Materials for spallation sources
-topics from IWSMT-

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Ibaraki University
(October 20, 2009)
A short pulse spallation neutron source in mercury target

- ASTE[ORNL,JAERI,ESS,LANL]
- Exp. at AGS/BNL, pressure wave and particle transport in 1997.
- Pressure wave exp. at WNR/LANL in 2001.
- US-SNS operating from 2006/4月, now 1MW.
- J-PARC MLF operating from 2008/12, now 0.02 MW
- ESS canceled in 2004, and revises mercury or rotating W target in 5MW/2mA.

Workshop on AHIPA, Fermi, Oct. 2009 / Kikuchi
# Liquid Metal Targets: Candidate Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Pb</th>
<th>Bi</th>
<th>LME *</th>
<th>LBE**</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td>elem.</td>
<td>elem.</td>
<td>Pb 97.5% Mg 2.5%</td>
<td>Pb 45% Bi 55%</td>
<td>elem.</td>
</tr>
<tr>
<td><strong>Atomic mass A (g/mole)</strong></td>
<td>207.2</td>
<td>209</td>
<td>202.6</td>
<td>208.2</td>
<td>200.6</td>
</tr>
<tr>
<td><strong>Linear coefficient of thermal</strong></td>
<td>solid</td>
<td>liqu.</td>
<td>2.91</td>
<td>1.75</td>
<td>4</td>
</tr>
<tr>
<td><strong>expansion (10^{-5} K^{-1})</strong></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td><strong>Volume change upon solidification (%)</strong></td>
<td>3.32</td>
<td>-3.35</td>
<td>3.3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Melting point (°C)</strong></td>
<td>327.5</td>
<td>271.3</td>
<td>250</td>
<td>125</td>
<td>-38.87</td>
</tr>
<tr>
<td><strong>Boiling point at 1 atm (°C)</strong></td>
<td>1740</td>
<td>1560</td>
<td></td>
<td></td>
<td>356.58</td>
</tr>
<tr>
<td><strong>Specific heat (J/gK)</strong></td>
<td>0.14</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Th. neutron absorpt. (barn)</strong></td>
<td>0.17</td>
<td>0.034</td>
<td>0.17</td>
<td>0.11</td>
<td>389</td>
</tr>
</tbody>
</table>

* Lead magnesium eutectic  ** Lead bismuth eutectic
SNS Hg target, 1GeV, up to 2WM / ORNL

SS316L.. the liquid mercury target vessel and water-cooled shroud

McManamy, ORNL
SNS Hg target, 3GeV / J-PARC

SS316L: Target & Helium vessels

Oyama, J-PARC
Solid target

- U: high neutron yield but difficult to handle
- W: erosion under high speed water flow
- Ta: decay heat, brittle or ductile?
- Au: ?
- Pt: ?
ISIS, Rutherford Appleton Laboratory

- Design for 800 MeV, 200μA
- Target types
  - Zircalloy-2 clad U-238
  - Tantalum
  - Tantalum clad W
- In operation since 1984
- Have highly developed remote handling capability

www.isis.rl.ac.uk/accelerator-2006

Sommer and Maloy, IWSMT9
The target module includes the clad segments, shroud and axle.

The joint between the target and drive modules must be very precise. This joint also includes a significant water seal assembly.

Concentric pipes inside the axle will require differential thermal expansion capability.
Conceptual Solution for the CSNS Rotating Target Disk

Xeujun, CSNS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Early operation</th>
<th>Upgrade option</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton energy</td>
<td>MeV 1600</td>
<td>1600</td>
</tr>
<tr>
<td>Beam power</td>
<td>kW 120</td>
<td>500</td>
</tr>
<tr>
<td>Power deposited in target</td>
<td>kW 50.00</td>
<td>210</td>
</tr>
<tr>
<td>Target</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer diameter of cylinder</td>
<td>cm 50.00</td>
<td>50</td>
</tr>
<tr>
<td>Full height of cylinder (solid part)</td>
<td>cm 5.00</td>
<td>5</td>
</tr>
</tbody>
</table>

Involute shaped segments with grooves on surface

Target shaft

Rotating target window

W

AlMg₃
Spent ISIS Target: The Tantalum Puzzle

Side view of a bent Ta specimen from an ISIS target irradiated to 13 dpa with 800 MeV protons

Chen et al, JNM 343 (2005) 227

Stress-strain curves of Ta specimens from an ISIS-target tested at a strain rate of $10^{-3}$/s

Engineering stress-strain curves for ISIS Ta at room temperature after neutron irradiation

TS Byun and SA Maloy JNM 377 (2008) 72
Cladding of LANSCE Tungsten Neutron Scattering Target with Tantalum

Plans underway to Clad MLNSC Target with Ta

- Main reason is to reduce activity for the water cooling system
- Initial HIP bonding tests at 1500°C were successful
- Plan to have new targets fabricated by March 2009
Result – Au alloys

◆ After irradiation

\[ T_i = 116^\circ C \quad T_i = 149^\circ C \quad T_i = 195^\circ C \quad T_i = 235^\circ C \]
(7.3dpa) (10.8dpa) (15.2dpa) (18.9dpa)

\[ T_t = 100^\circ C \quad T_t = 150^\circ C \quad T_t = 200^\circ C \]

Eng. stress (MPa) vs. Eng. strain (%)
Fracture surface
Unirradiated Au alloy
(75Au-9Ag-16Cu)

YUI01, 25°C

YUI02, 150°C X500

X500

X5000
Y07, 25°C
T_i=116°C (7.3dpa)

Y08, 100°C
T_i=149°C (10.8dpa)

Y07, 25°C
T_i=195°C (15.2dpa)

Y08, 100°C
T_i=235°C (18.9dpa)

Y04, 25°C
T_i=116°C

Y06, 150°C
T_i=149°C

Y04, 25°C
T_i=195°C

Y06, 150°C
T_i=235°C

Y05, 25°C
T_i=195°C

Y02, 200°C
T_i=235°C

Y05, 25°C
T_i=195°C

Y02, 200°C
T_i=235°C

Y03, 25°C
T_i=195°C

Y03, 25°C
T_i=235°C
Result – Pt alloys (95Pt-5Au)

◆ After irradiation

![Graph showing engineering stress vs. engineering strain for different temperatures and doses.]
$T_i = 150^\circ C$

$T_i = 196^\circ C$
(10.8 dpa)

$T_i = 200^\circ C$

$T_i = 261^\circ C$
(15.2 dpa)

$T_i = 250^\circ C$

$T_i = 360^\circ C$
(18.9 dpa)
- Tensile tests and fracture surface investigation were performed on Au and Pt alloys irradiated on STIP-II in order to know design data of mechanical properties on these.

- Au alloy (75Au-9Ag-16Cu) showed good tensile strength and elongation before proton irradiation.

- Significant ductility loss occurred after irradiation.

- Only samples tested at 150°C (Y06) and 200°C (Y02) showed significant loose of strength, which is more like embrittlement.

- The sample irradiated above 200°C (Y03, T_t=RT) shows rather ductile fracture surface.

- May be due to the gases (He, H) introduce by irradiation.

- Pt alloy (95Pt-5Au) showed rather unique deformation, which is kind of one side slip deformation.

- No significant deformation features were observed after irradiations for Pt alloys except for the UTS increase of about 200MPa.
Spallation neutron source for ADS

- MEGAPIE project in cooperation with PSI, ESS(CNRS, CEA, ENEA, FZ, SCK-CEN), JAERI, LANL, KAERI.
- Materials issues for the beam window, protons/LBE.
- In-situ test at LiSoR, 72MeV-P, flowing LBE and stress
- MEGAPIE run in 2006.8-12, at 0.75MW.
- MEGAPIE target samples will ship this year/2009.
- MIRRAH / SCK-CEN plans XADS (EU)
- PSI plans power-up in neutron flux in LIMETS.
- J-PARC Phase-II plans experiment facility for ADS.
the MEGAPIE target

final assembly

inserting the target into SING with the exchange flask
MEGAPIE LBE target, 600MeV, 1.2mA / PSI

Dai, PSI
The GOALS of LIMETS

Liquid Metal Target for routine operation at SINQ

which must (should) be

- safe
- robust
- easy to operate
- simple & reliable
- efficient
- interesting to a wider community
- cheaper than MEGAPIE
LiMeTS mock-up design (stage 1)

Basic technical parameters:

► Modular design allowing testing of different concepts of the THX, EMP, BEW

► Existing EMP (prototype of EMP1 for MEGAPIE) is adopted for the mock-up

► Working fluid PbBi eutectic (melting temp. 126°C) or Pb (327°C), volume 65 l

► Maximum operating temperature – 500°C

► Liquid metal flowrate, nominal – 4 l/s

► Design pressure – 10 bar

► extensive instrumentation (temp., pressure, flow)

► Electric heater – 170 kW (former MEGAPIE test heater)
MYRRHA spallation target LBE loop

2.2 mA at 600 MeV

Bosch SCK·CEN
Image of ADS with window

Beam duct

Main pump

Spallation target

Blanket

Steam generator

Reactor vessel

JPCA, F82H

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Buckling mode of the beam window
Sugawara et al. NUMA
T releases from SS316(L) and F82H(R) by TDS method.

SS316 showed peak and F82 showed two peaks in release curves.

Thermal desorption behavior of light gases from STIP samples

Hydrogen isotopes

- $^3$He
- $^4$He

- $^4$He

- $^2$H

- $^3$H

He$^4$ ~1100°C

$^3$H$^4$He (atoms/s)

Temperature (°C)

316 SS (8.6 dpa)

Oliver, Dai, IWSMT7
Irradiation Damage on the window in the 800MWth ADS after 300 FPDs

Nishihara, Kikuchi, NUMA 2008

<table>
<thead>
<tr>
<th>Particle</th>
<th>I</th>
<th>P</th>
<th>N</th>
<th>C</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux (/cm²/s)</td>
<td>7.57E+13</td>
<td>5.53E+12</td>
<td>8.28E+13</td>
<td>4.32E+15</td>
<td>4.49E+15</td>
</tr>
<tr>
<td>Averaged energy (MeV)</td>
<td>1500</td>
<td>107</td>
<td>42</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Cross section (b)</td>
<td>224</td>
<td>1010</td>
<td>6.4</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Heat (MeV b)</td>
<td>2155</td>
<td>2148</td>
<td>1697</td>
<td>4.5E-3</td>
<td>419</td>
</tr>
<tr>
<td>DPA</td>
<td>1.59</td>
<td>12.78</td>
<td>0.338</td>
<td>7.3E-7</td>
<td></td>
</tr>
<tr>
<td>^1H</td>
<td>0.37</td>
<td>0.013</td>
<td>3.3E-3</td>
<td>4.9E-7</td>
<td></td>
</tr>
<tr>
<td>^2H</td>
<td>0.083</td>
<td>1.9E-3</td>
<td>3.4E-4</td>
<td>3.5E-11</td>
<td></td>
</tr>
<tr>
<td>^3H</td>
<td>0.066</td>
<td>1.4E-3</td>
<td>1.3E-4</td>
<td>5.8E-4</td>
<td></td>
</tr>
<tr>
<td>^3He</td>
<td>0.36</td>
<td>0.039</td>
<td>0.021</td>
<td>375</td>
<td></td>
</tr>
<tr>
<td>^4He</td>
<td>229</td>
<td>75</td>
<td>7.2</td>
<td>63</td>
<td>375</td>
</tr>
<tr>
<td>Reaction Heat (W/cm³)</td>
<td>4.2</td>
<td>0.31</td>
<td>3.6</td>
<td>47</td>
<td>55</td>
</tr>
<tr>
<td>DPA (300 FPDs)</td>
<td>3119</td>
<td>1831</td>
<td>725</td>
<td>503</td>
<td>6179</td>
</tr>
<tr>
<td>^1H (appm,300 FPDs)</td>
<td>727</td>
<td>1.8</td>
<td>7.2</td>
<td>0.082</td>
<td>736</td>
</tr>
<tr>
<td>^2H (appm,300 FPDs)</td>
<td>163</td>
<td>0.27</td>
<td>0.72</td>
<td>0.054</td>
<td>164</td>
</tr>
<tr>
<td>^3H (appm,300 FPDs)</td>
<td>130</td>
<td>0.20</td>
<td>0.28</td>
<td>3.9E-6</td>
<td>130</td>
</tr>
<tr>
<td>^3He (appm,300 FPDs)</td>
<td>709</td>
<td>5.5</td>
<td>45</td>
<td>65</td>
<td>825</td>
</tr>
</tbody>
</table>

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He bubble formation on JPCA was observed at lower temperature compared to EC316LN on STIP-I irradiated samples.

Effect of Ti modification?

Ti as an over sized atom lowers the mobility of vacancies.

<table>
<thead>
<tr>
<th>wt%</th>
<th>Fe</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Mn</th>
<th>Ti</th>
<th>C</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPCA</td>
<td>Bal.</td>
<td>14.14</td>
<td>15.87</td>
<td>2.29</td>
<td>1.54</td>
<td>0.22</td>
<td>0.058</td>
<td>0.5</td>
<td>0.026</td>
<td>0.004</td>
<td>0.003</td>
</tr>
<tr>
<td>316LN</td>
<td>Bal.</td>
<td>17.45</td>
<td>12.2</td>
<td>2.5</td>
<td>1.81</td>
<td>-</td>
<td>0.024</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
<td>0.067</td>
</tr>
</tbody>
</table>

Workshop on AHIPA, Fermi, Oct. 2009 / Kikuchi

D. Hamaguchi, JNM 343 (2005) 262
In the sample irradiated to 19.5dpa to 450°C, some bubble agglomeration to boundaries is observed.

Agglomeration was not observed on the sample irradiated to 10.1dpa, 350°C.

Any influence on mechanical properties?
DBTT shift of F/M steels

Dai and Wagner, NUMA
Topics of material issues

- Spallation neutron source design needed proton irradiation data
- IWSMT1, 1996, ORNL
- STIP started in PSI, 1997
- Pressure wave and neutronic test were done at AGS/BNL, 24GeV, 1997
- Ductility remains in Ta spent target at ISIS, 8dpa
- Ductility loss in SS316L irradiated by proton at LANL, 4-5dpa
- Pitting found in Hg container for short pulse source
- Life time of Hg container is decided by pitting damage > irradiation damage
- Guideline for exchange is 5dpa in Hg target vessel
continued

- Modified SS316, JPCA, kept ductility up to 12dpa, AccApp03
- Compressive test of W LANSCE spent target shows no collapse
- STIP-III data for 19dpa stainless steels remains ductility and no intergranular fracture
- ORNL-SNS decided extension of life to 10 dpa at IWSMT9
- Consideration of weight balance in pitting and irradiation under full power
- A short pulsed target issue needs to deal with high intensity and neutron flux
- Solid target approach for high intensity power at CSNS, SNS-T2, ESS-BIBAO?
- LANL evaluation on W erosion

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