He-Cooled Divertor Concepts

L.V. Boccaccini
Task co-ordinator of TRP-001 in the EU PPCS

Principal Investigators:
P. Norajitra (FZK), C. Nardi (ENEA), P. Karditsas (UKAEA)

US-Japan Workshop on Fusion Power Plants and Related Advanced Technologies with participation of EU
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### Contributions

<table>
<thead>
<tr>
<th>FZK -</th>
<th>EFREMOV (RF)</th>
<th>ENEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>P. Norajitra,</td>
<td>I. Mazul,</td>
<td>C. Nardi</td>
</tr>
<tr>
<td>T. Ihli,</td>
<td>R. Giniyatulin</td>
<td>S. Papastergiou,</td>
</tr>
<tr>
<td>R. Kruessmann,</td>
<td>V. Kuznetsov,</td>
<td>A. Pizzuto</td>
</tr>
<tr>
<td>W. Krauss,</td>
<td>A. Makhankov,</td>
<td>G. Brolatti,</td>
</tr>
<tr>
<td>S. Gordeev,</td>
<td>I. Ovchinnikov</td>
<td>G. Mazzone,</td>
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<td>N. Holstein,</td>
<td></td>
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<tr>
<td>T. Chehtov</td>
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<tr>
<td>P. Sunyk,</td>
<td></td>
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<td>J. Weggen,</td>
<td></td>
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<tr>
<td>B. Zeep</td>
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</tbody>
</table>

| | | UKAEA |
| | | |
| | | P. Karditsas |
Outline

1. Introduction
2. Rationale of the He-cooled divertor concepts
3. Design of the proposed concepts of He-divertors
4. Related R&D
5. Conclusion and future work
Introduction: Fusion Power Plant (model C)

- 16 TF coils
- 8 upper ports (f) (modules & coolant)
- 176 blanket modules (a) (5-6 yrs. lifetime)
- 8 central ports (g) (modules)
- Vacuum vessel 70 cm (e) (permanent)
- Lower divertor ports (h) (8 remote handling, 16 coolant)
- Divertor plates (b) (1-2 yrs. lifetime)
- Coolant manifolds (d) (permanent)
- Cold shield 30 cm (c) (permanent)
- 8 lower divertor ports (h) (8 remote handling, 16 coolant)
## Fusion Power Plant Models investigated in the EU PPCS

<table>
<thead>
<tr>
<th>Development rating</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>near term</td>
<td>near term</td>
<td>advanced</td>
<td>very advanced</td>
<td>near term</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Blanket type</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>WCLL</td>
<td>HCPB</td>
<td>Dual Coolant</td>
<td>Self Cooled</td>
<td>HCLL</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Divertor type</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>water cooled</td>
<td>He cooled</td>
<td>He cooled</td>
<td>Liq. metal cool.</td>
<td>He Cooled</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Breeder / Multiplier</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-17Li / none</td>
<td>Li-ceramic / Be</td>
<td>Pb-17Li / none</td>
<td>Pb-17Li / none</td>
<td>Pb-17Li / none</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>Helium</td>
<td>Helium and Pb-17Li</td>
<td>Pb-17Li</td>
<td>Helium</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T-extraction</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-17Li circulation</td>
<td>He purging flow (1 bar)</td>
<td>Pb-17Li circulation</td>
<td>Pb-17Li circulation</td>
<td>Pb-17Li circulation</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Structural Material</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
<th>Model AB</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAFM</td>
<td>RAFM</td>
<td>RAFM (FW ODS plated)</td>
<td>SiC/ SiC</td>
<td>RAFM</td>
<td></td>
</tr>
</tbody>
</table>
### Boundary conditions for the in-vessel components

<table>
<thead>
<tr>
<th></th>
<th>In Blanket</th>
<th>Model A</th>
<th>Model B (AB)</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface heating</strong></td>
<td>0.6</td>
<td>0.5 MW/m²</td>
<td>0.6 MW/m²</td>
<td>0.5 MW/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2 / 3.0 MW/m²</td>
<td>2.0 / 2.4 MW/m²</td>
<td>2.23 / 3.1 MW/m²</td>
<td>2.6 / 3.4 MW/m²</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>In Divertor</th>
<th>Model A</th>
<th>Model B (AB)</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface heating</strong></td>
<td>5 / 15 MW/m²</td>
<td>5 / 10 MW/m²</td>
<td>5 / 10 MW/m²</td>
<td>/ 5 MW/m²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0 MW/m²</td>
<td>1.6 MW/m²</td>
<td>1.7 MW/m²</td>
<td>1.8 MW/m²</td>
<td></td>
</tr>
</tbody>
</table>
He cooled divertors have being proposed ...

- To use the same coolant flowing in the blanket systems: at the present three reactor concepts (HCPB [model B], Dual Coolant [C], HCLL[AB]) that are under investigation the EU Programme envisage He cooled divertors.
- To integrate the divertor loop in the power generation system increasing the overall efficiency of the reactor (He allows a design with temperatures comparable or higher than in the blanket system)
- To avoid safety concerns for incompatibility of water with breeding/multiplier materials (especially in the case of Be based concepts, Model B, to avoid the Be-steam exothermal reaction with H production)
Integration in the power generation system

HX1  1432 MW  300-480°C  FW
HX2  335 MW  480-615°C  Divertor
HX3  1976 MW  480-700°C  PbLi
HX4  248 MW  700-800°C  Divertor
Divertor cassette for Model C and Target Plate Requirements

Target Plate (outboard):

- length 1m
- heat peak: 10 MW/m²
- average heat: 5 MW/m²
- moving strike point: 40 cm
- protection layer: 5mm (W)
- allowable temperatures and stresses in the materials
- Pumping power / Thermal power < 0.1
Design loading conditions
The critical part of the design is the OB target plate in which incident heat fluxes not lower than 10 MW/m$^2$ are expected. These very demanding requirements can be fulfilled if these two issues can be successfully addressed:

1. The identification of a heat transfer mechanism between Helium and plasma side structure able to reach heat transfer coefficient greater than 30 kW/m$^2$ K.

2. The selection/development of materials with very good thermal properties and a large operational temperature window that can be used as structural material (high pressure helium containment) for the high flux region at the plasma side.
# Materials and anticipated operational temperature windows required for a high temperature divertor

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Min Temp.</th>
<th>Max Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiles</td>
<td>W</td>
<td>tbd (600°C) DBTT</td>
<td>2500°C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Melting temperature 3410°C</td>
</tr>
<tr>
<td>High heat flux structure (high pressure He containment)</td>
<td>W-alloy</td>
<td>600°C DBTT</td>
<td>1300°C re-crystallisation</td>
</tr>
<tr>
<td>Structure and manifolds</td>
<td>W-alloy</td>
<td>600°C DBTT</td>
<td>1300°C re-crystallisation</td>
</tr>
<tr>
<td></td>
<td>ODS</td>
<td>400°C DBTT</td>
<td>700-750°C strength limits</td>
</tr>
<tr>
<td></td>
<td>...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
High flux He-cooled divertor concept development

A) Plate design (enhancement of the heat transfer coefficient -> radial cooling):

- PPA-99: Unconventional design (FZK), qmax ~ 5 MW/m²
- PPCS/II (2000-2001): Simple slot (FZK), qmax ~ 6 MW/m²
- PPCS/III (2001): Modified slot (FZK), qmax ~ 10 MW/m² *(in Model B)*

B) Modular design (thermal stress reduction):

- PPCS/III (2002): Modified **HETS** (ENEA), qmax ~ 10 MW/m²
- PPCS/III (2002) - **Model C**: Pin-array **HEMP** (FZK), qmax ~ 10 MW/m²
- TRP-001 (2003-2004) – Investigation on design concepts based on **HETS**, **HEMP**, **HEMS** and **HEMJ**
Principle of the modular design and the radial cooling

- Finger
- Tile
- Cup
- Heat transfer promoter
- inlet/outlet separation cartridge
- Strip structure / manifolds
Cooling Technology: Heat transfer promoters

\[ \dot{q} = htc \cdot \frac{A_c}{A_{Armor}} \cdot (T_w - T_c) \]

- HETS single-jet
- HEMP pin array
- HEMS slot array
- HEMJ multi-jet
Cooling Technology: pin and slot array

Pin array

Slot array

HEMP

HEMS
Cooling Technology: Jet Impingement

Cooling technology applied in the fields of:

- Aircraft Engines
- Gas Turbines
- Burners

‡ DEMO Divertor

Jet Impingement

HOT

wall jet flow
free jet flow

impingement region
COOLING TECHNOLOGY: Jet Impingement in HEMJ

**Single-jet**

- Heat transfer coefficient
- (Low Re Number)
- \( D_{jet} = 0.6 \text{ mm} \)

**Multi-jet**

- Contours of Surface Heat Transfer Coeff. (W/m²K)
- Example
Comparison of Cooling Systems (1/2)

Velocity and temperature field in HETS (UKAEA)

Stress analysis for the HEMJ concept (EFREMOV)

Tokyo, January 12, 2005
• **Cooling performances** (according to the requirements on heat flux density, allowable temperatures and stresses, pumping power limitation, etc.)

• **Fabrication** (available technique, mass production, cost-efficiency, etc.)

• **Reliability** (sensibility to blockage and tolerances, mass balancing, etc.)

At present the design groups of ENEA and FZK have selected as reference option (for the starting of the mock-up tests) jet cooling concepts, namely the HETS and the HEMJ, respectively.
HETS Design
HETS: Detail of the flow mechanism

Calculated heat transfer coefficient in HETS ($\theta$ is the angle from the dome top)
## HETS: Hydraulic lay-out

<table>
<thead>
<tr>
<th>Finger type and dimens.</th>
<th>He in/out</th>
<th>Coolant pressure</th>
<th>Mass flow</th>
<th>Average Heat Transfer Coeff.</th>
<th>Pressure drops</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEX 35 mm</td>
<td>600-669°C</td>
<td>10 MPa</td>
<td>30 g/s</td>
<td>~ 30 kW/m² K</td>
<td>0.06 MPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>182</td>
<td>10</td>
<td>180</td>
<td>195</td>
<td>&gt;0.3</td>
<td>&gt;6.3</td>
</tr>
</tbody>
</table>

Tokyo, January 12, 2005

He-cooled Divertor Concepts

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HETS Manufacturing sequences (preliminary) 1/2

first brazing: filler based on Pd, Zr or Ni alloy to withstand 1000°C

second brazing: same filler as the first brazing
third brazing: filler based on Cu or Ni alloy to withstand ~800°C

fourth brazing: same filler as the 3th brazing
HEMJ Design

9-finger-unit

finger

FZK

strip
Layout example for Multiple-He-Jet-Cooled Divertor

Finger Unit
- a = 18 mm
- D = 15 mm
- W Alloy
- Steel
- jet-to-wall spacing H = 1.2 mm

Multiple Jet Cartridge
- center hole; D = 1 mm
- 24 holes; D = 0.6 mm
LAYOUT EXAMPLES

- rounded J1a
- sharp J1a
- sharp J1c
- rounded J1c
- sharp J1e
- rounded J1e

Limit for heat flux 10 MW/m²:

- rel. compressor power: 10%
- rel. compressor power: 7.1%
- rel. compressor power: 6.3%
Hydraulic lay-out of the target plate (schematic)

HEMP / HEMS: 3x30 fingers in parallel, in 2 sections in series

„left“ Modules

„right“ Modules
HEMJ Finger

Parts

- Armor (W)
- Cap (W Alloy)
- Transition Piece (12YWT or ODS-Eurofer)
- Pin (W Alloy)
- Cartridge

Cap/Tube with Spacers for Cartridge

Spacer
Advanced 9-Finger module (1/7)
Brazing (foil)
Brazing with cast copper

Advanced 9-Finger module
(3/7)
Welding (from below)
Insert (welding)

Advanced 9-Finger module (5/7)
Welding

Advanced 9-Finger module (6/7)
Welding

Advanced 9-Finger module (7/7)
High reliability, low waste during fabrication

Construction Kit Principle:
- Small Units advantageous for R&D progress
- Small Units can be tested before assembling

9-Finger Unit  Stripe-Unit  Target Plate  Divertor Cassette

Test, Assembly → Test, Assembly → Test, Assembly → Test, Assembly → …
Measurement of pressure drops for HETS with air

Measurement device (left) and detail of the test section (right) for pressure drop experiments.
HEBLO (FZK) – Test facility for CFD-Validation

Temperature Cycle
- operation pressure: 8 MPa
- helium flow rate: 120 g/s
- Helium temp. (max.): 430 °C
- He-heating power: 60 kW
- Surface heating: 3 kW

Testprogram for 2004 / 2005:
- 10:1 Mock-up for HEMJ
- 10:1 Mock-up for HEMS
- 10:1 Mock-up for HEMP
Pressure drops and HTC measurements for HEMJ with Helium

EFREMOV under FZK contract

Pressure drop measurements with the Gas Puffing Facility 2
HEMJ cartridges for GPF2 experiments

HEMJ J1a
HEMJ J1-b
HEMJ J1-c
HEMJ J1-d
HEMJ J1-e
Tube for mockup
Helium facility + EB at EFREMOV (in construction)

- EB
- Heater
- Test Section
- Cooler
- Pump

inlet Temperature 600°C
mass flow ~ 100 g/s
## Proposed fabrication and joint technologies

<table>
<thead>
<tr>
<th></th>
<th>HETS [ENEA]</th>
<th>HEMJ (HEMP/HEMS) [FZK]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tiles</strong></td>
<td>Plasma spray/ powder technology</td>
<td>Cutting from rods and grinding</td>
</tr>
<tr>
<td><strong>Cup (dome)</strong></td>
<td>Machining</td>
<td>Deep drawing from cross rolled WL10 + finishing</td>
</tr>
<tr>
<td><strong>Promoter</strong></td>
<td>-</td>
<td>(EDM, ECM, PIM, Laser)</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>Brazing of different parts (900)</td>
<td>Standard ODS alloy machining; tube: extrusion</td>
</tr>
<tr>
<td><strong>Joint: Tiles – Cup</strong></td>
<td>Plasma spray/ brazing</td>
<td>Brazing or bonding (T=1300° C) by commercial alloys, Zr, V, Stemet alloys, NiCu, NiTi</td>
</tr>
<tr>
<td><strong>Joint: Cup – Structure</strong></td>
<td>W-W Brazing, Cu or Ni based</td>
<td>Transition joint (Mechanical interlock + Cu sealing)</td>
</tr>
<tr>
<td><strong>Joint: Promoter – Cup</strong></td>
<td>-</td>
<td>(Brazing or bonding (T=1300° C) by commer. alloys, Zr, V, Stemet alloys, NiCu, NiTi)</td>
</tr>
</tbody>
</table>
Examples of W mock-up fabrication for cap and slot array

Mock-up of W-thimble with integrated slot array fabricated by EDM process.

W-slot array prepared by Laser process

EFREMOV under FZK contract
WL-10 showed satisfactory machining ability in comparison with conventional tungsten.
R&D on fabrication technologies: high temperature W-joint

Mock-up brazed with STEMET 1311 filler metal undergone successfully HHF screening tests

Screening test:

- 10 MW/m² 100 cycles OK
- 12 MW/m² 100 cycles OK
- 14 MW/m² 100 cycles OK
- 15 MW/m² 100 cycles OK
- 16 MW/m² 100 cycles OK
R&D on fabrication technologies: high temperature curved W-joint

Brazing successful
W-Cap – Steel Joint (Efremov Inst.)

W-Cap – Steel-Tube Joint MOCKUP

Cross-section of lock-area

- Cap W
- Cast copper layer
- Pins W
- Transition piece steel
R&D on fabrication technologies: W-steel joint

Finger mockup (without armour tile) after casting (left) and after post-testing examination (right).

Main elements for W-Steel joint with new (conic) lock

EFREMOV under FZK contract
HEMP Divertor: thermohydraulics design

\[ \Delta p_{\text{total}} \approx 0.44 \text{ MPa} \]
\[ P_{\text{pump}} \approx 8.6 \% \text{ of } Q_{\text{divertor}} \]

Zone I, 50 cm → 634 °C
Zone II, 50 cm → 701 °C
Baffle + dome → 717 °C
bulk → He 10 MPa, 540 °C, 9.6 kg/s

\( \Delta p \approx 0.17 \text{ MPa} \)
Replacement path of the divertor cassettes
Conclusions and future work

- Two divertor conceptual designs based on HETS (ENEA) and HEMJ (FZK) have been defined.
- Close link between the major fields: design, material/fabrication, performance analyses and experiments.
- Results of analyses show that 10 MW/m² could be achieved with satisfactory performances (pressure drop, Helium temperatures, efficiency of power generation systems, etc).
- Pressure loss and heat transfer coefficient have been calculated. A verification with experiments is ongoing (programme started in 2004).
- Promising fabrication methods for divertor components have been defined, further R&D works required.
- Technological experiments concerning W/W and W/steel joints successfully performed at Efremov, further R&D needed for improvement (FZK).
- Building of helium loop in EFREMOV started in 2004, first experiments can start presumably mid 2005.
Objectives: He-cooled Divertor on the way to ITER & DEMO

Materials, Design, Joining

Finger Units

9-Finger-Units

Small Parts Development

Reactors

DEMO

ITER 2020

Big Parts Development

Cassette, TDM

Targets

Stripe-Units

Big Parts Development

Finger Units

9-Finger-Units

Small Parts Development

Reactors

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ITER 2020

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