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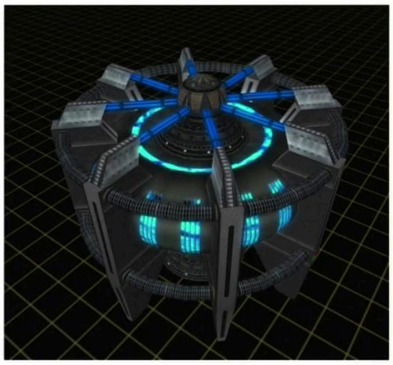
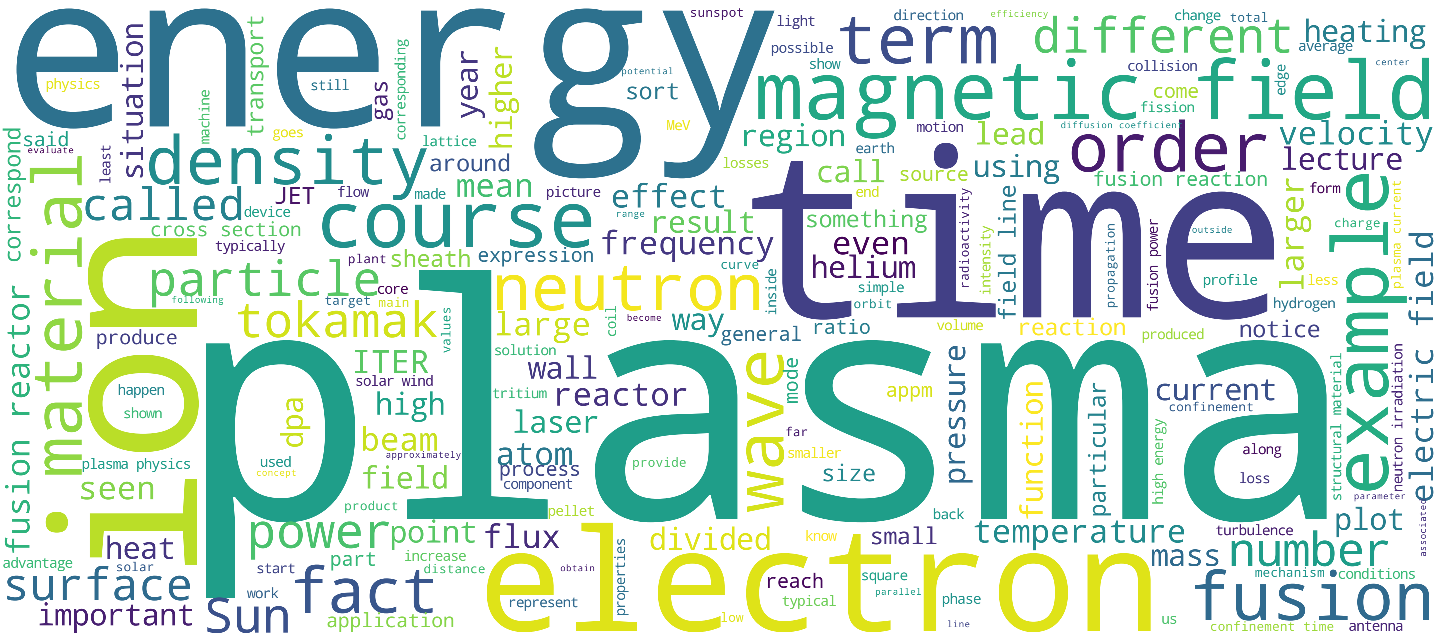


Fusion: the issue of structural materials

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 6f

Ambrogio Fasoli



Search MOOC

Video

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Introduction

- Requirements for fusion materials
- Fusion vs. fission
- Effects of 14 MeV neutrons
- Evolution of materials properties
- Candidate structural materials
- How to test fusion materials

Plasma

Welcome to the course on Plasma Physics and Applications. In the last lecture we have seen elements of the plasma wall interaction problem. We have seen how important is the choice of the first wall materials. Today, still in a simple way, we will look at each of the structural materials for fusion reactors. We will look at the requirements of these materials to satisfy. We will look at a small comparison between fusion and fission materials and the constraints that both cases have to satisfy, have to withstand. We will look at the effects of the high-energy neutrons that are issued by the fusion reactions and the evolution of the material properties under the neutron irradiation at these energies. We'll look at the candidate structural materials we have in mind for constructing the first reactors. And finally, how to test fusion materials and why we need to test fusion materials today.

Notes

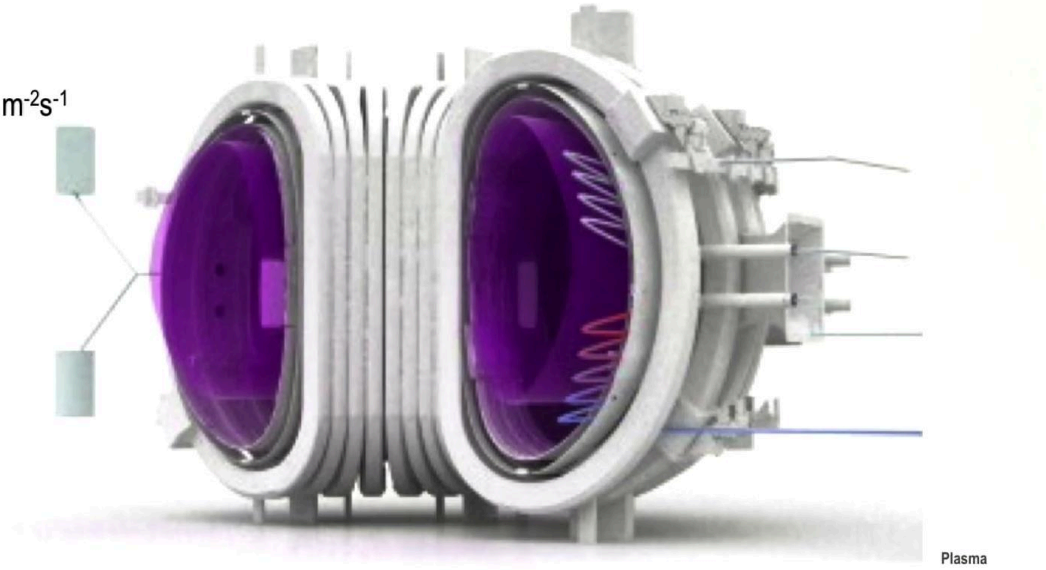
Summary

0m 05s

Requirements for reactor structural materials

Withstand very large fluxes of 14.1MeV neutrons

Ex. DEMO
flux ~ 10^{19}-10^{20} neutrons $m^{-2}s^{-1}$
fluence ~ 5MW y m^{-2}



First of all, reactor materials have to withstand a very large flux of high-energy neutrons, particularly 14.1 MeV neutrons. For example, in DEMO, we expect a flux between 10^{19} and 10^{20} neutrons per square meter per second. If we translate that into a fluence that is an integrated value, in this case we express that as a power times a time per unit surface, we have something like five megawatts year per square meter. That's a very very large value compared to the machines we have today.

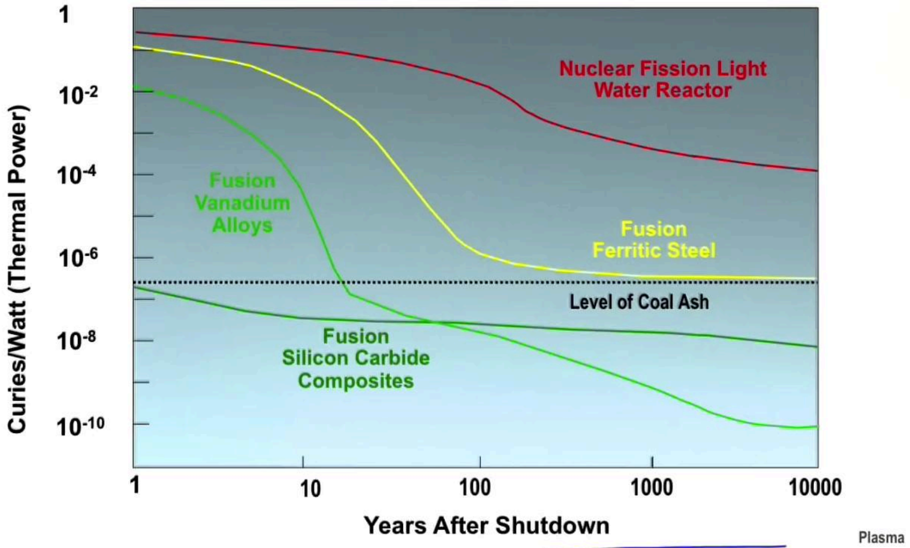
Notes

Summary

1m 00s

Requirements for reactor structural materials

As low activation as possible



As we have said in the lecture that introduced fusion in general and particularly its advantages, the reactor materials must have as low activation as possible because that's one of the key advantages of fusion with respect to fission. This is the same plot we have seen at that lecture, representing the radioactivity of a plant as a function of the number of years after it's shut down. Now remember that we said that the nuclear fission light-water reactor will be remaining at a very high level of radioactivity for thousands of years after it's shut down. That would be incompatible with a sustainable development approach. Fusion would have the advantage that activation would be much, much more short-lived. For materials that we know today, ferrritic steel, for example, we would have hundreds of years or even less for the radioactivity to reach the levels equivalent to coal ashes. But, if we need to reduce the activation even further we need to go to more advanced materials. And that's where the quest is on for the future generations of fusion reactors. For example, vanadium alloys in this plot or silicon carbide composites, in which case, the problem of radioactivity after the shut down of the plant is completely removed.

Notes

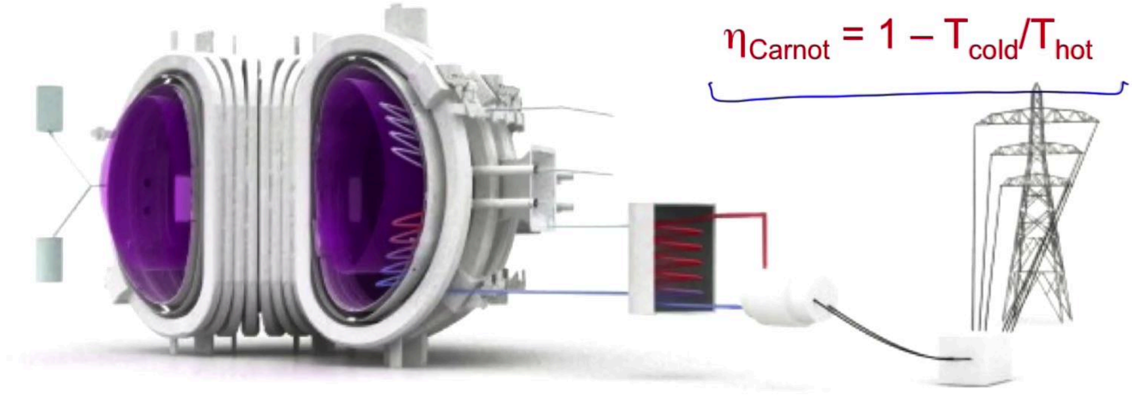
Summary

1m 39s

Requirements for reactor structural materials

Operate at the highest possible temperatures to optimise thermal efficiency of power plant

$$\eta_{Carnot} = 1 - T_{cold}/T_{hot}$$



Plasma

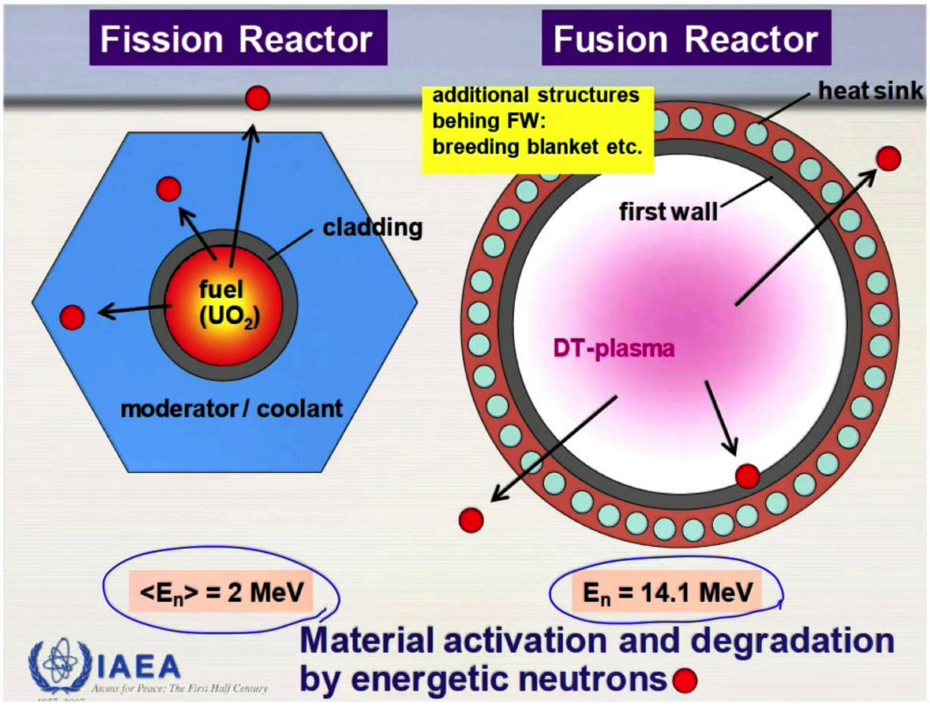
The reactor materials have to operate at the highest possible temperature simply based on the quest for the thermal efficiency. We all remember that the idealized Carnot cycle has an efficiency which is one minus the ratio of the cold and hot reservoirs temperatures. And of course the hot temperature, here, is that of the coolant which is embedded in the structural materials of the fusion plant that are incorporated in the blanket. So, the higher the temperature, the more efficient the reactor will be.

Notes

Summary

3m 01s

Fusion vs. fission



Courtesy of R.Kamendje

Plasma

Let's look briefly at a comparison between fusion and fission. Fission has a hot core, which is the fuel, for example UO_2 in this plot, surrounded by the moderator and the coolant. And the power fluxes that we are typically encountering in a fission reactor, first of all, they are steady states so they are stable in time, they don't vary, and second of all, they are of the order of 1MW/m². Fusion, on the other hand, has the problem that the power fluxes are, even in steady state, much higher, typically an order of magnitude higher. But also, fusion has these violent events, or transients, that we have discussed in the previous lecture that can reach thousands of MW/m², a gigawatt per square meter (1 GW/m²,) in terms of the wall loading. These are very short-lived, nevertheless very dangerous for the integrity of the materials. The second main difference between fusion and fission in terms of the materials, is that the spectrum of the neutrons is quite different. So in fission, if we take the average of the neutron energy, typically of the order of 2 MeV, whereas in fusion, as we know, the neutrons are produced at 14.1 MeV, from the DT reaction. So we have a much higher energy. Much higher energy for the neutrons, which translates into a higher activation, but, even more important, to a higher degradation of the material properties.

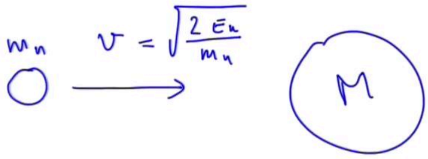
Notes

Summary

3m 39s

Effects of 14MeV neutrons

Mechanical effect of neutron of energy E_n hitting atom of mass M at rest in lattice



Max energy transfer $E_{max} = E_n \frac{4 m_n M}{(m_n + M)^2} \overset{m_n \ll M}{\sim} E_n \frac{4 m_n}{M}$

Ex. iron $M = 56$ amu ; $E_n = 14.1$ MeV

Plasma

Let's evaluate very simply, first, the mechanical effects of the neutrons, that they can have on the material atoms in the lattice, So, take a neutron of energy En that hits an atom of mass M, which is at rest in the lattice. We consider sort of a 1D situation, that's my neutron, we have a velocity that is associated with its energy, and it will hit an atom M, I draw it bigger because the atom will be, of course, of a larger mass that we suppose to be at rest in the lattice. And now we evaluate, based on a very simple theory of elastic collisions, that is, collisions that conserve energy and momentum, the maximum energy transfer in this event. So the maximum energy transfer, let's call it Emax, is given by the energy of the neutron times four times the product of the masses divided by the square of the sum of the masses. This is really simple elastic collisions theory. Now, the mass of the neutron is much smaller than the mass of our atom, so we can write that's equal to En, energy of the neutron, times four times its mass divided by the mass of the atom. Let's take now numbers, examples. I'll take Iron, so M is 56 atomic mass units (amu) and I'll take a neutron issued by a fusion reaction, that is a neutron with an energy of 14.1 MeV.

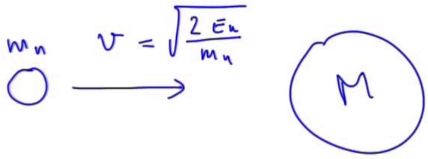
Notes

Summary

5m 23s

Effects of 14MeV neutrons

Mechanical effect of neutron of energy E_n hitting atom of mass M at rest in lattice



Max energy transfer $E_{max} = E_n \frac{4 m_n M}{(m_n + M)^2} \overset{m_n \ll M}{\sim} E_n \frac{4 m_n}{M}$

Ex. iron $M = 56$ amu ; $E_n = 14.1$ MeV

$E_{max} \sim 14.1 \times 10^6 \frac{4}{56} \simeq 1$ MeV $\gg E_{Wigner}$ (~ 25 eV)

└ threshold displacement energy

$\Longrightarrow$ iron atom is displaced and ejected from lattice !

Plasma

The max energy transfer, Emax, will be 14.1 x 10⁶, times 4 divided by 56, that's about 1 MeV. We notice this energy is very large, and it is, indeed, much higher than the so-called Wigner energy, which is typically about 25 eV. This Wigner energy is the threshold value for the energy at which we have a displacement of an atom. So this is the *threshold displacement energy*. So that means that the Iron atom will be displaced and ejected from the lattice.

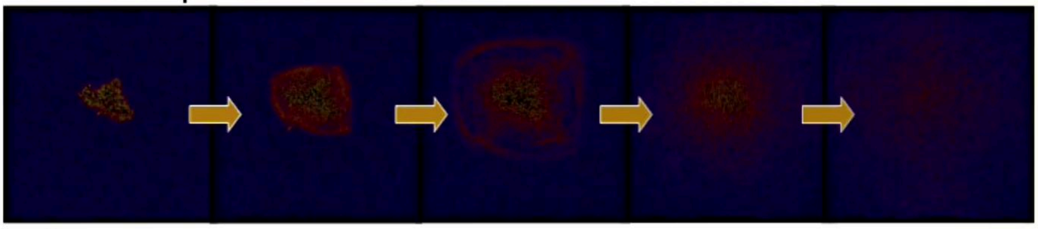
Notes

Summary

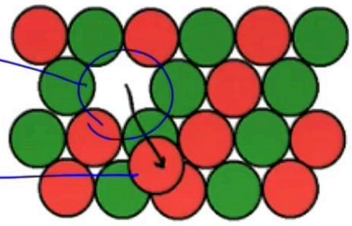
7m 05s

Effects of 14MeV neutrons

As $E_{max} >> E_{Wigner}$, the primary knock-on atom initiates a series of other knock-on events, leading to an atomic displacement cascade



- Point structure defects
  - The ejected atom leaves behind a vacancy and goes to an interstitial location (Frenkel pair)



- Damage is quantified in displacements per atom (dpa)

Plasma

And because this energy that is exchanged in a collision is much larger than the Wigner energy, much, much larger, this primary atom that is displaced, called the *primary knock-on atom*, will initiate a series of other knock-on events. And that will lead to what we call an atomic displacement cascade. So it's sort of a shower of displacements across my material. And this is shown in the simulation here. So the result is that we have a series of so-called *point structure defects* because the ejected atom will leave behind a vacancy, that is, a hole, there. And it will go somewhere where it doesn't belong to, and that somewhere is called an *interstitial location*. The pair formed by the vacancy and interstitial location is called a *Frenkel pair*. Now this sort of effect, I can call it damage because it damages the properties of the material is quantified in a unit called *dpa*, or displacements per atom. So this is the average number of displacements that the atom undergoes under the irradiation.

Notes

Summary

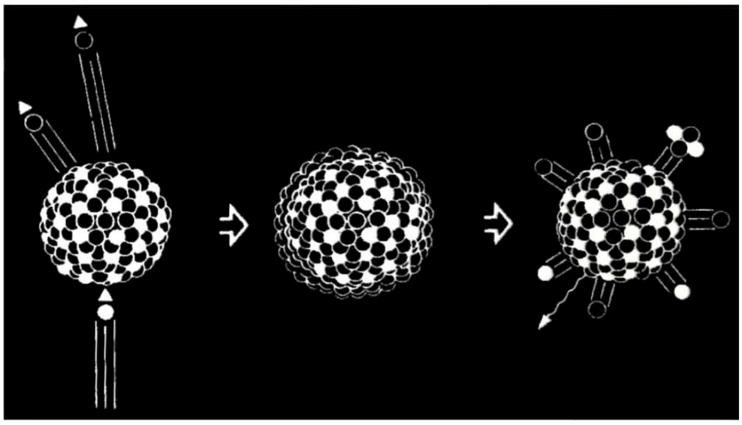
8m 08s

Effects of 14MeV neutrons

Transmutation nuclear reactions

- Generation of impurities
  He and H gas atoms

- Results in embrittlement
  of grain boundaries, void swelling



- Effect is quantified in atomic parts per million (*appm*) of He or H

Plasma

That was sort of the mechanical effect of the neutron hitting the atoms in the lattice, but the neutron will also cause nuclear reactions, in particular transmutations. These reactions will generate impurities in the form of helium or hydrogen gas. And the creation of gas inside the material lattice will result in embrittlement, embrittlement of grain boundaries, in particular, and swelling of the voids. So here the problem is the generation of helium and hydrogen impurities, and so this effect is quantified in atomic parts-per-million of helium or hydrogen, or *appm*. So we have the displacement per atom, *dpa*, that quantifies the mechanical damage and atomic parts-per-million resulting from the nuclear reactions of helium or hydrogen that quantify the effect of transmutations.

Notes

Summary

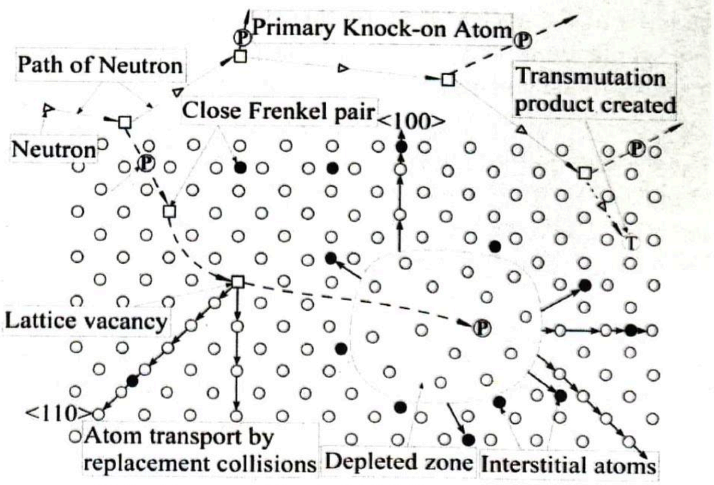
9m 30s

Effects of 14MeV neutrons

Important modifications of the microstructure lead to significant degradation of macroscopic chemical, physical and mechanical properties

First wall of fusion reactor (P_f~3GW)
~ 20-30 dpa/year in steels
ITER will reach ~ 3dpa at the end if its life

~ 10-15 appm He/dpa
~ 40-50 appm H/dpa
Much higher appm/dpa ratio than in fission



Peter Haasen , Physical Metallurgy, CUP 1996

Plasma

So we do have important modifications of the microstructure and these modifications will lead to a significant degradation of the macroscopic properties, chemical, physical, and mechanical. Here is again a figure that represents a sequence of possible events, the creation of a Frenkel pair, that is, a vacancy and an interstitial location, and a transmutation and also the migration of these defects across my lattice. And just to give you an example of orders of magnitude of the numbers involved in a fusion reactor, let's take a fusion reactor with a fusion power of 3GW. That will lead to a neutron irradiation effect of say, 20 to 30 dpa per year in steels. And just to compare that to what we are about to see in ITER, ITER at the end of its lifetime will only reach a few dpa. So this is really a completely different situation, that of an actual fusion reactor, much, much higher radiation of neutrons and therefore much, much more severe effects. In terms of the creation of helium and hydrogen in the reactor of that kind we will expect something like 10 to 15 appm of helium per dpa and 40 to 50 appm of hydrogen per dpa.

Notes

Summary

10m 33s

Effects of 14MeV neutrons

Important modifications of the microstructure lead to significant degradation of macroscopic chemical, physical and mechanical properties

First wall of fusion reactor (P_f~3GW)
~ 20-30 dpa/year in steels
ITER will reach ~ 3dpa at the end if its life

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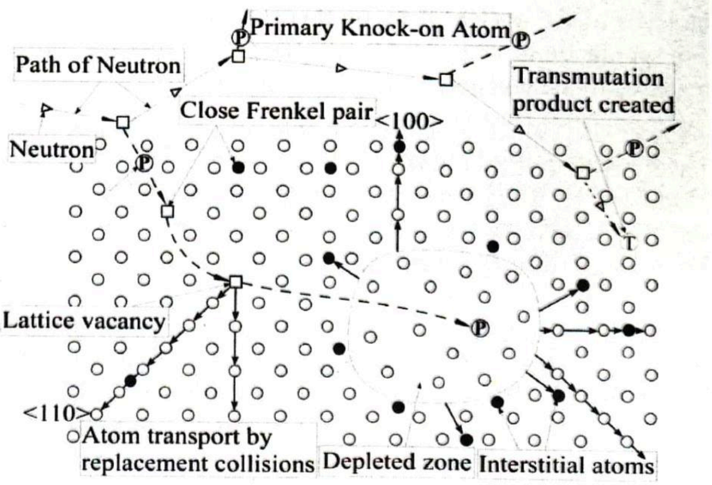


Peter Haasen , Physical Metallurgy, CUP 1996

Plasma

We notice of course that dpa's and appm's are related which complicates the dynamics of the whole process, or the whole set of processes and also makes it difficult to really calculate and simulate *a priori* what the effects can be. I also notice that these ratios of appm's to dpa's are much higher in fusion than in fission.

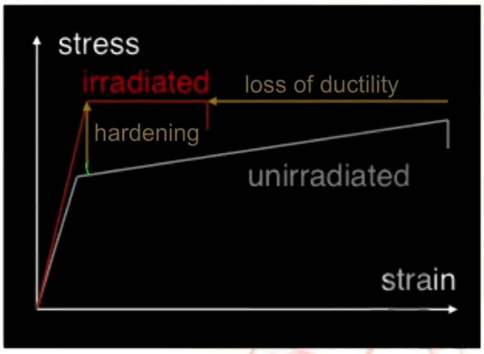
Notes

Summary

12m 00s

Evolution of materials properties – 14MeV neutrons

- Change in the chemical composition
- Physical properties – important for functional materials
  - Decrease of electrical conductivity (low temperatures) and of thermal conductivity (ceramic materials)
- Mechanical properties – important for structural materials
  - Loss of creep strength, change in ductile to brittle transition T
  - Embrittlement (hardening, loss of ductility, loss of fracture toughness)



Plasma

So in terms of the macroscopic material properties the 14 MeV neutrons will change, first of all, the chemical composition, will change the physical properties of the material, this is very important for material that has to perform a certain function. For example, the electrical conductivity will be decreased as well as the thermal conductivity, typically for surrounding materials. So this is something to be aware of when designing pieces that have to accomplish a particular function in the reaction. At least as importantly, the flux of 14 MeV neutrons will also influence mechanical properties. This is very important for structural materials, of course. There will be a loss of creep strength, that is, the resilience to long-time scale deformations. There will be a change in the transition temperature between ductile and brittle, and there will be, in general, a very severe effect of embrittlement. For example, there will be hardening. Hardening is represented here in this plot as the result of the change in the slope of the curve of stress versus strain. There will be a loss of ductility, which is represented by this arrow here.

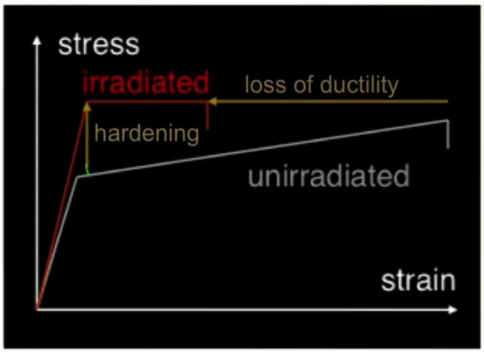
Notes

Summary

12m 26s

Evolution of materials properties – 14MeV neutrons

- Change in the chemical composition
- Physical properties – important for functional materials
  - Decrease of electrical conductivity (low temperatures) and of thermal conductivity (ceramic materials)
- Mechanical properties – important for structural materials
  - Loss of creep strength, change in ductile to brittle transition T
  - Embrittlement (hardening, loss of ductility, loss of fracture toughness)



Plasma

So this is the shortening of the plastic region for the deformation, and therefore a loss of the toughness to fractures, so the fracture limit will come down in terms of the value of the strain. So this is a set of very severe effects on the mechanical properties of the material.

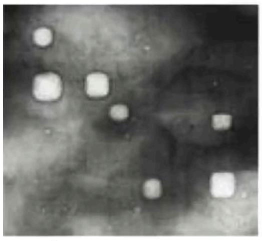
Notes

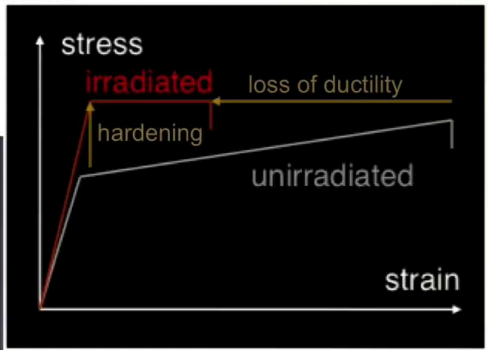
Summary

13m 46s

Evolution of materials properties – 14MeV neutrons

- Change in the chemical composition
- Physical properties – important for functional materials
  - Decrease of electrical conductivity (low temperatures) and of thermal conductivity (ceramic materials)
- Mechanical properties – important for structural materials
  - Loss of creep strength, change in ductile to brittle transition T
  - Embrittlement (hardening, loss of ductility, loss of fracture toughness)
- Mechanical dimensions
  - Swelling, irradiation creep





Plasma

There will also be actually a literal change of dimensions of the mechanical pieces. There will be swelling due to the radiation, due to the bubbles that will be created inside the lattice due to the generation of gas. There will be so-called irradiation creep, this is a slow deformation under irradiation of neutrons. And all of this will alter the physical structure of the materials.

Notes

Summary

14m 09s

Structural materials for fusion

- Candidate structural materials must have a chemical composition based on low activation elements: Fe, Cr, V, Ti, W, Si, C
- Based also on safety, waste disposal, and performance considerations, the leading candidate structural materials are
  - → Reduced activation ferritic/martensitic steels
  - → Vanadium alloys
  - → Tungsten alloys
  - → SiC/SiC composites

Plasma

So let's go to the possible choices that we have for the materials for fusion. We have said we want a low activation material, so we have to have low activation elements in the chemical composition of our candidate structure materials. For example; iron, chromium, vanadium, titanium, tungsten, silicon, and carbon. We also have to consider safety, waste disposal, and performance, both in terms of mechanical and thermal considerations in order to make our choice. So if we consider all of that the leading candidates for DEMO and for the reactors are listed here. So we have the reduced activation ferritic/martensitic steels as possible candidates, something we are already quite close to achieving, really good properties, vanadium alloys, a little more advanced, tungsten alloys and silicon carbide composites would be the lowest in terms of the activation under neutron irradiation, so it would be the preferable solution, in long-term, at least.

Notes

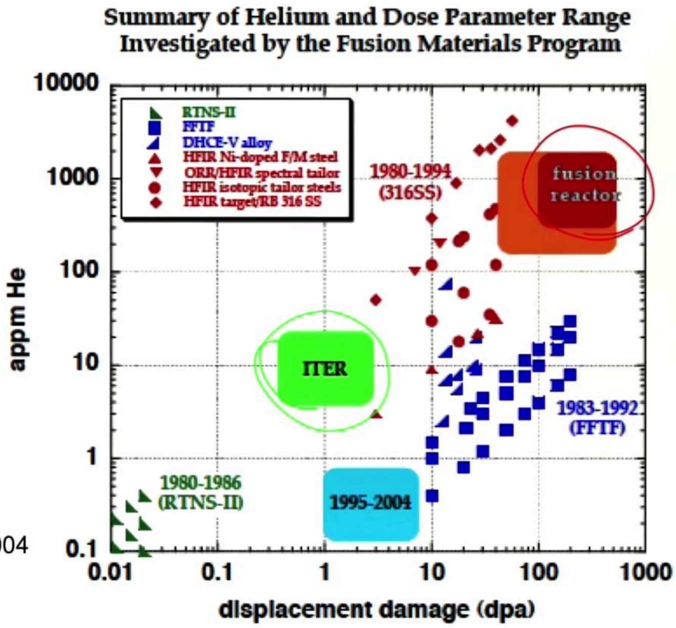
Summary

14m 38s

Need to test materials for fusion

- Experimental knowledge of materials behavior in fusion reactor conditions is very limited
  - Extrapolations from current conditions to fusion regime is much larger for fusion materials than for core plasma parameters

S.Zinkle, APP-DPP 2004



Plasma

I'd like to comment on the need to test materials for fusion. Because of what we have seen at the beginning of this lecture, that is, the fact that in fusion the spectrum of the neutrons is very different from that of fission and also the flux and fluence are very different. We have very little, if none, experimental knowledge of materials' behavior in conditions that are equivalent to what we expect for a fusion reactor. I'd like to highlight that in the plot here where we show the set of possible tests that have been done or will be done in materials on the axis in vertical of appm in helium and horizontal on dpa. Now we notice ITER is here in green, but the fusion reactor will work in a very different set of conditions. There will be a huge factor in the appm in Helium and a huge fhctor in the dpa. So even when we learn something from ITER in terms of the materials properties and the neutron irradiation from fusion, we'll be really very far from being in a regime that's of relevance for the reactor. And the point that's often made by materials scientists is that the extrapolation from current conditions to fusion regime is much larger, much bigger of a jump, than it is for the core plasma parameters.

Notes

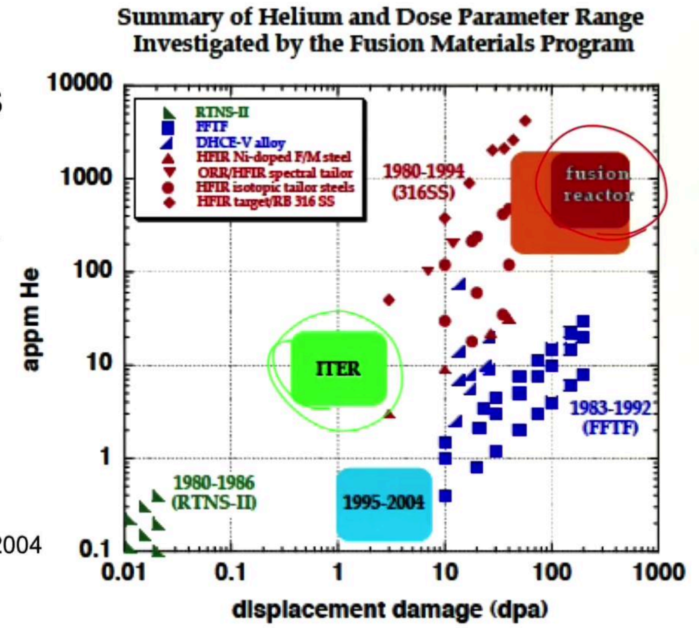
Summary

15m 44s

Need to test materials for fusion

- Experimental knowledge of materials behavior in fusion reactor conditions is very limited
  - Extrapolations from current conditions to fusion regime is much larger for fusion materials than for core plasma parameters

S.Zinkle, APP-DPP 2004



Plasma

So we are much further away from knowing the properties and materials and the neutron irradiation in fusion than we are from knowing the properties of the core plasma based on present experiments and present experimental knowledge.

Notes

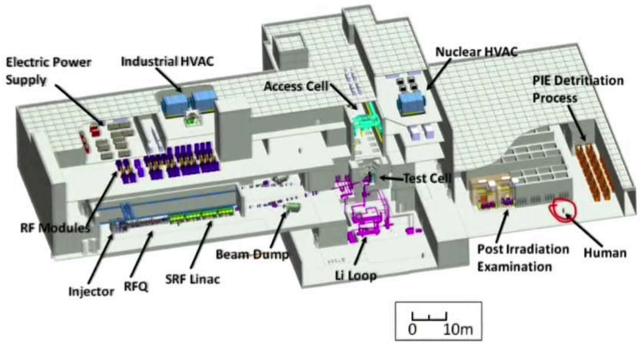
Summary

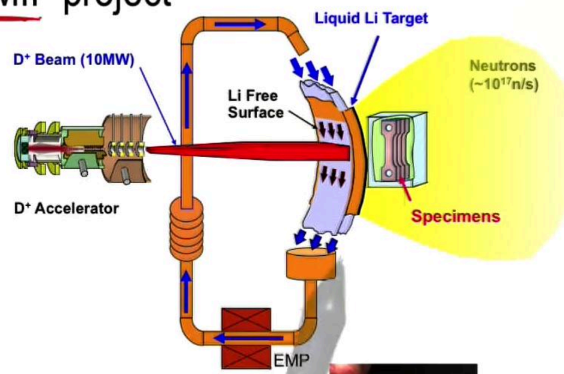
17m 16s

Need to test materials for fusion

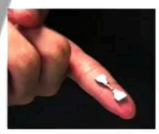
Urgency of fusion materials tests is universally recognized

- Volumetric neutron sources, e.g. low fusion gain tokamak (component test facility)
- Accelerator based irradiation facilities; the IFMIF project





- Must extrapolate results obtained in small volume (0.5l at 20dpa/y) to large reactor: small specimen test technology



Plasma

Which is why, I think, it's fair to say that we universally recognize the need to go expeditiously toward tests of materials for fusion. There are two approaches that can be taken, in fact can be taken in parallel. We can think of volumetric neutron sources, for example, fusion tokamaks that don't need necessarily to have a high gain, because all they need to do is to produce a large neutron flux. Of course, of the same spectrum as you anticipate for the reactor, that is, neutrons produced by DT. This is something we refer to as components test facility, there are several ideas and several designs that have already been considered around the world. And in parellel with that we can actually consider facilities based on accelerators. An example of that is the international IFMIF project that's under design and discussion. This is an accelerator-based test facility, you can see the size of it, this is a human being, very very small compared to the overall size of the installation. The main part of this facility here is the accelerator, which accelerates a beam of deuterium ions. That beam is then made to impinge on the liquid lithium target which will therefore generate neutrons of a similar spectrum to those that we anticipate for the DT reactors.

Notes

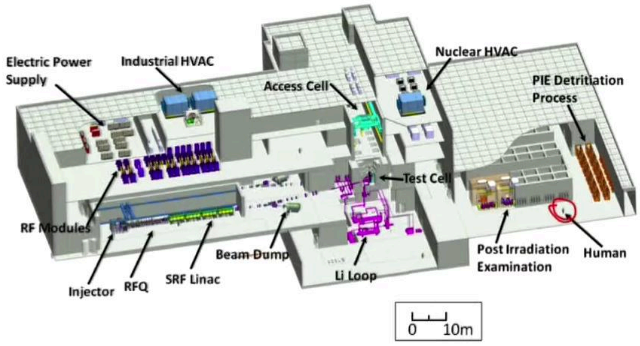
Summary

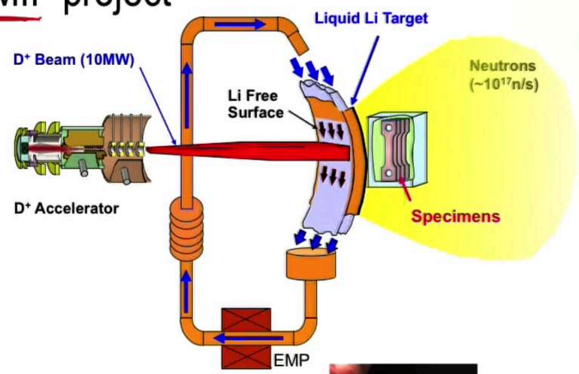
17m 33s

Need to test materials for fusion

Urgency of fusion materials tests is universally recognized

- Volumetric neutron sources, e.g. low fusion gain tokamak (component test facility)
- Accelerator based irradiation facilities; the IFMIF project





- Must extrapolate results obtained in small volume (0.5l at 20dpa/y) to large reactor: small specimen test technology

Plasma

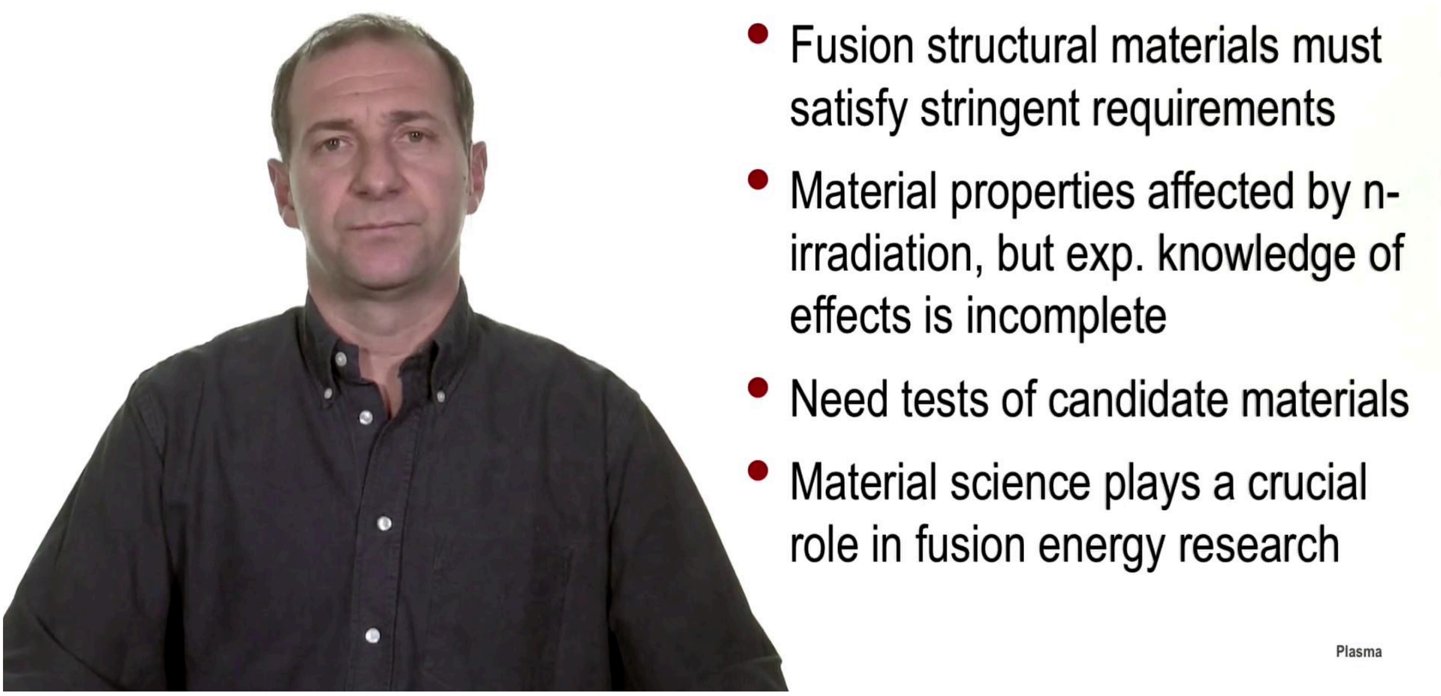
An interesting issue is that there will be only a very small volume that will be subject to the irradiation, irradiation levels that are, say, reactor-relevant. So a volume that will go up to 20 dpa or so per year, after a year of full operation, by the way, will be less than a liter, will be typically half a liter. And so there actually is sort of a scientific discipline that will teach us how to extrapolate the results obtained in such a small volume, with specimens that are very small as in this example in the picture, to the behavior of a very large structural material construction such as that that we need for the fusion reactor. This is so-called *small specimen test technology*.

Notes

Summary

19m 08s

Summary



In summary, we have had a relatively simplistic and quick discussion of the problem of materials in fusion. Nevertheless, we have been able to identify a few key elements. Fusion materials really must satisfy a number of stringent requirements. The material properties are severely affected by the irradiation of the neutrons issued by the fusion reactions, that is, neutrons at high energy, with 14.1 MeV of energy. We also underlined the fact that our experimental knowledge of the effects of these neutrons on materials is very incomplete. And therefore we need to really move quickly towards the phase in which we test the properties of the candidate materials that we foresee for the fusion reactors. In both the previous lecture and this lecture we underlined the fact that I like to conclude this lecture with, and that is; materials science plays an absolutely crucial role in fusion energy research in general.

Notes

Summary

19m 54s