Materials Engineering Challenges in Fusion Reactors

Presentation · March 2020

DOI: 10.13140/RG.2.2.33744.46087

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"Materials is the queen technology of any advanced technical system. The economics eventually depend upon the materials, the reliability depends on the materials and safety depends upon the materials. I assure you that before we are through with fusion, the physicists will give way to the materials engineers as being the leading lights of fusion."

–E.E. Kintner
Director of U.S. Fusion Program 1975-81

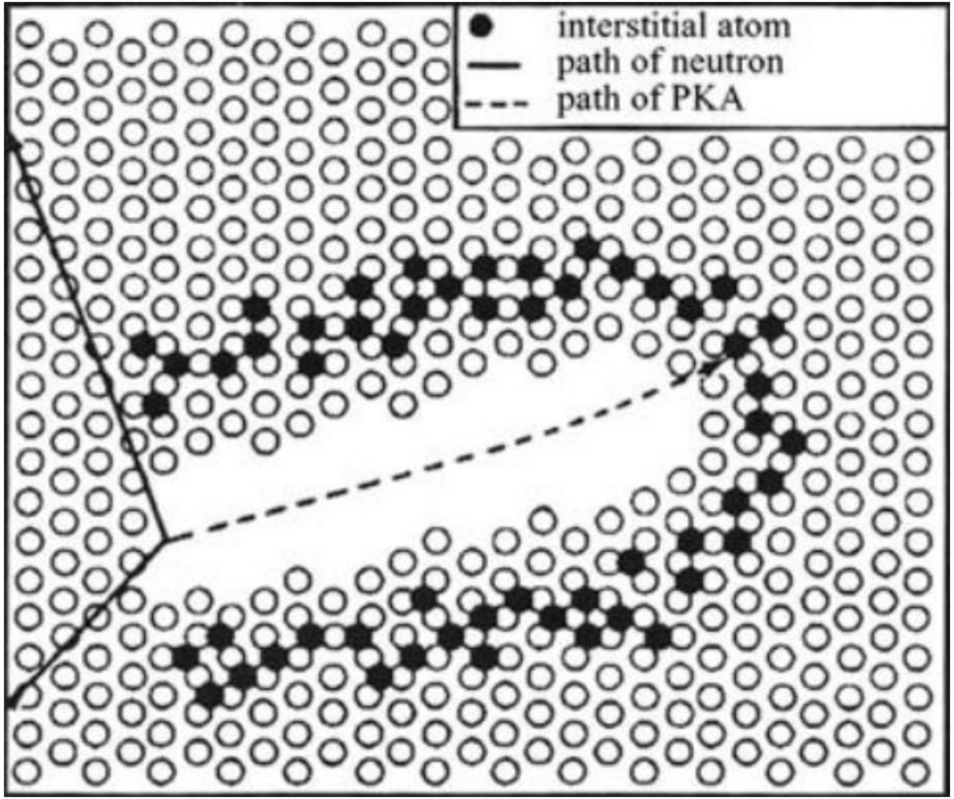
Topics

1. *Radiation Damage and Effects*
2. *Plasma-Materials Interactions (PMI)*

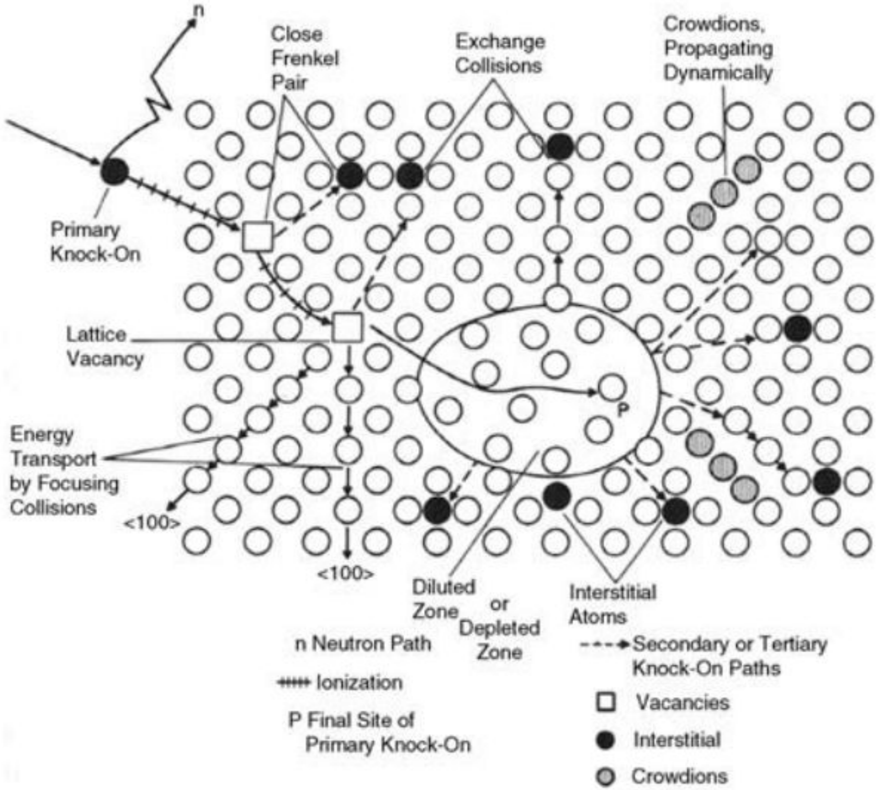
1. Radiation Damage and Effects

Fast Neutron Damage

- *80% of the DT fusion reaction energy is carried off by 14 MeV neutrons.*
- ***The damage takes two principal forms:***
    - *Due to collisions, lattice atoms are displaced, creating vacancies and interstitials, and initiating displacement cascades [displacements per atom (dpa)].*
    - *The (n, α) and (n, p) reactions occur, resulting in the formation of gases (He and H) within the lattice and changing its elemental composition [atomic ppm (appm)].*



Brinkman's picture (1956)



Seeger's refined picture (1962)

Radiation Defects

- *Impurity atoms: produced by transmutation.*
- *Thermal spikes: regions with atoms in high-energy states.*
- *Displacement spikes: regions with vacancies and self-interstitials.*
- *Depleted zones: regions with vacancy clusters (depleted of atoms).*
- *Voids: large regions devoid of atoms.*
- *Bubbles: voids stabilized by gases.*
- *Replacement collisions: scattered self-interstitials falling into vacancies after dissipating their energies through lattice vibrations.*

From Micro Damage to Macro Effects

- *Atomic-level radiation damage occurs within microseconds and leads to effects that take from minutes to months to show up on the bulk of the material.*
- *Some effects have incubation periods which makes them hard to detect.*

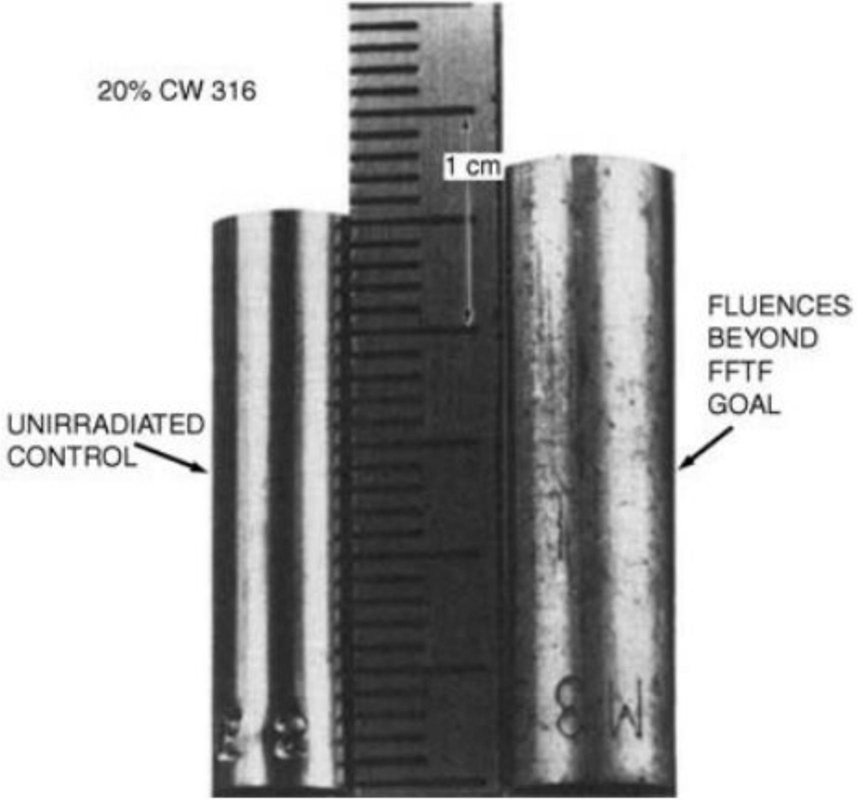
Radiation Effects

Swelling

- *Materials swell due to voids and bubbles.*

Growth

- *Carbon has an enormous advantage as a neutron moderator, but suffers from strong neutron-induced growth, leading to elongation at 10-20 dpa.*



Radiation Effects

Embrittlement

- *Stainless steel suffers total loss of ductility by 100 dpa and 6,000 appm He.*
- *Long before this point, the ability of a 1000-m^2 steel vacuum vessel, subject to thermal cycling, to maintain vacuum integrity will have been lost.*

Fatigue

- *Pulsing of the magnets "works" the metal, inducing fatigue and potential failure.*
- *The role of radiation in this process is little understood.*

Radiation Effects

Creep

- *Many of the structural components, such as the vacuum vessel, are subject to high stress and high temperature, resulting in plastic deformation over long periods: creep.*
- *The creep rupture lifetime of stainless steel is reduced 50% by neutron irradiation.*
- *Even a small plastic deformation will make component disassembly and replacement difficult or even impossible.*

Radiation Effects

Induced radioactivity

- *While DT fusion burns clean, i.e., the fuel ash itself is not radioactive, the neutron bombardment of the reactor walls induces radioactivity via transmutations.*
- *The radioactive (structural) waste to be disposed of at the time of decommissioning the reactor would be less than the radioactive (fuel-ash-plus-structural) waste from a fission system.*
- *Therefore, a strong incentive exists to use "exotic" metallurgies, such as that of vanadium, for fusion structural components.*

2. Plasma-Materials Interactions (PMI)

Plasma-Materials Interactions

- *PMI are the most understood of all fusion materials problems.*
- *This is due to the fact that while the neutron damage and breeding blanket materials questions relate to future machines, PMI occur in the operating ranges of current devices.*
- *Central plasma temperatures can exceed 10^8 K.*
- *The insulating effect of the magnetic field supports a strong temperature gradient across the plasma.*
- *Edge plasma temperatures, i.e. of the plasma in actual contact with the walls, fall to 10^6 K, which is still high!*

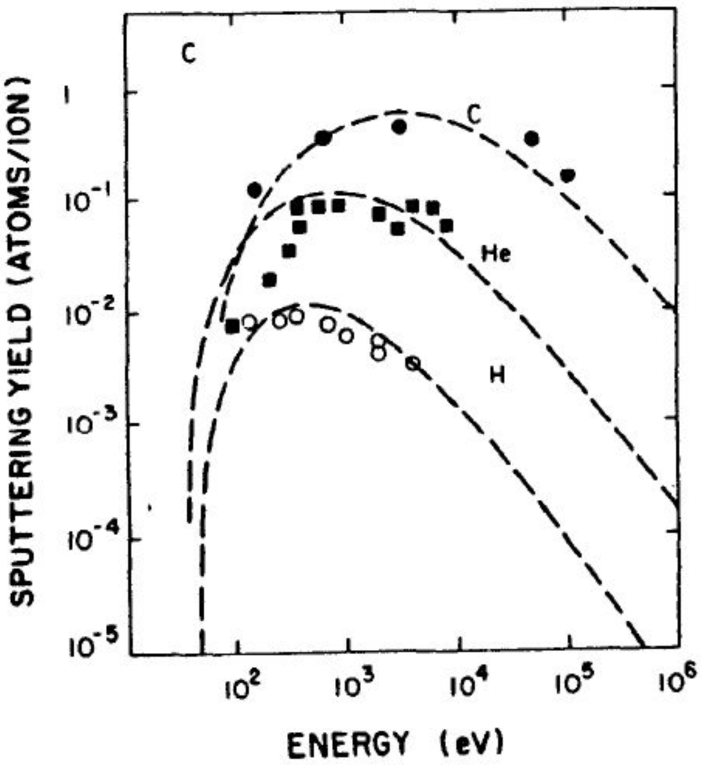
Sputtering

- *PMI leads to erosion of the surface due to a number of processes, the most seriuos of which is physical sputtering.*
- *Physical sputtering is the result of momentum transfer from the fast-moving plasma particles to atoms in the solid lattice, knocking them out.*
- *This erosion process is quantified by the experimentally measured yield [atoms/ion], which is dependent on the elemental composition of projectile and substrate, and the projectile energy.*

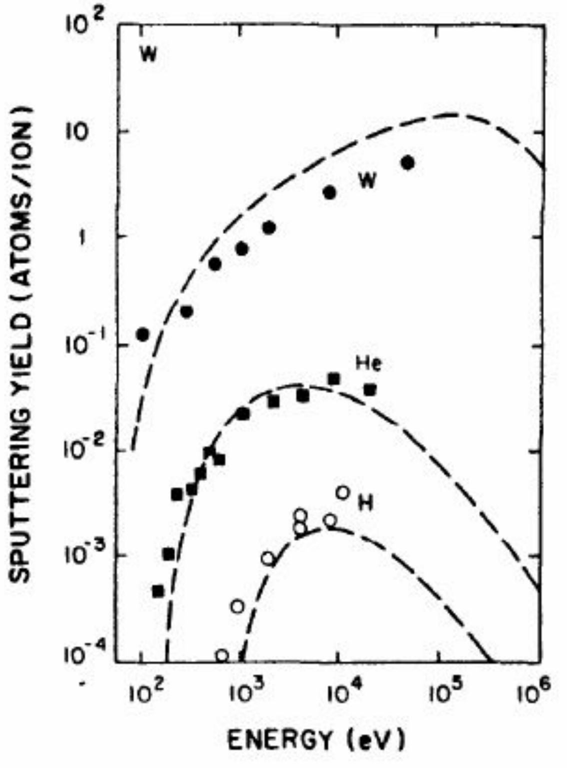
Sputtering

- *Removal rates may exceed 1 atom/ion for impacting energies of ~100 eV.*
- *Initially, only the hydrogenic ions cause sputtering.*
- *The sputtered impurity atoms are quickly ionized upon entering the plasma, and in steady-state return to the solid surface at the same rate, causing self-sputtering.*
- *Since impurity ions carry more momentum than hydrogenic ones, their sputtering yield is higher.*

Sputtering



Sputtering of C by H, He and C ions



Sputtering of W by H, He and W ions

Sputtering

- *Removal rates may exceed 1 atom/ion for impacting energies of ~100 eV.*
- *Initially, only the hydrogenic ions cause sputtering.*
- *The sputtered impurity atoms are quickly ionized upon entering the plasma, and in steady-state return to the solid surface at the same rate, causing self-sputtering.*
- *Since impurity ions carry more momentum than hydrogenic ones, their sputtering yield is higher.*

Sputtering

High erosion rates are unacceptable for at least three reasons:

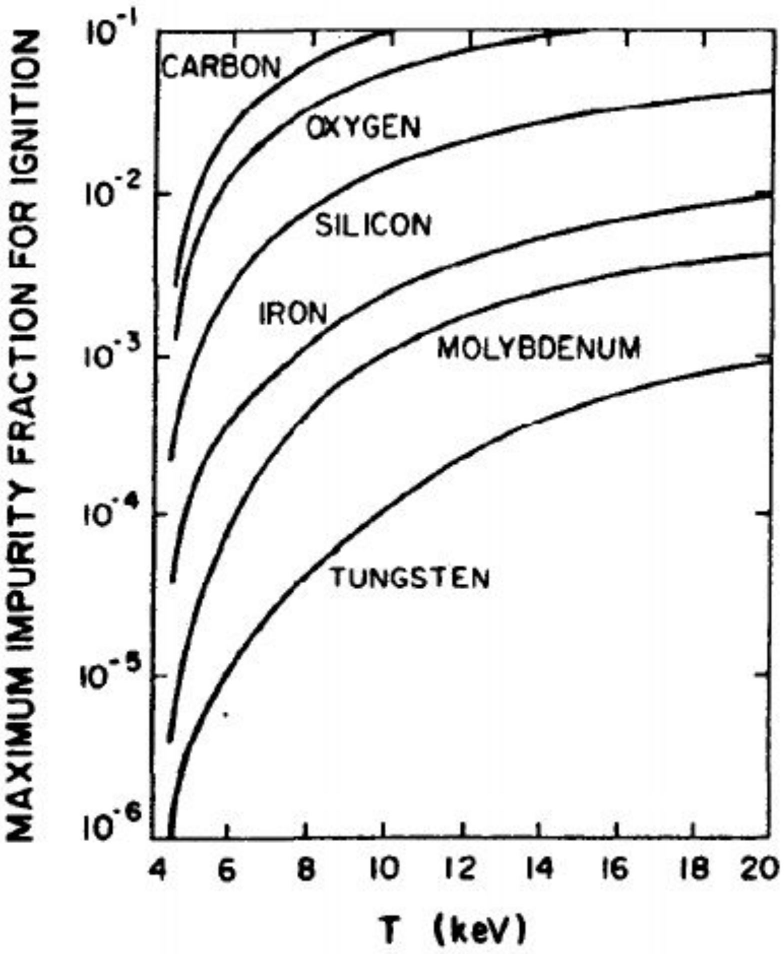
1. *The wall material, present in the plasma as an unwanted impurity, radiates away the plasma heat content, preventing net energy production.*
2. *The wall wears out and its frequent replacement is not compatible with economic plant operation.*
3. *Gasified impurities such as methane enter the exhaust/clean-up system, which extracts unburnt tritium and returns it to the plasma in a completely pure form.*

Radiative Cooling

- *The fusion flame is so hot, yet so vulnerable.*
- *This vulnerability is a valuable safety feature: any departure from designed operating conditions of a fusion power reactor will increase the PMI, contaminating and extinguishing the flame.*
- *Fusion plasmas radiate X-rays due to electrons colliding with nuclei in the plasma. The power of this collisional radiation varies as* Z^2.

Radiative Cooling

- *This figure indicate the maximum tolerable impurity fraction for ignition of a DT plasma versus temperature for various impurity species.*
- *Ignition is the point at which plasma self-heating rate by the fusion reaction equals the radiative cooling rate.*



Other Effects Caused by Impurities

Fuel dilution

- *High-Z impurity ions fill the plasma with many extraneous electrons.*
- *Each electron adds to the plasma pressure as a D/T fuel ion, and since the confining pressure exerted by the magnetic field, $B^2/2\mu_0$, is limited, the result is fuel dilution.*
- *Since the fusions power, P_F, varies as $n_D n_T$, i.e., n_{fuel}^2, a small impurity fraction reduces P_F enormously, even for low-Z impurities.*
- *For example, 5% carbon reduces n_{fuel} by ~30%, hence P_F by ~50%.*

Other Effects Caused by Impurities

Density limit

- *Finite magnetic pressure aside, one would think that n_{fuel} could be raised to any desired level simply by puffing more D_2 or T_2 into the plasma.*
- *Unfortunately, an upper density limit occurs for stable operation of the plasma at plasma pressures only a small fraction of the available magnetic pressure: ~1%.*
- *The cause of this serious limit is not completely understood, but is almost certainly due to impurities, since purer plasmas have higher density limits.*

Other Effects Caused by Impurities

Re-deposition

- *In addition to self-sputtering, when sputtered ions hit the surface they can aslo be re-deposited.*
- *Whatever surface is initially introduced into the device, it will quickly become a re-deposited surface, with its own unique properties.*
- *It is therefore important to carry out materials tests on re-deposited materials created in conditions identical to a working device.*

To Recap

- *Due to radiation damage and plasma-materials interactions, the elemental composition and mechanical properties change.*
- *Most of these changes are only understood qualitatively.*
- *Test facilities are needed for more quantitative understanding, and more research is needed to develop modelling techniques and improve existing ones.*
- ***From swords to tokamaks, the materials science guy will always have a job.***

Thanks!