The effect of lead bismuth eutectic on structural materials for the accelerator driven system MYRRHA

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MYRRHA = Accelerator Driven System

Key Objectives

1. Demonstrate the ADS concept at pre-industrial scale
2. Demonstrate transmutation
3. Multipurpose and flexible irradiation facility (with fast neutron source)

Accelerator
- particles: protons
- beam energy: 600 MeV
- beam current: 2.4 to 4 mA

Reactor
- power: 65 to 100 MW$_{th}$
- $k_{eff}$: 0.95
- spectrum: fast
- coolant: LBE

Target
- main reaction: spallation
- output: $2 \times 10^{17}$ n/s
- material: LBE (coolant)

Source: SCK•CEN MYRRHA Project Team, MYRRHA Business Plan
MYRRHA is a multipurpose research facility, addressing end-markets with both significant societal and economic impact.
Goal of the materials program

Provide data and information for a justified materials choice in the design

- Liquid metal corrosion & erosion
- Mechanical properties in liquid metals
- Materials in accidental conditions
- Return of experience/Literature research

Practical considerations lead to a pre-selection of 316L, 1515Ti, T91
Materials research is not a linear process

- Parameter studies
- Long term experiments
- Mitigation strategies
- Feasibility studies

- Very high temperatures experiments
- Temperature excursions
- Burst testing

- Tensile, Fracture, Fatigue
- Specialized installations
- Welding
- Reference testing

- Return of experience
- Material justifications
- Q/A procedures

Liquid metal corrosion & erosion

Mechanical properties in liquid metals

Accidental conditions

Material choices and justifications
MYRRHA materials R&Q program principal directions

- Identification of materials issues
  - Collaboration with designers, fuel, safety and coolant chemistry groups
  - Learning lessons from Gen II/III
  - (Pre-)licensing activities
  - Assistance in design
    - Materials choice justification
    - Various scenarios related to materials failure
    - Preliminary assessment of materials damage mechanisms
    - Support for development of surveillance programs

- Assessment of materials properties & qualification of materials
  - Basic mechanical characterization
  - Development of testing procedures
  - Identified materials issues and related R&D program
    - Liquid Metal Corrosion (LMC)
    - Effect of LBE on mechanical properties
    - Irradiation effects
    - Synergetic effects
  - Irradiation experiments

- Development of testing infrastructure
Large scale LBE facilities in support of MYRRHA R&D

- Corrosion loop: CRAFT – in operation
- Chemistry test loop: MEXICO – in operation
- Fracture toughness & fatigue setups: LIMETS 3 & 4 – in operation
- Filter test loop: LILLIPUTTER – in operation
- Robotics test facility: RHAPTER – in operation
- Oxygen conditioning facility: HELIOS III – in operation
- Components test loop COMPLOT – end of commissioning phase
- Thermal Hydraulics test pool ESCAPE – under construction
Specialized set-ups for mechanical tests in LBE

**LIMETS 1**
Tensile & Fracture toughness tests in LBE

**LIMETS 2**
Tensile and FT tests of irradiated* steels in liquid metal

*Licensed for α (Po) contaminated specimens

**LIMETS 3**
Fatigue tests in LBE
Commissioning stage

**LIMETS 4**
Tensile & Fracture toughness tests in LBE

**Hot cell 12 & LIMETS 2**
Tensile and FT tests of irradiated* steels in liquid metal

*Licensed for α (Po) contaminated specimens
Materials degradation effects to be investigated

- Liquid Metal Embrittlement (LME)
- Liquid Metal Corrosion (LMC)
- Irradiation effects/synergetic effects
Liquid Metal Embrittlement (LME) effect

Degradation of steel’s mechanical properties in contact with liquid metal

Potentially can affect:
- Tensile properties
  - Total elongation
- Fracture toughness
- Fatigue properties
  - Endurance
  - Crack Growth Rate
- Creep properties
  - Creep rate
- Creep-fatigue properties
Effect of dissolved oxygen concentration

Stress-strain curves of **T91 steel** in Ar+5%H₂ and in LBE at 350 °C and at strain rate at 5·10⁻⁵s⁻¹.
### Fracture toughness of T91 in LBE

<table>
<thead>
<tr>
<th>Test environment</th>
<th>Test temperature (°C)</th>
<th>Pre-cracking environment</th>
<th>Average $J_Q$ (kJ/m²)</th>
<th>Fracture surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar-5%H₂</td>
<td>350</td>
<td>Air</td>
<td>417 ± 23</td>
<td>Ductile</td>
</tr>
<tr>
<td>LBE</td>
<td>350</td>
<td>Air</td>
<td>303 ± 4</td>
<td>Ductile with quasi-cleavage side cracks</td>
</tr>
<tr>
<td>LBE</td>
<td>350</td>
<td>LBE</td>
<td>63 ± 14</td>
<td>Quasi-cleavage</td>
</tr>
</tbody>
</table>

85 % reduction in fracture toughness in LBE

Investigation of susceptibility of 316L

SSRT

Fractography

Fatigue

ln N = 6.891 - 1.92 ln(ε_a - 0.112) (Chopra and Shack, 2007)

ln N = 6.954 - 2.0 ln(ε_a - 0.167) (ASME Code Mean Curve)

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Materials tested at SCK•CEN for susceptibility to LME by SSRT

- **T91** DEMETRA heat - screening tests completed - > susceptible
  - Irradiated - screening tests completed - > susceptible
- **316L** DEMETRA heat - > screening tests completed - > not susceptible
  - Irradiated (up to 30dpa) - > not susceptible
- **1.4970** - > screening tests completed
  - Solution annealed - > not susceptible
  - Cold worked - > not susceptible
  - Cold Worked+irradiated - > not susceptible
- **CLAM & Si doped CLAM** - > susceptible
- **Eurofer 97 heat 2** - screening tests completed - > susceptible
- **EP-823** analog - screening tests completed – very susceptible
- **Si doped FeCr** steels - > screening tests completed – very susceptible
- **Fe10CrAl (exp. heat)** - > screening tests completed – > susceptible
- **ODS 12%Cr (KOBELCO)** - > screening tests completed - > susceptible
Options to handle LME for design

- To use materials, which are not susceptible to LME
  - Pro: readily available materials & data (ideally in construction codes)
  - Con: significant reduction of candidate materials
  - Challenges: demonstration of immunity

- Incorporation of LME by reduction of mechanical properties
  - Pro: widening list of candidate materials
  - Con: extensive research, development and qualification required
  - Challenges: how to define the ‘reduction’

- Mitigation techniques
  - Pro: ‘vanishing’ of susceptibility
  - Con: extensive research, development and qualification required
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Liquid metal corrosion

1. **Oxidation**
   - Multi-layered oxide scales form in contact with O-containing LBE on steel surface
   - If protective at service conditions, oxide scales minimize further attack of steel by LBE

   **316**: 500°C, 4000 h
   (S. Gavrilov, SCK•CEN data)

2. **Dissolution**
   - Loss of steel alloying elements (Ni, Mn, Cr)
   - LBE penetration
   - Ferritization of dissolution zone due to loss of austenite stabilizers (Ni, Mn)

   **316L**: 500°C, ∼4000 h, $7 \times 10^{-7}$ wt%, 2m/s LBE
   (S. Gavrilov, SCK•CEN data)

3. **Erosion**
   - Severe material loss & compromise of structural integrity
   - Observed at high LBE flow velocities, two-phase flow, and sites of flow diversion

   **316L**: 600°C, 2000 h, $C_0 \approx 10^{-6}$ wt%, flowing LBE ($v \approx 2$ m/s)
Temperature Dependence of 316L Dissolution Corrosion

- Cold-drawn 316L steel heats
- Solution-annealed 316L steel heat

Corrosion layer thickness vs. Temperature, °C

- 316LH1
- 316LH3
- 316L Demetra
- 316LH4
- 316LH2
Temperature Dependence of 316L Dissolution Corrosion

- LBE penetration faster than dissolution (leaching)
- LBE penetration & leaching: equally fast

Corrosion layer thickness vs. Temperature, °C
Temperature Dependence of 316L Dissolution Corrosion

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- LBE penetration & leaching: equally fast

Solution-annealed 316L steel heat

Cold-drawn 316L steel heats
SCK•CEN corrosion data base

- **316L -> tentative design correlation**
  - solution annealed, cold drawn, controlled deformation (20, 40, 60 %), components
  - \( T: 350 \div 550 \, ^\circ \text{C} \)
  - \( t: \) specimens up to 20.000 h / components up to 100.000 h (>11 years)
  - \([O]: \) very low ( <\( 10^{-12} \) wt. %), controlled (\( 10^{-5}, 10^{-6}, 10^{-7} \) wt.%), saturation
  - Stagnant and flow (up to 2.2 m/s)
  - Irradiated up to 35 dpa in contact with LBE

- **1.4970 -> tentative design correlation**
  - AIM1, cold worked, reference cladding tubes, solution annealed, welded plugs
  - \( T: 350 \div 1000 \, ^\circ \text{C} \)
  - \( t: \) cladding tubes up to 20.000 h
  - \([O]: \) very low ( <\( 10^{-10} \) wt. %), controlled (\( 10^{-8}-10^{-4} \) wt.%)
  - Stagnant and flow (up to 2.2 m/s)
  - Irradiated up to 35 dpa in contact with LBE

- **T91, EP823, MAX phases, S2439, S2440, surface modifications**
Materials degradation effects to be investigated

- Liquid Metal Embrittlement (LME)
- Liquid Metal Corrosion (LMC)
- Irradiation effects/synergetic effects
Irradiation experiments

- **TWIN-ASTIR**
  - Irradiation experiment in BR2 reactor (SCK•CEN, Belgium)
  - Materials: T91, 316L, High Silicon Steels, welds
  - Doses: 0, 1.5 and 2.5 dpa
  - Environment: LBE & PWR water H₂O
  - Temperatures: 300-320°C (H₂O), 350-370°C & 460-490°C (LBE)
  - Specimens: Tensile, DCT, corrosion plates

- **LEXUR II**
  - Irradiation experiment in BOR-60 reactor (RIAR, Russia)
  - Materials: T91, 316L, 15-15Ti, ODS (Pb)
  - Doses: 0, 6÷35 dpa
  - Environment: LBE, Pb
  - Temperatures: 350°C (LBE) & 550°C (Pb)
  - Specimens: Tensile, DCT, corrosion discs, pressurized tubes
Strong influence of LBE on the tensile properties of irradiated T91
No influence of LBE on the tensile properties of irradiated 316L
~6 dpa in LBE tested in air

~6 dpa in LBE tested in LBE

0 dpa annealed in LBE tested in LBE
Belgian Government decision on September 7, 2018

- **Decision to build** in Mol a new large research infrastructure MYRRHA
- Belgium **allocated budget** of 558 M€ for the period 2019 - 2038:
  - 287 MEUR investment (CapEx) for building MINERVA (Accelerator up 100 MeV + PTF) for 2019 - 2026
  - 115 MEUR for further design, R&D and Licensing for phases 2 (accelerator up to 600 MeV) & 3 (reactor) for 2019-2026.
  - 156 MEUR for OpEx of MINERVA for the period 2027-2038
- **Establishment of an International Non-Profit Organization**
  - in charge of the MYRRHA facility for welcoming international partners
- **Political support** for establishing MYRRHA international partnerships
  - Belgium mandates Vice Prime Minister Kris Peeters for promoting and negotiating international partnerships
A jump in the future for innovation in Belgium