Prospects of new ODS steels

Annual Fusion Seminar
VTT Tampere, June 2-3, 2010

Seppo Tähtinen
VTT Technical Research Centre of Finland
Fusion advantages

- Unlimited fuel
- No CO\textsubscript{2} or air pollution
- Major accidents impossible
- No radioactive "ash" and no long-lived radioactive waste
- Competitive cost if reasonable availability
- Meets the urgent need

Residual radioactivity in the blanket

- Activation falls rapidly after some hundred years
- No waste for permanent repository disposal

However, more research and development is needed
Low activation materials

Low activation elements: C, Si, V, Cr, Fe, Y, Ta, W

• Recycling limit will be reached within ~100 yrs

• Impurities may dominate activation behavior in engineering alloys

• Avoid Ni, Co, Nb, Mo

Note that N produces $^{14}$C

RAFM steels (ferritic martensitic)

EUROFER97: 8-10%Cr, 1-2%W, 0.5%Mn, 0.2%V, 0.14%Ta, 0.11%C, Fe bal.

ODS RAFM steel

EUROFER97 reinforced with 0.3% Y$_2$O$_3$ particles

ODS RAF steels (ferritic)

12-14%Cr, 1-3%W, 0.1-0.5%Ti + 0.3%Y$_2$O$_3$

SiC/SiC, V-alloys, W-alloys
# Fusion development issues and machines

## role of devices on the ‘Fast Track’

<table>
<thead>
<tr>
<th>Issue</th>
<th>Approved devices</th>
<th>ITER</th>
<th>IFMIF</th>
<th>DEMO Phase 1</th>
<th>DEMO Phase 2</th>
<th>Power Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plasma physics/Plasma performance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disruption avoidance</td>
<td>2</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Steady-state operation</td>
<td>2</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Divertor performance</td>
<td>1</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Burning plasma (Q&gt;10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start up</td>
<td>1</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Power plant plasma performance</td>
<td>1</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td><strong>Enabling technologies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superconducting machine</td>
<td>2</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Tritium inventory control &amp; processing</td>
<td>1</td>
<td>3</td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Power plant diagnostics &amp; control</td>
<td>1</td>
<td>2</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Heating, current drive and fueling</td>
<td>1</td>
<td>2</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Remote handling</td>
<td>1</td>
<td>2</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td><strong>Materials &amp; Component performance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials characterisation</td>
<td></td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Plasma-facing surface</td>
<td>1</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Vessel/First Wall/blanket/divertor materials</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Vessel/First Wall/blanket/divertor components</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>T self efficiency</td>
<td>1</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td><strong>Final System</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licensing for power plant</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>R</td>
</tr>
<tr>
<td>Electricity generation at high availability</td>
<td>1</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
</tbody>
</table>

- **Outputs:**
  - 1: Will help to resolve the issue
  - 2: May resolve the issue
  - 3: Should resolve the issue
  - 4: Must resolve the issue

- **Inputs:**
  - R: Pre-existing Solution is desirable
  - 0: Pre-existing Solution is a requirement

**UKAEA October 2007 (revised/updated version of original table in UKAEA ECRS 521, 2005).**

---


---

- IFMIF will provide 14 MeV neutron at 20 dpa/y.
- ITER will provide knowledge on plasma and PFM behaviour but DEMO have different requirements for materials.
- T-breeding will be provided in DEMO but blanket test module (RAFM steel) will be already tested in ITER.
Comparison of fusion devices

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>DEMO</th>
<th>Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Power</td>
<td>0.5 GW</td>
<td>2.5 – 5 GW</td>
<td>2.5 - 5 GW</td>
</tr>
<tr>
<td>Heat flux (first wall)</td>
<td>0.1-0.3 MW/m²</td>
<td>0.5 MW/m²</td>
<td>0.5 MW/m²</td>
</tr>
<tr>
<td>(divertor)</td>
<td>~ 10 MW/m²</td>
<td>~15-20 MW/m²</td>
<td>~20 MW/m²</td>
</tr>
<tr>
<td>Neutron Load (First Wall)</td>
<td>0.78 MW/m²</td>
<td>&lt; 2 MW/m²</td>
<td>~ 2 MW/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated Neutron Load</td>
<td>0.07 MW·year/m²</td>
<td>5 - 8 MW·year/m²</td>
<td>10 - 15 MW·year/m²</td>
</tr>
<tr>
<td>(First Wall)</td>
<td>(3 years operation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement per atom (dpa)</td>
<td>&lt; 3 dpa</td>
<td>50 - 80 dpa</td>
<td>100 - 150 dpa</td>
</tr>
<tr>
<td>Transmutation product rates at first wall</td>
<td>~10 appm Helium / dpa</td>
<td>~45 appm H / dpa</td>
<td></td>
</tr>
</tbody>
</table>

- Plasma facing component design is a priority issue
- Available material selection is based on existing commercial materials (Be, CfC, W, CuCrZr, 316(LN))
- Radiation damage is low

- Radiation damage has a high priority
- Low activated materials must be developed and characterised (7-9%Cr RAFM steel, W-alloys, ODS alloys, SiC/SiC, V-alloys)
- ITER operation temperature low compared to DEMO
Impact of 14 MeV neutrons on materials

The fusion neutrons produce atomic displacement cascades and transmutation nuclear reactions similar to fission neutrons.

Transmutation nuclear reactions produce stable elements (e.g. H and He atoms)

Atomic displacement cascades produce point defects (vacancies, interstitials)

Final microstructure results from a balance between radiation defects and thermal annealing. (Note that radiation defects are mobile)
Evaluation of microstructure

- The microstructure of the irradiated material results from interactions between the various irradiation-induced defects

- Small defect clusters
- Dislocation loops
- Stacking fault tetrahedra
- Precipitates
- Voids
- He bubbles

Key parameters:
- accumulated damage, dose (dpa)
- damage rate (dpa s⁻¹)
- production rate of impurities (He/dpa, H/dpa)
- temperature
Evaluation of mechanical properties

- **Low temperature range** (up to ~0.35 $T_m$, dose >0.1 dpa)
  Hardening and loss of fracture toughness.

- **Intermediate temperature range** (up to ~0.45 $T_m$, dose >10 dpa)
  Irradiation creep, reduced ductility

- **High temperature range** (~0.3 - 0.6 $T_m$, dose >10 dpa)
  Radiation induced/enhanced segregation and precipitation
  Swelling from void formation
  He embrittlement of GB,s

- Fusion specific transmutation He (and H) will promote low temperature embrittlement, void swelling and He embrittlement of GB,s.
Development of irradiation-resistant steels/alloys

- Basic requirements:
  - Precipitate structure, stable, high density, nanoscale
  - Dislocation structure, stable, high density
  - High creep strength

- Benefits:
  - Trapping of He to in fine scale bubbles to avoid void swelling and grain boundary embrittlement
  - Operation temperature above displacement damage regime, above 0.3 – 0.4 Tm to avoid radiation hardening and embrittlement
Reduced activation steels with ODS / NFA / TMT

- Reduced activation steels
  - 7-9%Cr ferritic-martensitic steels (RAFM)
    - F82H, Eurofer97

- ODS / NFA reduced activation steels
  - 8-12%Cr ferritic-martensitic steels (RAFM)
    - ODS Eurofer97 (~0.3wt% $Y_2O_3$)
  - 12-14%Cr ferritic steels (RAF)
    - MA957, PM2000, 12YWT (0.2-0.5wt% $Y_2O_3$)

- Microalloyed reduced activation steels
  - 9%Cr ferritic-martensitic steels
    - TMT (N, C, B, Ti, Ta, V, Nb)

- Good high temp. properties
- Good irradiation properties
- Complicated, expensive
- Non-uniform particles
- Joining

ODS (Oxide dispersion strengthening), NFA (Nanostructured ferritic alloy), TMT (Thermo-mechanical treatment)
Radiation resistant steels?

- Radiation resistant material must manage the **inevitable primary defect production** in ways that minimize or direct microstructural evolution and damage accumulation so as to mitigate property degradation.
- Recent development on ODS steels indicate that by refining the microstructure (e.g., nano-scale precipitates/clusters, dislocations) to provide **sinks for radiation defects and He atoms** improve both radiation resistance and high temperature creep properties.

Nano-clusters prevent bubble and void growth by increasing sink density for vacancies and SIA’s.

Expensive production method with no large scale production experience.

Mechanical alloying, hot extrusion or hot isostatic pressing, rolling, heat treatment.
Design stress-temperature window

- **Low temperature** radiation embrittlement regime:
  - Hardening / low fracture toughness / DBTT
    - $K_j < 30$ MPa m$^{-1/2}$
  - **Intermediate temperature** ductile regime:
    - Reduced ductility
      - $S_e = 1/3S_u$
  - **High temperature** thermal creep regime:
    - e.g. 1% strain in $10^5$ hours

- For RAFM steel:
  - Design window is 350-550$^\circ$C
    - Maintain structures >350$^\circ$C
    - Anneal regularly to suppress damage
  - ODS RAFM extent to ~650$^\circ$C
  - ODS RAF extent to ~800$^\circ$C
    - Coating or functional material
DEMO divertor development – He-concept

- Operating temperature 600-700°C
- Radiation dose level 20-40 dpa yr⁻¹
- Thermal conductivity ~100 Wm⁻¹K⁻¹
- Max. allowable temperature >1000°C

Rules out
- Cu-alloys
- RAFM steel
- Be and CfC

Only possibility is refractory metals e.g. W-alloys and ODS RAF steels

Resent results on ODS RAF steels shows promising strength and creep properties up to 800°C.

Design window for W is very narrow showing brittle behaviour up to ~900°C and recrystalisation at ~1300°C.

W-allows show some improvements.

Note: need for ODS RAFM/RAF steels also in GEN4, space nuclear power and other high temp. application.
Summary

- ODS/NFA exhibit significant potential as high-performance radiation resistant alloys

- Needs:
  - Cost effective manufacturing method (industrial scale)
  - Joining methods
  - Homogeneous, isotropic, repeatable microstructure
  - Alloy optimisation, property characterisation
  - Further understanding of the detailed nature of the NF’s
Conclusion

- Materials are the key issue on the path to fusion power reactors
  - Plant thermal efficiency (operative temperature)
  - Public acceptance (low activation)

- Material choices will not solve all design problems
  - Design is complex and have to be used to overcome material limitations
Main candidate materials for plasma facing and breeding blanket components

<table>
<thead>
<tr>
<th>Function</th>
<th>First wall</th>
<th>Breeding blanket</th>
<th>Divertor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma facing material</td>
<td>W-base alloy, W-coated ODS steel, Flowing liquid Li</td>
<td>-</td>
<td>W-base alloy, W-coated SiC/SiC, Flowing liquid Li, Ga, Sn, Sn-Li</td>
</tr>
<tr>
<td>Neutron multiplier material</td>
<td>-</td>
<td>Be, Be12Ti, Be12V, Pb</td>
<td>-</td>
</tr>
<tr>
<td>Tritium breeding material</td>
<td>-</td>
<td>Li, eutectic Pb-Li, Li-base ceramic material</td>
<td>-</td>
</tr>
<tr>
<td>Structural material</td>
<td>RAFM steel, ODS steel, V-base alloy, SiC/SiC</td>
<td>RAFM steel, ODS steel, V-base alloy, SiC/SiC</td>
<td>ODS steel, W-alloy</td>
</tr>
<tr>
<td>Coolant</td>
<td>-</td>
<td>Water, Helium, eutectic Pb-Li, Li</td>
<td>Water, helium</td>
</tr>
</tbody>
</table>
Design temperature window

- RAFM steel is at present the most promising structural material for plasma facing components and breeding blanket.
  - Design window is 350-550°C
    - Maintain structures >350°C
    - Anneal regularly to suppress damage
  - ODS RAFM extent to ~650°C
  - ODS RAF extent to ~800°C
    - Coating or functional material
- Tungsten alloys are most promising plasma facing materials but they are brittle and difficult to machine.
Defect configuration in FCC and BCC metals

Surviving vacancy and SIA defect cluster configuration (larger and more compact in fcc) and nature (sessile SFT’s in Cu compared to more glissile loops in Fe) are different in fcc and bcc structures.
Quest for high temperature and radiation resistant materials

Figure 3 – LIFE engine showing key materials: tungsten first wall, oxide dispersion strengthened steel structure, beryllium neutron multiplication blanket, fission blanket, and molten fluoride salt coolant.

Figure 8: Dual-coolant blanket (model C), equatorial outboard blanket module (1.5 x 3.0 x 1.6 m² rad x tor x pol).
Roadmap to fusion power

- **ITER (International Thermonuclear Experimental Reactor)**
  
  **Demonstrate plasma burn and reactor scale technologies**
  
  under construction

- **IFMIF (International Fusion Material Irradiation Facility)**

  **Material test reactor with 14 MeV fusion neutrons**

  engineering design

- **DEMO: (Demonstration Prototype Fusion Power Plant)**

  **Prototype reactor with Tritium breeding**

  planning
ITER superconducting magnets

Superconducting magnets are technologically feasible but development is still needed:

- **Higher magnetic field**
  - Fusion power \( \sim \beta^2 B^4 \)
  - Better plasma confinement
  - Higher stresses \( \sim B^2 \)
- **Higher current density**
- **Higher temperature operation**
  - High temperature superconductor
  - More simple gryostat design
- **Higher strength and radiation resistance for structural and insulating materials**
- **Cost reduction**
ITER divertor development - manufacturing

Plasma facing material: Be, W, CfC
Compliance layer: OFHC Cu
Heat sink: CuCrZr
Structural material: 316L(N)

- Brazing
- Casting
- Active metal casting
- Pre-brazed casting
- Electron beam welding
- Hot isostatic pressing
- Hot radial pressing

15 MWm\(^{-2}\) – 2000 cycles after 0.5 dpa at 200°C
18 MWm\(^{-2}\) – 1000 cycles

23 MWm\(^{-2}\) – 2000 cycles after 1 dpa at 200°C
15 MWm\(^{-2}\) – 1000 cycles

The design of ITER plasma facing components (divertor, blanket) have a high technology readiness level.

The design is robust enough to give acceptable critical heat flux margin to survive off-normal plasma disruptions.
VTT creates business from technology