Overview of materials research for LFR in China

— R & D of SIMP steel for LFR

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2. Institute of Metal Research, CAS

Oct. 15–17, 2019, VIC, Vienna, AUSTRIA
Outline

1. Motivation
2. R & D of SIMP steel
3. Summary & Future works
**Motivation**

LFR — One of advanced nuclear energy systems

LFR — advantages:
- Sustainability
- Safety
- Economy

Plans ——
- SVBR-100 and BREST in Russia
- ELSY, ALFRED, MYRRHA in Europe
- SSTAR in USA
- ...

China —— Small module lead cooled reactors,
CiADS (China inititave Accelerator Driven System), ...

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Motivation

CiADS (China initiative Accelerator Driven System)

Design sketch

Construction site
### Motivation

**Materials serve in extreme conditions**

**Challenges for materials**

<table>
<thead>
<tr>
<th></th>
<th>Thermal neutron fission reactor</th>
<th>Fast reactor</th>
<th>Fusion reactor</th>
<th>ADS</th>
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</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>300 - 900</td>
<td>350 - 600</td>
<td>300 - 600</td>
<td>300-800</td>
</tr>
<tr>
<td>Damage rate (dpa/year)</td>
<td>Up to 2</td>
<td>20</td>
<td>20 - 30</td>
<td>100</td>
</tr>
<tr>
<td>Yield of He (appm/dpa)</td>
<td>Up to 10*</td>
<td>~ 0.2</td>
<td>10 - 15</td>
<td>~100</td>
</tr>
</tbody>
</table>
Motivation

Material — Bottleneck for R&D of LFR
### Motivation

**Candidate materials for R&D of LFR**

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>MYRRHA</th>
<th>EFIT</th>
<th>ELFR(ELSY)</th>
<th>ALFRED</th>
<th>BREST-OD-300</th>
<th>SVBR-100</th>
<th>SSTAR</th>
<th>DLFR</th>
<th>JAEA’s reference</th>
<th>ADS</th>
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</thead>
<tbody>
<tr>
<td>Developer</td>
<td>SCK•CEN</td>
<td>EURATOM</td>
<td>EURATOM</td>
<td>EURATOM</td>
<td>NIKIET (Russia)</td>
<td>AKME (Russia)</td>
<td>DOE National Laboratories</td>
<td>Westinghouse</td>
<td>JAEA</td>
<td></td>
</tr>
<tr>
<td>Power (MWt/MW)</td>
<td>110/</td>
<td>400/</td>
<td>1500/600</td>
<td>300/</td>
<td>700/300</td>
<td>280/100</td>
<td>45/20</td>
<td>500/210</td>
<td>800/</td>
<td></td>
</tr>
<tr>
<td>Primary system type</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td>Pool</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>(U-Pu)O₂,MOX</td>
<td>U-free Pu+MA</td>
<td>(U-Pu)O₂,MOX</td>
<td>MOX</td>
<td>(U+Pu+MA)N</td>
<td>UO₂, mixed oxide, UPuN</td>
<td>TRU Nitride-N15 enriched</td>
<td>UO₂</td>
<td>(Pu+MA)N+ZrN</td>
<td></td>
</tr>
<tr>
<td>Coolant</td>
<td>LBE</td>
<td>Pb</td>
<td>Pb</td>
<td>Pb</td>
<td>Pb</td>
<td>Pb</td>
<td>LBE</td>
<td>Pb</td>
<td>Pb</td>
<td>LBE</td>
</tr>
<tr>
<td>Inlet/outlet (°C)</td>
<td>270/400</td>
<td>400/480</td>
<td>400/480</td>
<td>400/480</td>
<td>420/540</td>
<td>340/490</td>
<td>420/567</td>
<td>390/510</td>
<td>300/410</td>
<td></td>
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<tr>
<td>Cladding</td>
<td>15-15Ti/T91</td>
<td>T91</td>
<td>T91, Fe-Al coated</td>
<td>15-15Ti</td>
<td>FM</td>
<td>EP823</td>
<td>Si-enhanced FM steel</td>
<td>D9 coated with Al₂O₃</td>
<td>First :T91 or F82H Second: 316 or JPCA</td>
<td></td>
</tr>
<tr>
<td>Wrapper</td>
<td>T91</td>
<td>T91</td>
<td>T91</td>
<td>15-15Ti/T91 Aluminized</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D9 First :T91 or F82H Second: 316 or JPCA</td>
<td></td>
</tr>
<tr>
<td>Steam generators</td>
<td>T91</td>
<td>T91</td>
<td>T91</td>
<td>T91/316L</td>
<td>EP302-M</td>
<td></td>
<td>316L/347, possibly coated</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Primary Pump</td>
<td>MAXTHAL,316L</td>
<td>MAXTHAL (Ti₃SiC₂)</td>
<td>MAXTHAL ,316L</td>
<td>Al, Ta coated</td>
<td>T91, 316L, MAXTHAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor Vessel</td>
<td>316L</td>
<td>316L,Al coated</td>
<td>316L</td>
<td>316L</td>
<td></td>
<td>316(L) First :T91 or F82H Second: 316 or JPCA</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
R&D of new structural material (for future ADS)

Properties: Significant tolerance to high-T, dpa, LBE

- The existing reactor materials cannot be directly used as LFR and ADS structure materials.
- Material / LBE compatibility data is limited.
- Synergetic effect of irradiation/LBE/high-T is lack of study.
Outline

1. Motivation
2. R & D of SIMP steel
3. Summary & Future works
R & D of SIMP steel

Collaboration ——
Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS)
IMR Institute of Metal Research(IMR), CAS

SIMP steel —— FeCr base martensitic alloy

Steel designed by IMP-CAS and IMR-CAS

Supported by Strategic science and technology leading project of Chinese Academy of Sciences
Chemical composition design

9-12Cr martensitic steels: good creep property

1%-2% Si containing ferritic/martensitic steels exhibit lower oxidation rate
Microstructure design

Tempered martensite:
Excellent thermal stability and good irradiation and corrosion resistance

Microstructure thermal stability
- T/P91, T/P92
- Tempered martensite

Radiation resistance
- Euro97, F82H, 9Cr2WVTa, CLAM, JLF-1
- Tempered martensite

Liquid metal corrosion resistance
- EP823
- Mainly Tempered martensite

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Smelting & casting

Industrial grade!

Control: purity, homogeneity, mechanical property
The mechanical of SIMP steel is superior to T/P91 in a temperature range from RT to 550 °C.
Processing

- **Tubes/pipes**
  - Ø60mm × 10mm
  - Ø60mm × 5mm
  - Ø60mm × 1mm
  - Ø5mm × 1mm

- **Thin foil**

- **Panel / plate**

- **Component**
Welding property

Welding property assessment (ASME code)

- Mean impact energy at weld: 117J
- Mean impact energy at HAZ: 81J

SIMP steel shows good weldability and satisfactory post-weld ductility
Liquid LBE corrosion resistance

450°C/600 °C, static, saturation oxygen

Liquid LBE corrosion resistance:
SIMP is better than T91
Liquid LBE corrosion resistance

600 °C, static, saturation oxygen

Liquid LBE corrosion resistance:
SIMP is better than T91
Oxidation resistance in supercritical water

Corrosion Test in SC Water
(600℃, 25MPa, 1000h)

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Cr</th>
<th>Mn</th>
<th>W</th>
<th>Ta</th>
<th>V</th>
<th>Nb</th>
<th>Ni</th>
<th>Mo</th>
<th>S/ppm</th>
<th>P/ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMP</td>
<td>0.22</td>
<td>1.22</td>
<td>10.24</td>
<td>0.52</td>
<td>1.45</td>
<td>0.12</td>
<td>0.18</td>
<td>0.01</td>
<td>—</td>
<td>—</td>
<td>43</td>
<td>40</td>
</tr>
<tr>
<td>T/P91</td>
<td>0.1</td>
<td>0.26</td>
<td>8.5</td>
<td>0.46</td>
<td>—</td>
<td>—</td>
<td>0.20</td>
<td>0.04</td>
<td>0.17</td>
<td>0.92</td>
<td>20</td>
<td>30</td>
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<tr>
<td>T/P92</td>
<td>0.1</td>
<td>0.38</td>
<td>8.63</td>
<td>0.42</td>
<td>1.59</td>
<td>—</td>
<td>0.164</td>
<td>0.053</td>
<td>0.15</td>
<td>0.37</td>
<td>10</td>
<td>14</td>
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<tr>
<td>TP347</td>
<td>0.08</td>
<td>0.6</td>
<td>18</td>
<td>1.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.8</td>
<td>10</td>
<td>—</td>
<td>&lt;30</td>
<td>&lt;40</td>
</tr>
<tr>
<td>304</td>
<td>0.09</td>
<td>&lt;0.03</td>
<td>18</td>
<td>&lt;1.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.05</td>
<td>9.7</td>
<td>—</td>
<td>&lt;10</td>
<td>&lt;40</td>
</tr>
</tbody>
</table>

304, TP347: 奥氏体不锈钢
SIMP, P91, P92: 马氏体不锈钢

[Graph showing weight gain per mg/m² for different steels under SC water conditions]
Ion irradiation swelling resistance:

SIMP > T91 > RAFM*

Samples are irradiated at the same condition

196 MeV Kr ions swelling at the damage peak

SIMP steels irradiated at SINQ-PSI, (n/p, ~ 20dpa, 2012-2014)
Post Irradiation Examination (PIE) is under way.
Ion irradiation resistance

He-effect

Samples are at the same condition

Mean size of helium bubbles, $5 \times 10^{16}$ ions/cm$^2$, 200 keV He ions

He-bubble size: SIMP < T91
Irradiation/LM corrosion resistance

Irradiation/LM corrosion resistance

247MeV Ar, 350°C, LBE-SO, 0.6 m/s, J Nucl Mater 523 (2019) 260
Outline

1. Motivation

2. R & D of SIMP steel

3. Summary & Future works
1. SIMP steel, a novel FeCr base martensitic alloy, was developed;

2. An industrial scale of 5 tons SIMP steel ingots have been produced.

3. A series of tests shown that SIMP steel exhibits good performance under processing, high temperature, liquid metal and ion irradiation.

4. The synergistic effect of irradiation and liquid LBE is a key issue for the future development of SIMP steel.
Future works

- **Database**

Evaluations at “true” environment — Synergetic effects
(Coolant, DPA, High-T, Dopant, Stress, ...)

- **Criteria/standard + License + …**

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Thank You!

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