Cooling Concepts for DEMO Reactors and their Impact on Design & Materials

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In-vessel components related to critical materials issues
In-vessel components: functions & thermal loads

**First wall + Blanket**
- thermal energy extraction
- tritium breeding
- fast neutron impingement
  ⇒ neutron wall loading
  (~2 MW/m²)
  ⇒ power exhaust: ~80%

**Divertor**
- particle exhaust (He ash)
- impurity barrier
- directed plasma bombardment
  ⇒ high-heat-flux loads
  (10~20 MW/m²)
  ⇒ power exhaust: ~20%

Heat transport via coolant to power conversion
Cooling concepts for blanket & divertor
Blanket cooling concepts: pros & cons

Water
- effective cooling, PWR database
- lower operation temperature (steel embrittlement/low efficiency), corrosion

Helium
- chemical inertness, higher operation temperature (high efficiency)
- lower heat removal capability (pumping power cost, large tube size)

Liquid metals
- effective heat removal, simultaneous T breeding, low pressure
- MHD effect (pressure drop), safety issue
Divertor cooling concepts: pros & cons

Water
- excellent cooling capability (~20 MW/m²), mature technology (ITER)
- low operation temperature (tungsten brittleness, reduced efficiency)

Helium
- high temperature (above DBTT of tungsten), compatible with He-cooled blanket
- low power exhaust capability, suitable structural material not available yet

Lifetime: ~2 FPY (2.2 MWe/m², ~20 dpa)
Loads & materials requirements of plasma-facing components
Plasma-facing components

First wall module (W-coated)

Divertor target element (W mono-block)

Generic structure
- plasma-facing armor
- heat sink (cooling channel)

Loading characteristics
- plasma particle bombardment ⇒ surface erosion, T implantation
- high-heat-flux loads ⇒ thermal shock, thermal stress
- fast neutron irradiation ⇒ cascade damage, transmutation
Materials requirements for DEMO divertor

Heat sink (as structural material)

- high thermal conductivity
- toughness/high temperature strength
- machinability/weldability
- recovery from dpa damage (desired)
- watertight
- aqueous corrosion resistance
- reduced activation (desired)

Water-cooled: copper alloys
Helium-cooled: tungsten

ODS ferritic-martensitic steel
Materials requirements for DEMO divertor

Armor (as functional material)
- low sputtering yield
- low tritium solubility
- high melting point
- high thermal conductivity
- thermal shock resistance
- involatility under oxidation
- reduced activation (desired)

Cracking on W surface under transient load
(1.27 GW/m², 1 ms)

Tungsten?
Tungsten alloys?
Tungsten composites?

Electron beam pulse
J. Linke (PFMC 2011)

XFEM simulation
M. Li, JH You
Design constraints for divertor target
Water-cooled divertor

10 ~ 20 MW/m²

150 ~ 250 °C

15 MW/m²

1100 °C

420 °C

Tc= 150 °C

Copper alloys: 250 °C < T < 320 °C
Tungsten: ~600 °C < T < 1300 °C

15 MW/m²

Thermal stress

150 °C < T < 320 °C

15 MW/m²

W

CuCrZr

15 MW/m²

Cu

(Tc)

Cracking in armor

15 MW/m²

Tc=200 °C

15 MW/m²

Tc=250 °C
Tungsten (600~800°C < T < 1300°C)

ODS ferritic steel (350°C < T < 700°C)

5~10 MW/m²

18mm hex AF

W tile

WL10 thimble

ODS Eurofer

10 MW/m², He flow rate: 240 m/s, 6.8 g/s

W tile: 1720°C (2500), 244 MPa (445)

W thimble: 1175°C (1300), 280 MPa (400)

ODS steel: 700°C (700)

1720°C 1175°C

Tungsten thimble: irradiation behavior?
Novel materials for water-cooled divertor target

Heat sink: high-temperature strength
Armor: enhanced toughness
Fiber-reinforced copper composites

Tungsten wire

W wire-reinforced Cu composite
25 heat flux cycles (10 MW/m²)

A. Herrmann (IPP)

SiC fiber

Strength of SiC₇/Cu composite

V. Paffenholtz (IPP)

IR image during a HHF test

10.5 MW/m²
W/CuCrZr composite for graded heat sink

Test mock-up with graded interlayer (interlayer: 3mm)

W70/Cu30
W50/Cu50
W30/Cu70

High-heat-flux fatigue test
10 MW/m²: 100 cycles
15 MW/m², 10 cycles

A. Zivelonghi (IPP)

GLADIS
$W_f/W$ composite for toughening of armor

Microstructure / Interface

Bending test (single-fiber composite)

In-situ synchrotron tomography


Conclusions

Water-cooled target

- Envisaged goal of power exhaust implies elevated operation temperature.
- This requires use of advanced materials (e.g. composites) as compulsory option.
- For novel materials, materials-design interface is a critical R&D element.

Helium-cooled target

- Design studies (& tests) predict power exhaust capability of 5~10 MW/m².
- Tungsten Irradiation data, demanded for structural design, is still missing.
- Metallurgical issues (e.g. tough tungsten, joining) are the most critical engineering challenge.
Plastic fatigue of heat sink tube

Softening of CuCrZr by over-ageing

Impact of softening on plastic fatigue (FEM)

15 MW/m²

(300°C)

800 MPa

360 MPa

-0.6 -0.3 0 0.3 0.6

Strain (%)

-400 0 200 400

Stress (MPa)

-400 0 200 400

Stress (MPa)

0.04 0.05 0.06 0.07 0.08 0.09

Equivalent plastic strain

0 1 2 3 4 5 6 7 8 9 10

Number of heat load cycles

simulated by Chaboche model

hardened state

softened state

$N_f \sim 10^6$

$N_f < 10^3$

JH You, M Miskiewicz, JNM (2008)