PFC Development Needs

ReNeW: Theme III & IV JOINT Gaps and Needs in PFC Cooling

D.L. Youchison & R.E. Nygren
Sandia National Laboratories

Alice Ying
University of California, Los Angeles

Dick Majeski
Princeton Plasma Physics Laboratory

Los Angeles, CA
March 4, 2009
Outline

- Uncertainties in the Plasma Edge (ELMS, disruptions, radiative power fraction, radial transport)

- Develop high temperature materials: quest for ductile W & ODS FS

- Gaps & Opportunities for Helium-cooled heatsinks for PFCs
  - Early work on copper heatsinks using cold helium
  - Recent efforts on refractories for high temperature applications

- 3 primary design concepts - 1) foam (Ultramet/SNL)
  2) tee-tube (PPI/UCSD)
  3) HEMJ (FZK/Efremov)

- Liquid metal issues for PFC applications
  - Lithium films CDX-U, LTX, NSTX
  - Flowing liquid metal walls MHD effects, LM handling
  - LM heatpipes for leading edges and diagnostics
Project robust PFC design and development for the ~ 1000 MWe Demo
(Possibly: Γn-max =3 MW/m², FW φ-max= 0.5-4.0 MW/m²\ Div φ-max = 10 MW/m² (SS) + 20 MW/m²(10-100s) pulses) TBD
“Difficult to achieve an engineering margin of 1.3 (TBD)”

Requirements:
Surface heat transfer performance
• Provide proven and robust heat removal designs for the chamber wall, divertor, limiters, and beam dumps, for specific set of Demo parameters and for all operation scenarios of Demo – coolant parameters & power conversion compatibility (coolant circuit des. & hydraulic connectors)

Testing (VV & blanket interfaces?)
• Provide thermal, structural and integrated testing for PFC components including damage stresses from thermal, low and high cyclic effects and impact from high fluence, corrosion

Testing facilities:
• Provide necessary facilities for non-irradiated and irradiated components tests and examinations (full-size?)
• Provide necessary facilities for thermal hydraulics tests
• NDE facility, during fab and in-situ inspection

Qualification strategies:
Provide fusion relevant qualification strategies for Demo PFC including:
• testing requirements (leak, pressure, flow, heat flux)
• investment protection – diagnostics (temperature & stress, calorimetry)
• reliability requirements (PRA and lifetime modeling)

Components operation and technology limits

Develop predictive capability via modeling of material properties evolution and support RAMI data base
Huge uncertainties exist regarding the plasma edge. ITER FW heat loads are higher than originally anticipated.

Parallel power flux, ELMS require better heat removal performance. Radiative mantle in DEMO?

Figure 3. Calculated parallel power flux on the inner and outer wall for a range of assumptions concerning far-SOL transport for the ITER $Q_{DT} = 10$ scenario

Figure 4. Calculated parallel energy fluxes during ELMs at the upper X-point region for the ITER $Q_{DT} = 10$ scenario for uncontrolled and controlled ELMs. The dashed area indicates the range for the ELM energy fluxes assumed for the ITER first wall design

A. Loarte, IAEA, 2008
Radial transport significant in ITER DEMO will have high heat loads on FW.

Fast radial transport leads to significant parallel power fluxes deep into the Scrape-off Layer.

C. Lowry, IAEA, 2008
The Materials Development Gap

Qualified materials do not exist for DEMO!

- Ductile W and others, Mo, V
- ODS Ferritic Steel

Kurishita, US-Japan HHFC Workshop, 2002
Gaps in helium-cooling

1. Ductile W-alloy development, and other refractories: Mo, V
2. Low-cost fabrication techniques w/ integrated manifolding
3. Joining development, armor and RAFLS
4. Innovative, low-pressure-drop thermal designs
   CFD/HX modeling of porous media, helium jets, manifolding
5. Fabricate & test large area, multi-channel prototypes
6. Flow instabilities in multi-channel devices
7. High temperature, high pressure testing capabilities
8. Tritium permeation into the coolant
9. Purity control and high temperature diagnostics
### Background: Helium-cooled modules developed for PFCs

<table>
<thead>
<tr>
<th>Year</th>
<th>Type of Test Article</th>
<th>Fabricator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>Cu Micro-channel HX (~100μ channel size) Cu Divertor mockup A (0.46mm channels) Cu Porous (40%) metal HX (0.43mm dia.)</td>
<td>Creare, Inc. General Atomic Thermacore, Inc.</td>
</tr>
<tr>
<td>1994</td>
<td>Cu Dual channel porous metal HX Cu Div. mockup A retest, higher heat loads</td>
<td>Thermacore, Inc. General Atomic</td>
</tr>
<tr>
<td>1999</td>
<td>Div. mockup B retest, added diagnostics</td>
<td>Thermacore, Inc. Ultramet, Inc.</td>
</tr>
<tr>
<td>2000</td>
<td>W tubes with W foam</td>
<td>Thermacore, Inc. Ultramet, Inc.</td>
</tr>
<tr>
<td>2000</td>
<td>W FW module with W porous medium</td>
<td>Ultramet, Inc.</td>
</tr>
<tr>
<td>2001</td>
<td>VPS W tube with VPS porous medium</td>
<td>Plasma Processes</td>
</tr>
<tr>
<td>2006</td>
<td>W tube with W foam in axial flow</td>
<td>Ultramet, Inc.</td>
</tr>
<tr>
<td>2008</td>
<td>Sq. Mo w/ Mo foam, circumferential flow</td>
<td>Ultramet, Inc.</td>
</tr>
<tr>
<td>2009</td>
<td>4-Channel, Larger Area Mo panel</td>
<td>Ultramet, Inc.</td>
</tr>
<tr>
<td>2009</td>
<td>W Tee-tube Jet impingement</td>
<td>Plasma Processes</td>
</tr>
</tbody>
</table>
Helium-cooling for DEMO

HHF He Cooled PFC Development
- all refractory metal heat sink
- helium-cooled, high Delta-T heat sink
- high efficiency gas turbine technology
- hydrogen production

**goals:**
- investigate heat transfer analyses for porous media and jet impingement - identify useful modeling approaches
- demonstrate performance in medium scale test (implies we have a test stand and a capable loop)
- deploy helium-cooled module in toroidal facility

**needed development:**
- incorporate low-cost fabrication concepts for refractories including manifolding and connectors
- accommodate thermal stresses in face plates
- adequate heat transfer analyses for porous media and jets
Advances in helium HXs have surpassed current PMTF HeFL capabilities!

New Helium Flow Loops will be required for higher temperature (>600°C), higher pressure (8-10 MPa), higher mass flow (1 kg/s) operation for both PFC and BM testing.

- Oxygen gettering and gas analysis
- In-line helium heaters
- Larger capacity blowers or compressors
- High efficiency helium/water heat exchangers
- Fast actuating, high temperature valves
- High temperature diagnostics
- Niobium or super-alloy piping
Ultramet single channel testing completed in EB-60

FY08-FY09 testing campaign – Brayton cycle relevant (large ΔT)

- W DBTT < 600°C
- Mo DBTT < RT
- W recrystallization ~ 1100°C
- Mo recrystallization 1180°C
Ultramet has created larger panels for phase-II.

Testing in late summer 2009

- Multiple channel (4)
- Flat surface
- All refractory
- Short flow paths
- 600 C inlet temps

Investigate:
- Larger heated areas
- Flow instabilities
Plasma Processes Tee-Tube Concept

• ARIES CS design

concept 2
HEMJ from FZK/Efremov (Norajitra)

2007

w/ FS: 600 C -700 C helium operating window!

Tsefey

Tile (W)

Thimble (W-alloy)

Conic sleeve (steel)

Transition piece (steel)

Cartridge (steel)

W / W brazed joint

600C, 10 MPa, 25 g/s
Gaps in Liquid Metal Cooling (free surface, excludes PSI)

1. MHD modeling: mass transport and heat transfer
2. HHF Maragoni Effects, temperature limits (ELMS)
3. Materials development
   • Refractory metals, SiC
   • Insulators
   • Porous media
4. Tritium permeation, transport, & control
5. Purity control & handling systems
6. Lack of test systems (loops), diagnostics
Experiments and Modeling on Liquid Metal Free Surface Flows under Spatially Varying Magnetic Field Conditions: STATUS

• Qualitative and quantitative behavior of developing flows of liquid metal under divertor relevant magnetic field configurations through experiments
  – Focus on the effect of the three field components on film evolution
  – Investigate the different flow regimes and associated liquid metal film dynamics

• The development of a 3D incompressible free surface liquid metal MHD simulation capability (HIMAG) for film flow modeling under spatial varying magnetic field conditions.

• Findings:
  – At proposed NSTX conditions (velocity of film 10-15m/s ($Re>18,000$)) there is no sudden jump in film height (followed by stagnant flow)
  – The combined toroidal and surface normal field create a film with a non uniform thickness in the span wise direction (non uniformity of the order of (1mm-5mm))
  – The increase in film thickness ranges from 2X-4X at the downstream location (~30 cm from the inlet)
  – Even though the magnitude of the surface normal field is three times smaller in the NSTX divertor configuration, the MHD effects on the film are the strongest. The surface normal field component tends to detach the film from the walls creating bare spots. The surface normal field also leads to electromagnetic coupling between the LM film flow and the feeder channel flow.

*The divertor film flow should be designed to encounter minimum surface normal component*
The applied magnetic field tends to modify the turbulence characteristics of the free LM film flow (This depends on $Ha/Re$) Ga alloy in MTOR.

<table>
<thead>
<tr>
<th>Speed</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.86 m/s</td>
<td>No field 3-D turbulent structures</td>
</tr>
<tr>
<td>2.86 m/s</td>
<td>With NSTX-like gradient toroidal field</td>
</tr>
<tr>
<td>1.76 m/s</td>
<td>With Surface Normal Field: Significant film height increases caused by MHD drag</td>
</tr>
</tbody>
</table>
Effect of surface normal field on LM Free Surface Flow (NSTX surface normal field replicated)

**initial film height: 2 mm; channel length: 40 cm**

The flow tends to go through a sudden increase in film thickness (referred to as jump), at a particular downstream location. This dissipates a large amount of flow energy and slows down the liquid.

The jump location moves further downstream as the inlet flow velocity is increased and changes shape in the span wise direction.

At higher flow velocities (~2.5 - 3.0m/s) the liquid metal tends to get pushed inwards from the side walls of the conducting channel, creating separation zones and bare spots. The jump is not observed at high velocity.
Film evolution under toroidal, surface normal and combined field

- The span wise (toroidal) field tends to increase the film thickness locally near the side walls and this is eventually transmitted to the bulk.
- The wall normal field acts to increase the film thickness uniformly in the bulk of the film and tends to detach the film from the side walls.
- The combined field increases the film thickness locally in one half of the span.

Cross section at 30 cm downstream

Cross section at 10 cm downstream

Initial film thickness: 2mm

Initial film thickness: 2mm
LM jets and droplet streams are expected to be less sensitive to magnetic field gradients and direction changes

- Jets are stabilized by reduction of turbulence and secondary flows in nozzle (see below)
- In general, current paths remain in the jet or droplet – they don’t close through structures or thin boundary layers at structure interfaces
- However, sensitivity to Marangoni effects in high heat fluxes have not yet been investigated

MHD results in damping of vortex structure while elongating along the flow direction

LM Jet flows in MTOR under increasing field strength (Bmax varies from 0 to 1.1 T left to right)
Results from the CDX & LTX lithium programs

- Free surface liquid lithium PFC installed and operated in a tokamak
  - Surface required to be ~ conformal to a flux surface ($B_{\text{normal}} \sim 0$)
  - Plasma currents forced to flow parallel to $B_{\text{toroidal}}$
  - Design not applicable to divertors, however
- Safety issues addressed in CDX-U experiments
  - Secondary high-speed vacuum system installed to maintain chamber pressure < 100 - 200 Torr if vacuum boundary compromised
  - Venting, filter system to deal with passivation of LiD
- Wide array of materials issues
  - Compatibility, wetting of many metals tested (favorites: stainless, moly, tantalum best - but Ta not used due to H permeation issue)
  - Electroplated coatings tested (esp. hard chrome - failed)
  - Plasma sprayed porous coatings for wide-area retention of liquid lithium developed with PPI (Huntsville, AL)
    - Insulator compatibility ($\text{MgO}$, $\text{Y}_2\text{O}_3$), wetting barriers (tungsten), etc.
- Very high power handling of a free-surface liquid lithium target established
  - No experiments to test effects of strong magnetic fields
- Low recycling of clean liquid lithium established
- Record enhancement of Ohmic tokamak confinement demonstrated
Tray filled with *liquid* lithium under argon (1.01 atm)

- Filling technique developed with UCSD
  - Load liquid lithium onto 500°C tray
  - High temperature promotes wetting
  - “Injection” of liquid lithium eliminates solid contaminants

- Thin coatings appear between runs
  - Removed/dissolved by GDC, heating
- One fill active for up to ~1 year
  - Pumped for hundreds of discharges
Entire plasma-facing surface of a tokamak first wall can be faced with liquid lithium entrained in a porous metal

- Engineered porous molybdenum surfaces have been developed with Plasma Processes of Huntsville (Phase I & II SBIR)
- Plasma spray process can produce 70% porous molybdenum coatings
  - Interconnected porosity
- Porous metal readily wicks liquid lithium
  - Retention through surface tension
- Lithium-wicking porous metals have also been formed by sintering in stainless steel and tungsten

Lithium wetting tests on 70% porous plasma-sprayed molybdenum, 304L stainless steel substrate

- Candidate actuators for lithium flow:
  - Gravity
  - Capillary forces
  - Marangoni effect (temperature-dependent surface tension)
  - Thermoelectric effect
  - $\mathbf{J} \times \mathbf{B}$ and $\nabla \mathbf{J} \times \mathbf{B}$ forces
TR6 supports physics mission

NSTX LLD

- 4 Toroidal 90° segments separated by graphite Diagnostic Tiles
- Each copper substrate segment is clad with a thin stainless steel barrier with a front face of porous flame sprayed Mo
Deployment & Integration

- Requires close cooperation between toroidal facility and technology provider.
Technology Evolution

present devices >>> ITER >>> int. step >>> DEMO >>>

ITER

Intermediate Step (NHTX, CTF)

DEMO

 existing

Augmented mission for C-Mod+, DIII-D+, NSTX+

active cooling — high temperature — neutron damage

• He/W deployment
• RAFTS and W and ?

• understand, mitigate failures
• confirm models, design tools
• predict performance/lifetime