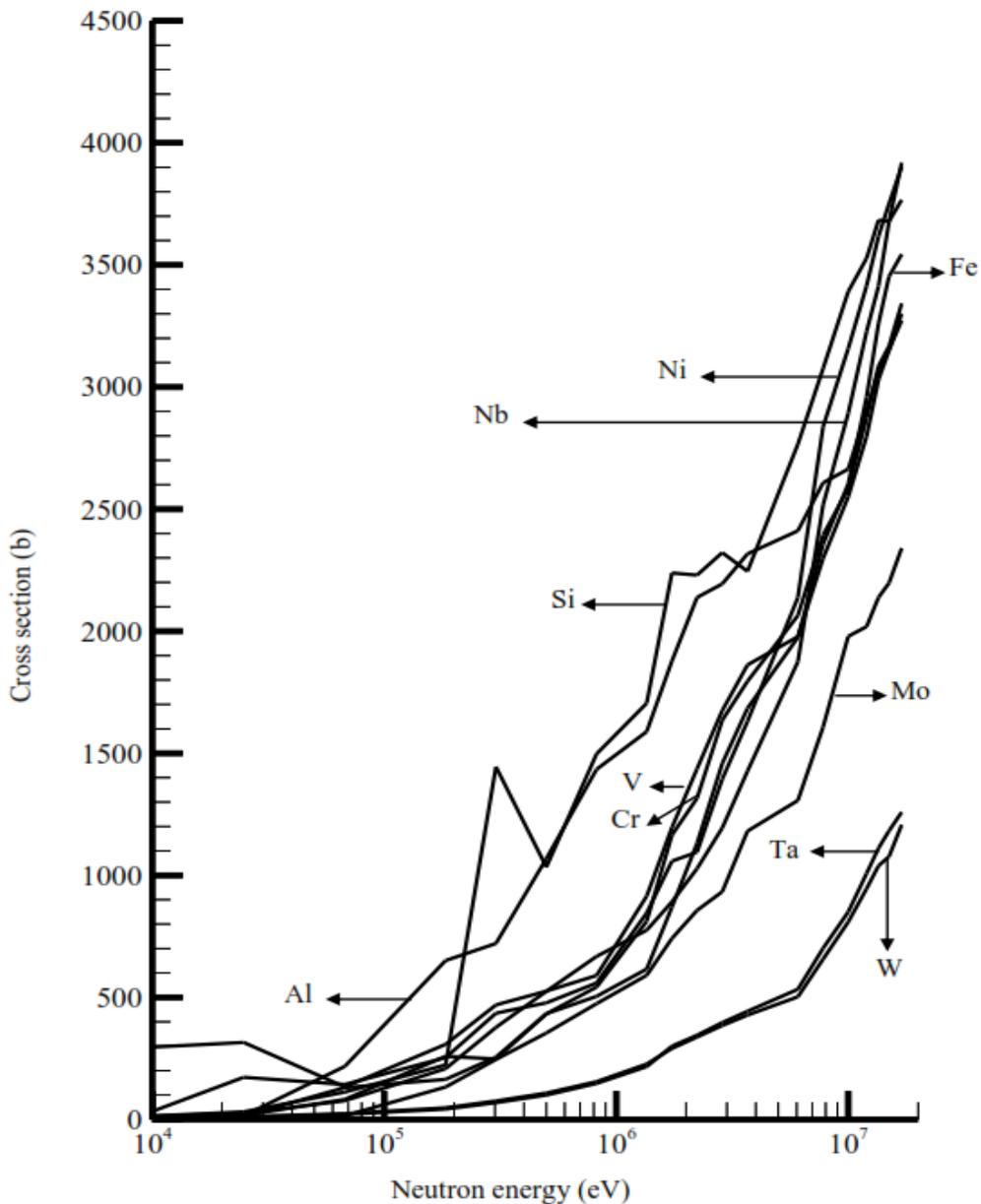

Figure 2. Atom displacement cross-section for structural material candidates

2. Gas Production

In fusion blankets, another very serious damage mechanism for structural materials will be gas production in the metallic lattice resulting from diverse nuclear reactions, mainly through (n,p) and (n,α) and to some extent through (n,d) and (n,t) reactions above a certain threshold energy. Materials suffer from embrittlement due to gas bubble formation even for fission applications, which is in general at lower MeV range. As the energy of the fusion neutrons with 14 MeV is significantly higher than the energy of the fission neutrons (~ 2 MeV), gas production in fusion reactors might build up at levels several orders of magnitude higher than in fission reactors. The hydrogen isotopes will diffuse out of the metallic lattice under high operation temperatures, but α-particle's will remain in metal and generate helium gas bubbles. These reactions will limit the lifetime of the first wall to few years.

Figure 3 depicts the helium production cross-sections for selected metals from the CLAW-IV data library [1]. The (n,α) cross-section has threshold energy for metals in MeV range. Therefore, helium gas production in fusion reactors will be substantially higher than in LWRs and in LMFBRs. Furthermore, helium production in some refractory metals, such as. V, Nb, W, is lower than in Fe, which is the main constituent of steel.
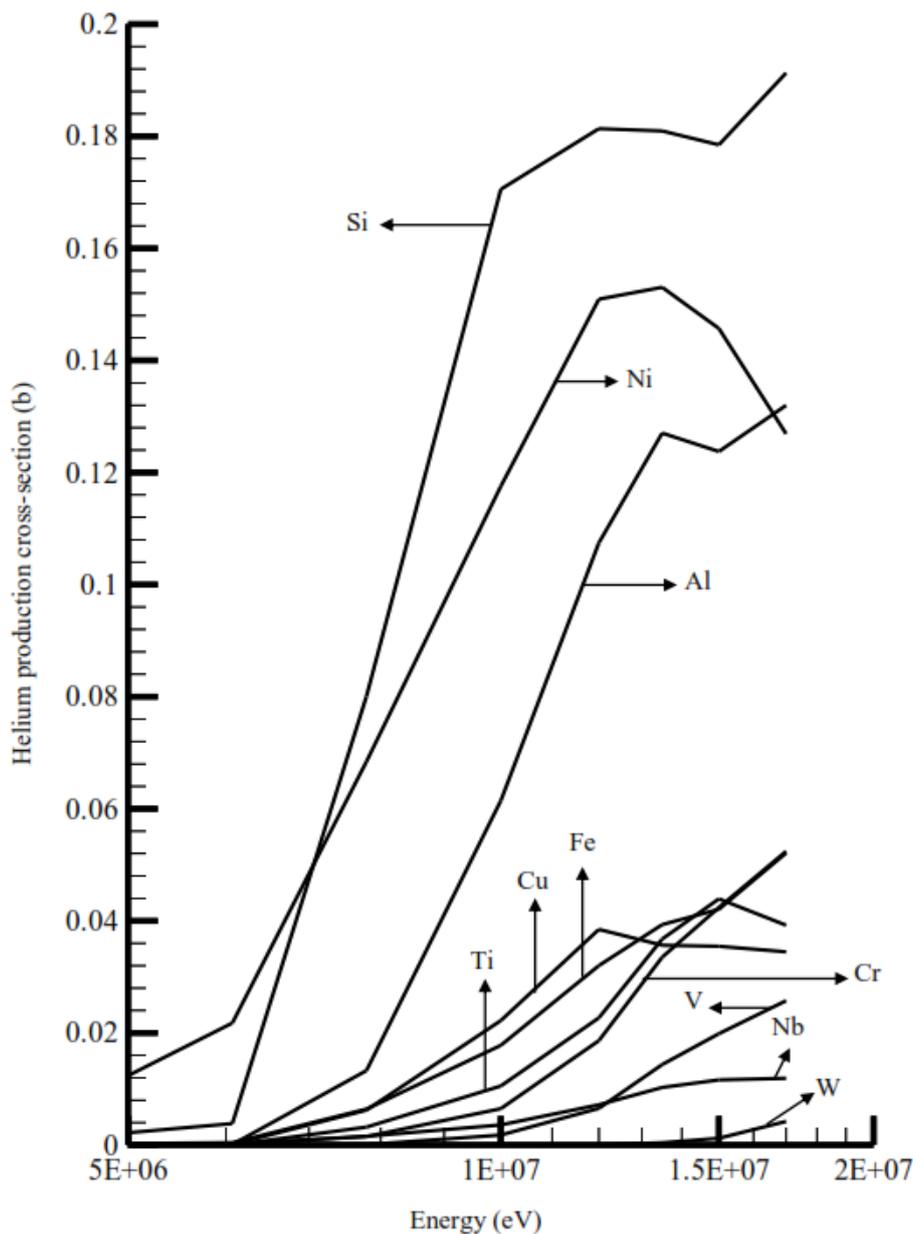

Figure 3. Helium production cross-section for structural material candidates

3. Nuclear transmutation

Foreign atoms production): Impurity atoms are produced by nuclear transmutations. Neutron capture in a reactor structure produces an isotope, which, in turn, may be unstable and produce an entirely new atom as it decays. For example, through single or successive neutron captures in the different isotopes of a specific element, titanium metal is transmutated to vanadium, vanadium to chromium, chromium to manganese, manganese to iron, iron to cobalt, cobalt to nickel, and finally nickel to copper. These transmutations alter, gradually, the metallurgical properties of the structures in the course of the plant operation. For most metallic materials long irradiations at high flux levels are necessary to produce significant property changes due to impurity buildup.

3.1. Micro Melting

Spikes are caused by the intense local heating as knocked-on atoms and fission fragments energize particles along their track. This may occur as high degree of excitation of the atoms without their leaving a stable lattice position (thermal spike) or as a shower of secondary displacements which drive interstitials into the surrounding lattice (displacement spike). In either case there is intense local heating with temperatures, sometimes rising well above the melting point. If melting occurs, the new lattice may form on the old lattice with new vacancies and interstitials replacing the original ones. Recrystallization and phase change may occur. The sudden cooling in a spike area for steel will result in the local formation of hard, brittle martensite! Localized melting, diffusion, and phase changes are all possible with such heating in the spike area.

3.1.2. Ionization Effects of Gamma Rays, or Charged Particles

Ionization effects are caused by the passage through a material of gamma rays, or charged particles. This is particularly important with materials which have either ionic or covalent bonding. Materials such as insulators, dielectrics, plastics, lubricants, hydraulic fluids, and rubber are among those which are sensitive to ionization. Plastics with long-chain-type molecules having varying amounts of cross-linking may have sharp changes in properties due to irradiation. Metals with shared electrons, relatively free to wander through the lattice, are affected very little by ionization.

Macroscopic Radiation Damage Effects

The microscopic radiation damage will lead to visible defect agglomerations. The radiation-induced changes in the microstructure finally lead to-mostly detrimental- changes in many macroscopic properties of materials in a nuclear environment. Some of them are of great technological importance since they can determine the lifetime of reactor components. Main macroscopic radiation damage effects are:

1. High-Temperature Embrittlement

High temperature embrittlement is mainly caused by the nucleation and growth of bubbles filled with (n,α)-produced helium. If located on grain boundaries, such bubbles can lead to intergranular failures accompanied by drastic reductions in the lifetime and ductility of reactor components. High-temperature embrittlement leads to Dimensional changes; swelling and irradiation creep. $(> 0.5 \ T_M)$

2. Low-Temperature Embrittlement

Low-temperature embrittlement results from an agglomeration by radiation-induced defects, leads to an increase in the yield stress! $(< (0.5 \ T_M$ "melting temperature in ^{o}K) and shift in the DBTT "Ductile-Brittle Transition Temperature".

2.1. Degradation of Material Properties
2.1.1. Dimensional Changes

The radiation-induced changes in the dimensions of materials are swelling and irradiation creep. Swelling in metallic material is caused by the nucleation and growth of vacancy agglomerates (voids). They appear in a temperature range of 0.3 to 0.5 of the melting temperature (T_M) and are due to a preferential absorption of interstitials at dislocations, leaving surplus of vacancies. The complex dimensional changes in graphitic materials are caused by strong lattice anisotropies parallel and perpendicular to the hexagonal planes, and they lead to

irradiation-induced positive and negative length changes. This irradiation-induced growth depends on a variety of defect reactions (cluster formation and disappearance) that depend on microstructure and temperature.

2.1.2. Changes in Mechanical Properties

It is assumed that the most severe degradation of mechanical properties in irradiated fusion materials is embrittlement. It is customary to divide this phenomenon into two groups: low-temperature ($0.5\,T_M$) and high-temperature ($0.5\,T_M$) embrittlement. This distinction is sensible because different mechanisms operate in the different temperature regimes: Low-temperature embrittlement is due to hardening by radiation-induced defect agglomerates that act as obstacles for dislocation movement. This leads to an increase in the yield stress and, particularly in body-centered cubic alloys, to a shift in the DBTT. Table 1 shows the temperature range of the main macroscopic radiation damage effects.

Table 1. Temperature range of the main macroscopic radiation damage effects.

Effect	Temperature	Important for
Segregation and changes in precipitation structure	$T > 0.2\,T_M$	Corrosion, weldability
Increase of DBTT	$0.1\,T_M < T < 0.3\,T_M$	BCC steels and refractory alloys for pressure vessels
Irradiation creep under mechanical load	$0.2\,T_M < T < 0.4\,T_M$	Most nuclear materials
Irradiation growth	$0.1\,T_M < T < 0.3\,T_M$	Non-cubic materials (Zr and its alloys, U, graphite)
Void swelling	$0.3\,T_M < T < 0.5\,T_M$	Austenitic steels
Helium high temperature embrittlement under creep and fatigue loads	$T > 0.45\,T_M$	First wall structures

TEMPERATURE LIMITS FOR FUSION REACTOR STRUCTURES

Structural materials under neutron and gamma ray irradiation have an unconventional behavior. Here, one can distinguish between lower (not observed by conventional heat machines) and upper temperature limits. The lower temperature limits are caused and strongly influenced by radiation effects. For BCC materials such as ferritic-martensitic steels and the refractory alloys, radiation hardening at low temperatures can lead to a large increase in the DBTT. For SiC/SiC composites, the main concerns at low temperatures are radiation-induced amorphization (with an accompanying volumetric swelling of ~11 %) and radiation-induced degradation of thermal conductivity. The radiation hardening in BCC alloys at low temperatures ($< 0.3\,T_M$) is generally pronounced even for doses as low as ~ 1 DPA. The amount of radiation hardening typically decreases with irradiation temperature $>0.3\,T_M$, and radiation-induced increases in the DBTT may be anticipated to be acceptable at temperatures above ~ $0.3\,T_M$ (although experimental verification is needed, especially for the Mo, W and Ta alloys).

The upper temperature limit for structural materials in fusion reactors may be controlled by four different mechanisms (in addition to safety considerations): Thermal creep, high temperature helium embrittlement, void swelling, and compatibility/corrosion issues. Figures 4 and 5 show the neutron wall load (NWL) for temperature-limited and stress-limited cases, respectively. These limits are defined as the values of the NWL at which the maximum operating temperature or design stress of the material is exceeded. The maximum operating temperatures for the materials with low residual radioactivity are: 550 °C for ferritic steel, 700 °C for ODS, 700 °C for V-Cr-Ti, 1000 °C for SiC-SiC composites. For higher temperature range refractory materials can be considered with maximum operating temperatures: 1100 °C for Nb1Zr, 1200 °C for TZM, 1300 °C for T-111, and 1500 °C for tungsten.
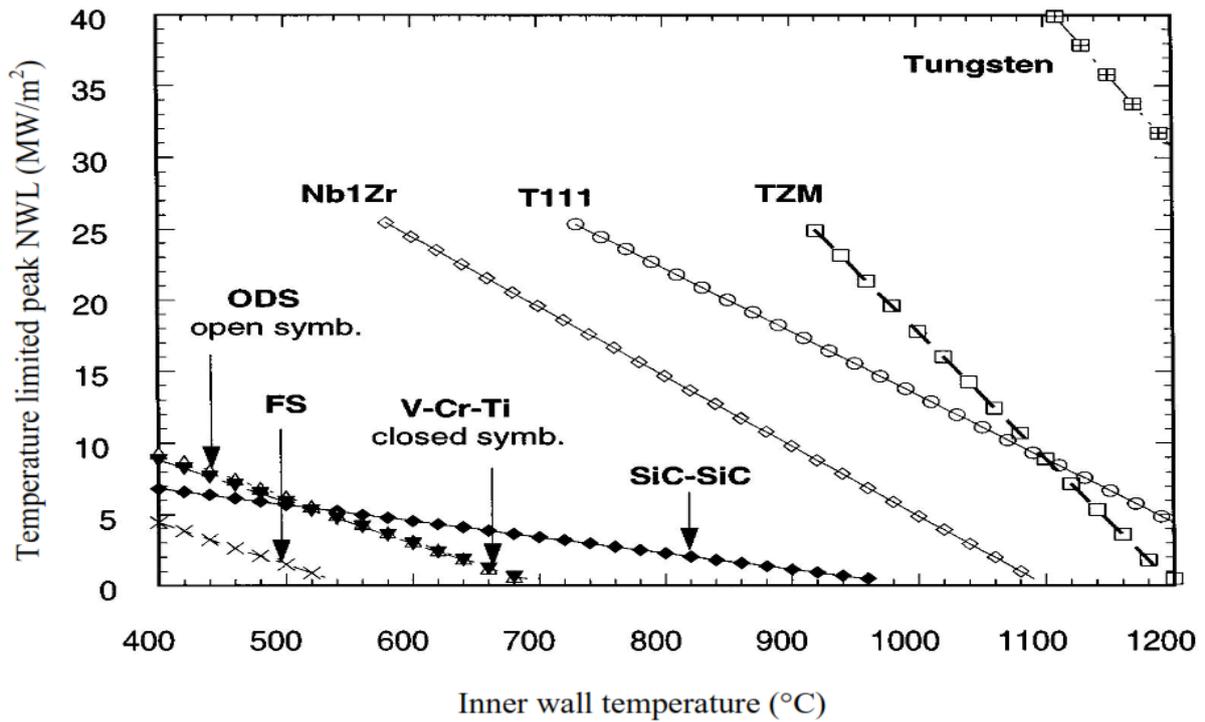
Figure 4. Temperature limited peak neutron wall limits for first wall materials with respect to inner wall temperature
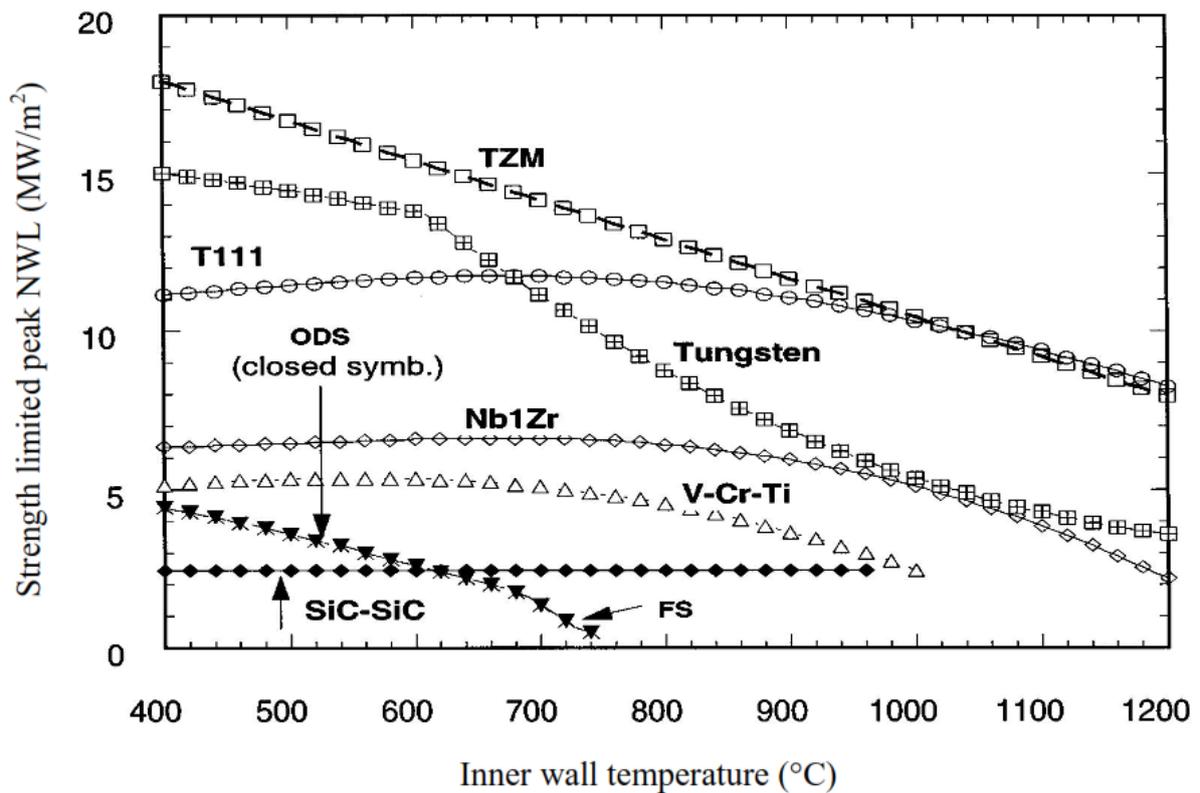

Figure 5. Strength limited peak neutron wall limits for first wall materials with respect to inner wall temperature

NUMERICAL CALCULATIONS WITH A PROTECTIVE LIQUID WALL

Innovative concepts with a protective liquid wall inside the fusion plasma chamber can unify several advantages, namely ① achieving very high neutron load values, ② along with low maintenance costs due to the

largely extended lifetime of the first wall structure (the most sensitive and very expensive component of a fusion reactor), using ③ low cost steels structures, ④ based on wide technological data base, and ⑤ with a low residual radioactivity. A FLIBE zone of ~ 50 cm thickness as flowing wall liquid protection in front of the solid ODS first wall reduces material damage below permissible limits. It allows shallow burial of structure after final reactor decommissioning.

The calculations are conducted for a fusion power generation of 1 GW_{el} over 30 years of reactor operation with a thermos-dynamical conversion efficiency of 35 % leading to 2.857 GW_{th} by a capacity factor of 100 %. High energetic 14 MeV-(D,T) fusion neutrons are the main damage source on the first wall and other structures. The neutron transport calculations are conducted with the help of SCALE6.2 code package by solving the Boltzmann transport equation with code XSDRNPM [2] in S_8-P_3 approximation with Gaussian quadratures (Şahin, 1991) and using the 238 groups library, derived from ENDF/B-V [3]. One of the candidates as structural material is the oxide dispersed steel (ODS). At first, a fusion-fission (hybrid) with a multi-layered spherical blanket has been investigated, which is composed of a first wall made of oxide dispersed steel (ODS, 2 cm); neutron multiplier and coolant zone made of LiPb; ODS-separator (2 cm); a molten salt FLIBE coolant and fission zone; ODS-separator (2 cm); graphite reflector. Without an internal liquid wall protection, major damage mechanisms have been calculated as DPA = 50 and He = 170 appm per year at the ODS first wall. This will oblige to change the ODS first wall every ~ 3 years. Hydrogen production is calculated as 650 appm/year. Hydrogen will diffuse out of the structure by high operation temperatures. The alternative version to include a FLIBE zone of ~ 50 cm thickness as flowing wall liquid protection in front of the solid ODS first wall reduces material damage below permissible limits. It allows shallow burial of structure after final reactor decommissioning.

In the second phase, LiPb coolant zone behind the first wall has been removed. But instead, a flowing liquid protective first wall is included in front of the solid first wall in order to reduce material damage and residual radioactivity after final disposal of the latter. The flowing protective liquid wall in front of the solid wall will relax the radiation load and so extend the life-time and reduce the production cost of the latter. In that case, SS-304 type steel, SiC and graphite can be considered as structural materials of magnetic fusion energy (MFE) reactor blankets. Figure 6 shows the calculation model of the investigated multi-layer blanket. The SiO_2 zone (#10) serves as thermal shield.
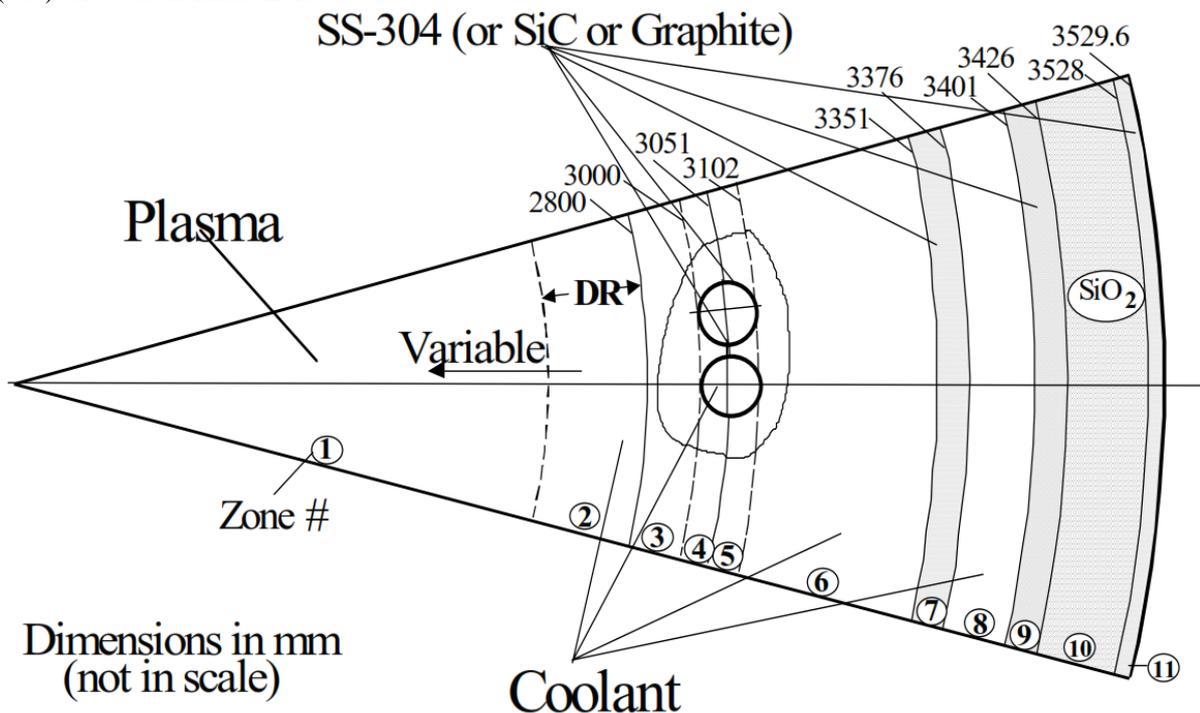

Figure 6. Calculation model of the investigated fusion reactor blanket

Different types of liquid coolant with tritium breeding capabilities (FLIBE, $Li_{17}Pb_{83}$, natural lithium, all with natural lithium component) are investigated to protect the first wall from neutron- and Bremsstrahlung

radiation and fusion reaction debris. Figure 7 shows the DPA values over the plant operation period with SS-304 as structural material. One can see highest protection against atomic displacements in the steel structure with FLIBE, whereas $Li_{17}Pb_{83}$ and natural lithium reveal poor performance.
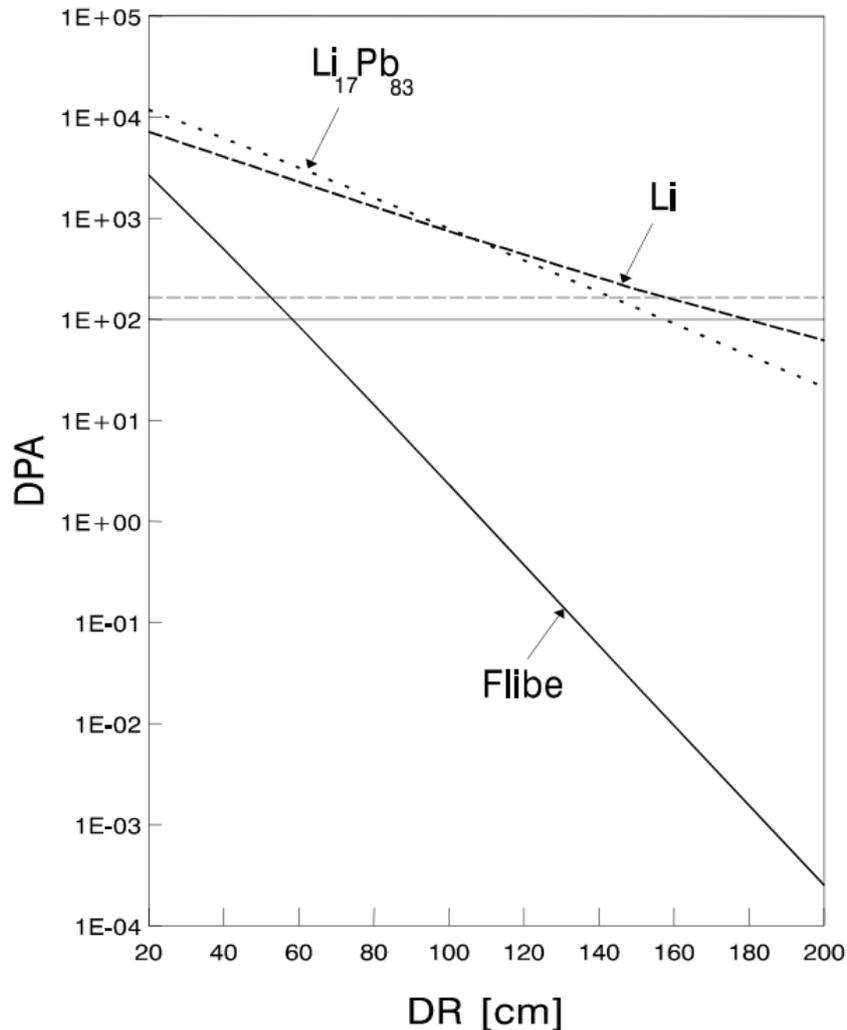

Figure 7. Displacement per atom (DPA) in the SS-304 first wall over 30 years versus coolant thickness (DR)

Figure 8 shows the accumulation of helium gas in the SS-304 as structures over the plant operation period. FLIBE and $Li_{17}Pb_{83}$ both provide highest protection against helium production in the SS-304 as structures, but natural lithium fails. Calculations have led to the following liquid wall thickness requirements under consideration of the mainline design criteria;

1. ~ 60 cm FLIBE, ~ 160 cm $Li_{17}Pb_{83}$, ~ 180 cm natural lithium and for material protection measured on displacement per atom (DPA < 100 after 30 years of operation), and ~ 60 cm FLIBE, ~ 60 cm $Li_{17}Pb_{83}$, ~ 150 cm natural lithium measured on helium gas production (He < 500 appm after 30 years of operation),
2. ~ 40 cm Flibe, ~ 80 cm $Li_{17}Pb_{83}$, ~ 40 cm natural lithium for sufficient tritium breeding (TBR = 1.1),
3. ~ 50 cm FLIBE, ~ 160 cm $Li_{17}Pb_{83}$, ~ 140 cm natural lithium for a shallow burial index (SBI = 1).

Such a blanket would strongly reduce the shielding for super conducting coils around the fusion plasma chamber and would open the possibility of utilization of conventional stainless steel for fusion reactors due to the sufficiently low residual radioactivity in the structural materials after decommissioning of the plant.

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5. ~ 40 cm Flibe, ~ 80 cm $Li_{17}Pb_{83}$, ~ 40 cm natural lithium for sufficient tritium breeding (TBR = 1.1),

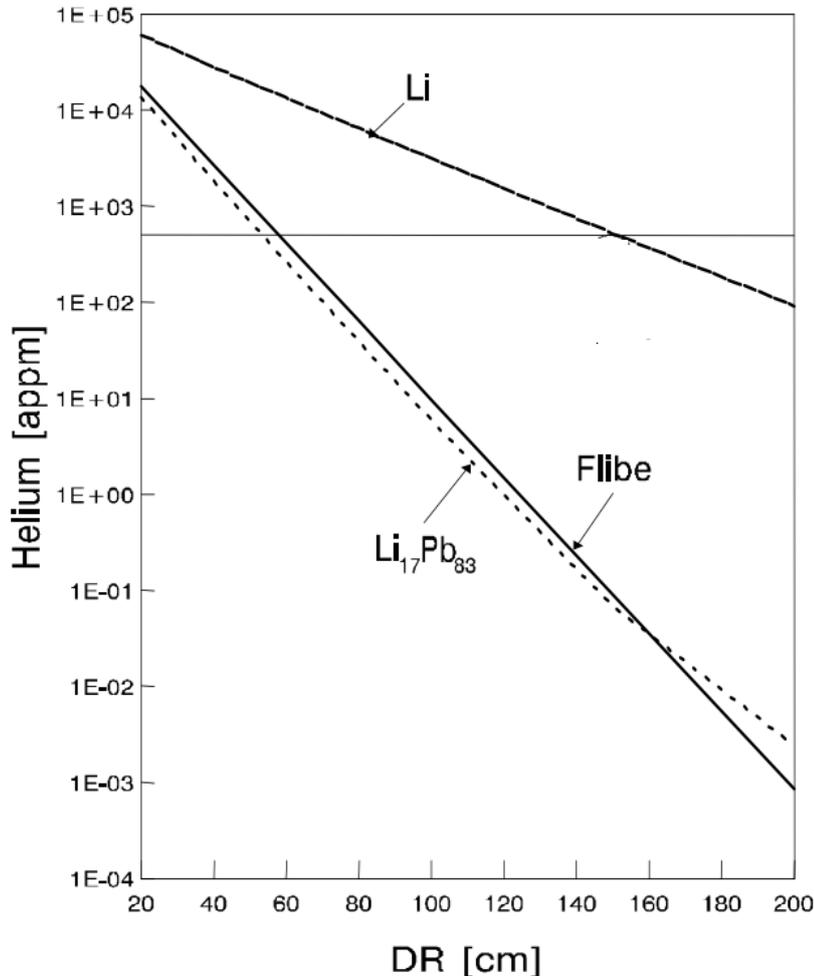6. ~ 50 cm FLIBE, ~ 160 cm $Li_{17}Pb_{83}$, ~ 140 cm natural lithium for a shallow burial index (SBI = 1).

Figure 8. Helium production in the SS-304 first wall over 30 years versus coolant thickness (DR)

Such a blanket would strongly reduce the shielding for super conducting coils around the fusion plasma chamber and would open the possibility of utilization of conventional stainless steel for fusion reactors due to the residual radioactivity in the structural materials after decommissioning of the plant conform to the 10CFR61 regulations for the shallow burial disposal of the radioactive waste [4,5].

CONCLUSIONS

A variety of structural materials has been investigated for the first wall of fusion reactors. Main conclusions of the study can be summarized as follows:

- Steels have the highest data base and the most advanced technology experience, furthermore lowest cost among other candidate materials. They are preferred structural materials for working temperature up to 500 to 600 °C and medium neutron wall loads values < 5 MW/m^2.
- SiC and carbon fibers are also strong candidates. However, they are not yet reached technological maturity for widespread applications.

- High neutron wall loads and high operation temperatures require refractory materials, such as vanadium, chromium alloys and tungsten. They are extremely difficult for fabrication and cause high costs.

- A flowing protective liquid first wall can increase the life of the solid first wall over the entire plant life time, allows shallow burial repository after plant decommissioning. In that case steels can be considered as solid first wall.

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