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

E. Stergar, S. Gavrilov, V. Tsisar, P. Marmy

SCK•CEN Belgian Nuclear Research Center

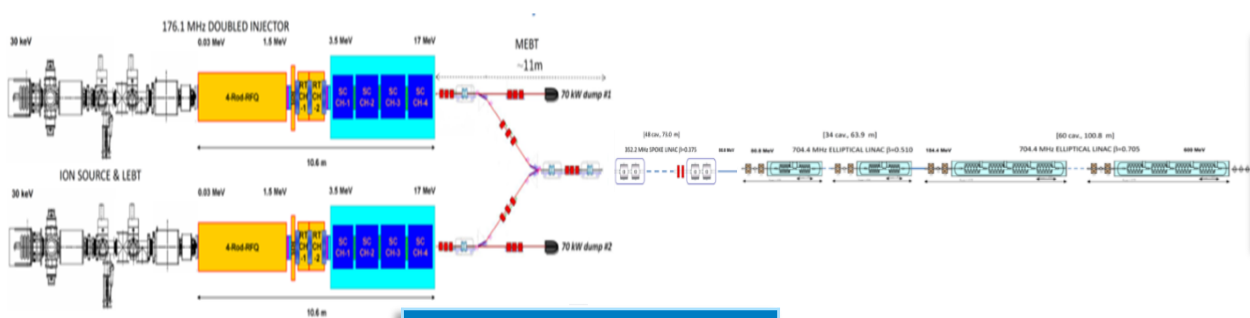
estergar@sckcen.be

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

MYRRHA = Accelerator Driven System

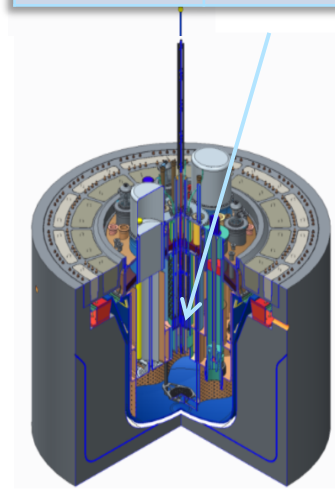
Key Objectives

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



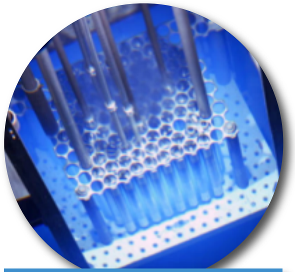
Accelerator	
particles	protons
beam energy	600 MeV
beam current	2.4 to 4 mA

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



Reactor	
power	65 to 100 MW_{th}
k_{eff}	**0,95**
spectrum	fast
coolant	LBE

MYRRHA is a multipurpose research facility, addressing end-markets with both significant societal and economic impact



Fission GEN IV

Waste

Radio-isotopes

Multipurpose
h**Y**brid
Research
Reactor for
High-tech
Applications

Fusion

Fundamental research

SMR LFR

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

→ Materials justification and Licensing

Practical considerations lead to a pre-selection of 316L, 1515Ti, T91

Materials research is not a linear process

Liquid metal corrosion & erosion

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

Mechanical properties in liquid metals

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

Accidental conditions

- Very high temperatures experiments
- Temperature excursions
- Burst testing

Material choices and justifications

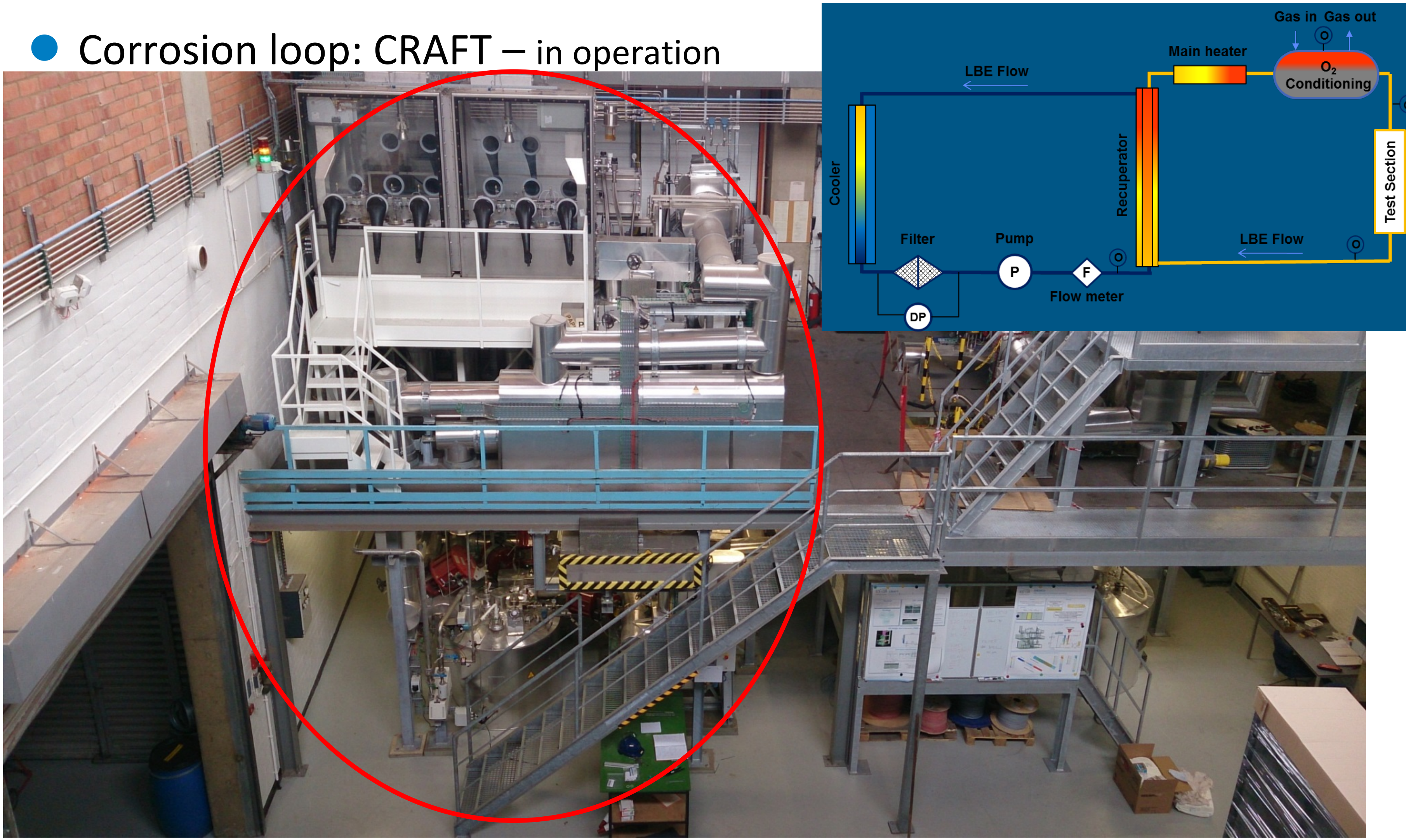
Return of experience
- Material justifications
- Q/A procedures

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



Specialized set-ups for mechanical tests in LBE

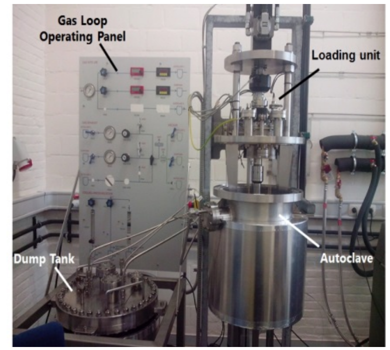
LIMETS 1

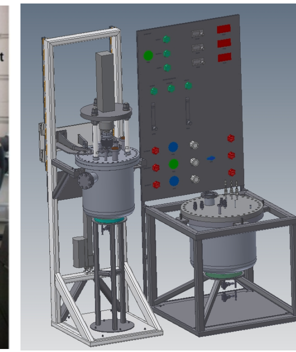
Tensile & Fracture toughness tests in LBE

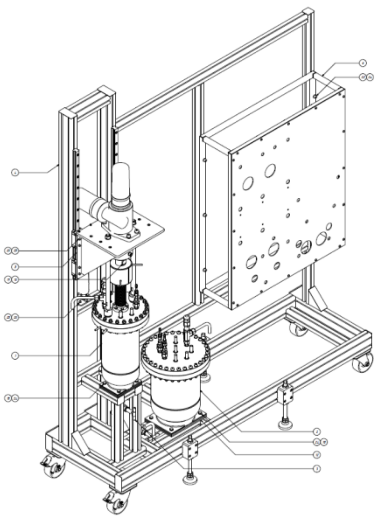
LIMETS 3

Fatigue tests in LBE

Commissioning stage







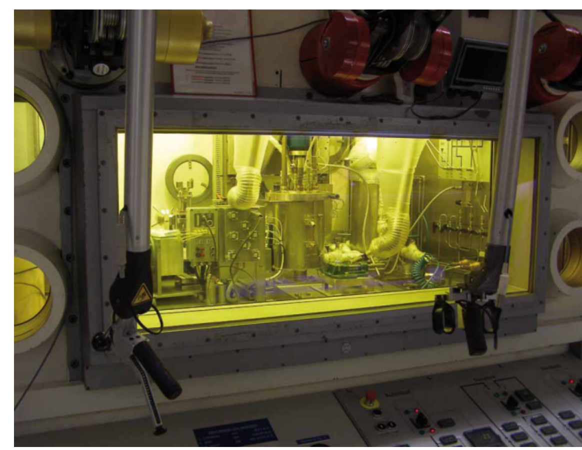
LIMETS 4

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

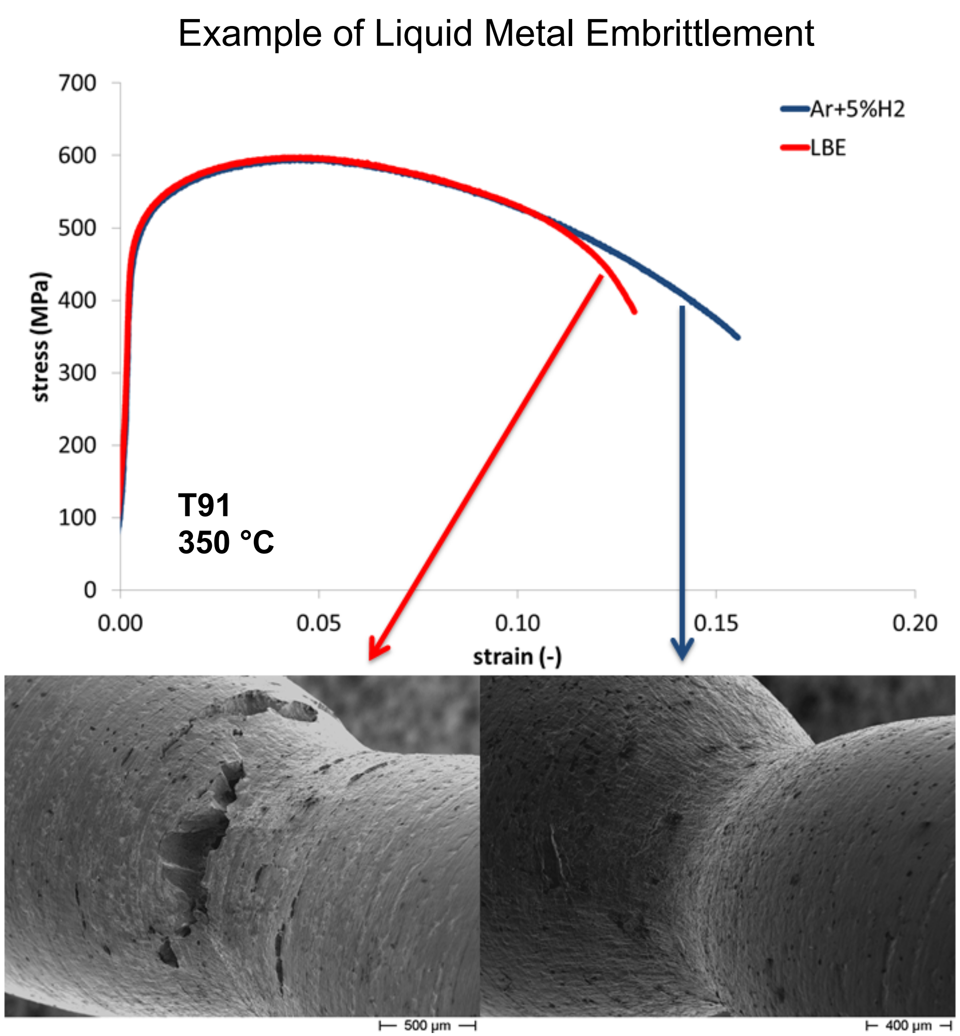
- Liquid Metal Embrittlement (LME)
- Liquid Metal Corrosion (LMC)
- Irradiation effects/synergetic effects

Liquid Metal Embrittlement (LME) effect

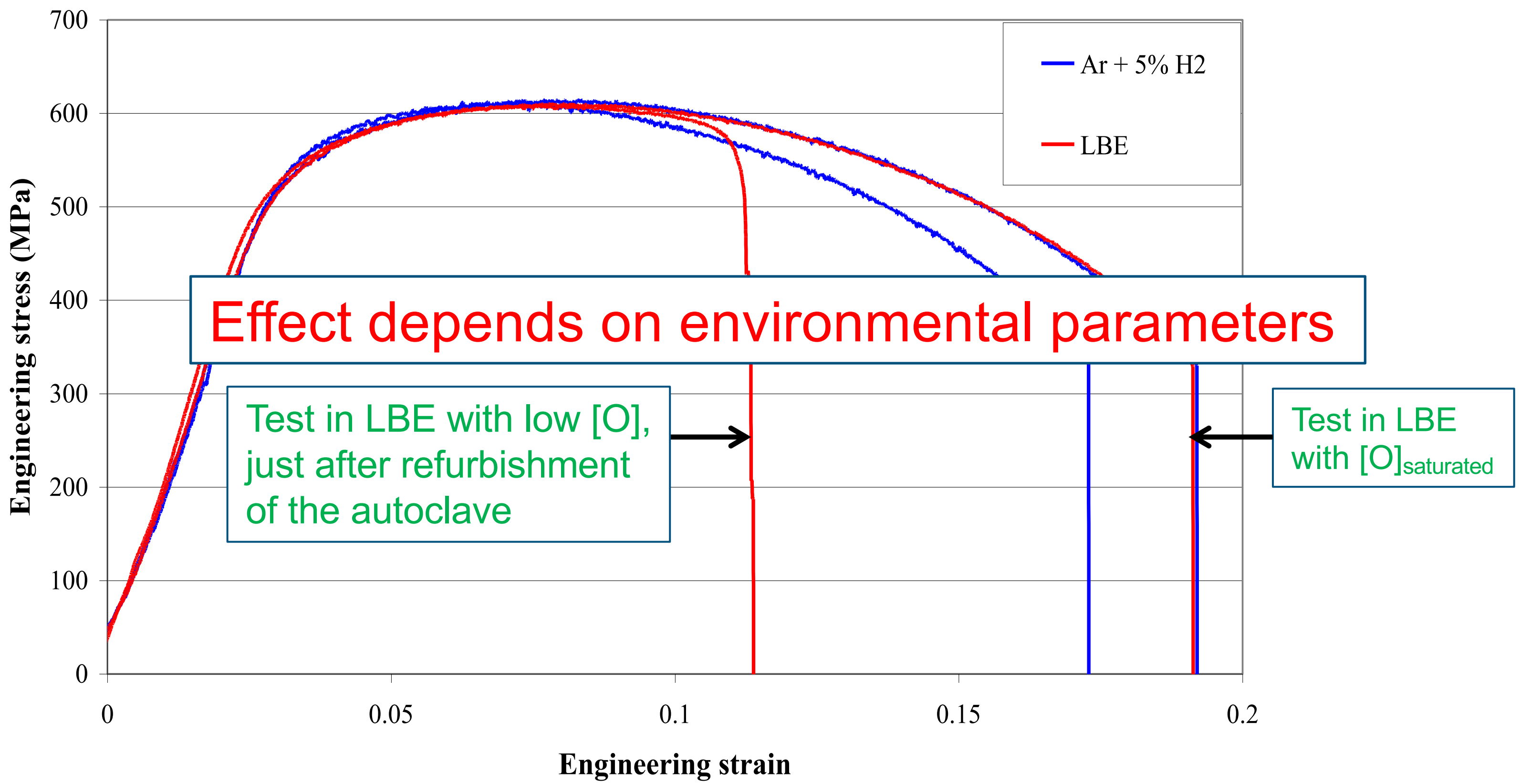
Degradation of steel's mechanical properties in contact with liquid metal

Potentially can affect:

- Tensile properties
  - Total elongation
- Fracture toughness
- Fatigue properties
  - Endurance
  - Crack Growth Rate
- Creep properties
  - Creep rate
- Creep-fatigue properties



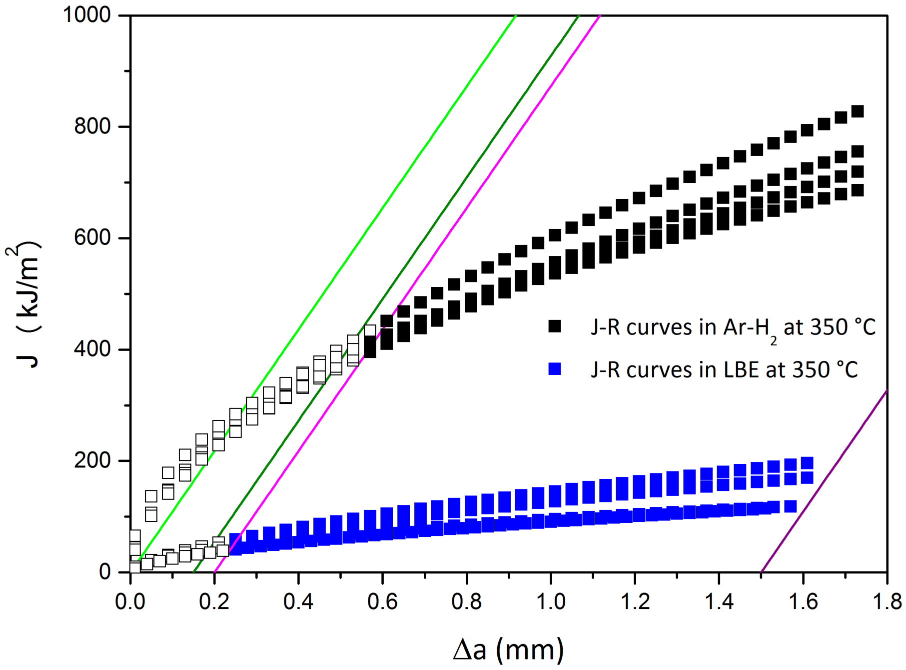
Effect of dissolved oxygen concentration



Stress-strain curves of **T91 steel** in Ar+5%H_2 and in LBE at 350 °C and at strain rate at $5 \cdot 10^{-5} s^{-1}$

Fracture toughness of T91 in LBE

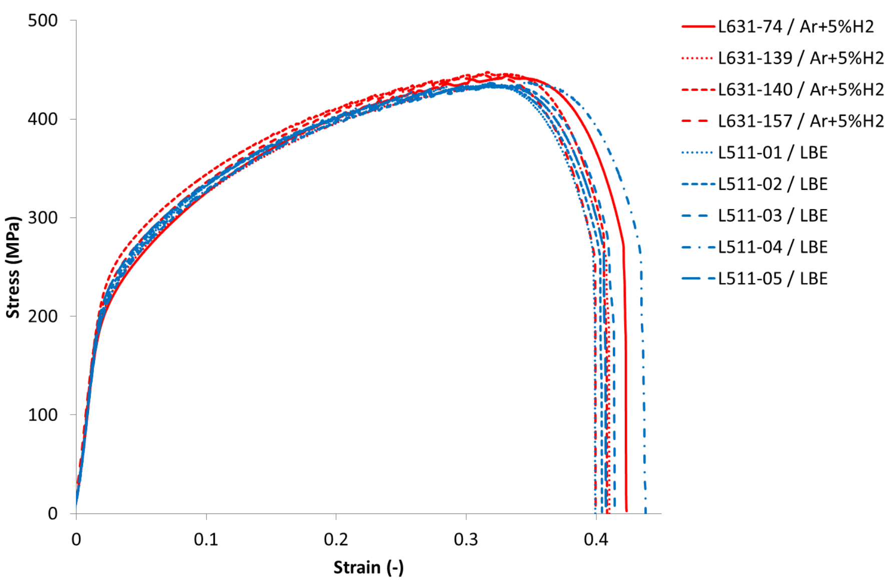
Test environment	Test temperature (°C)	Pre-cracking environment	Average J_Q (kJ/m^2)	Fracture surface
$Ar\text{-}5\%H_2$	350	Air	417 ± 23	Ductile
LBE	350	Air	303 ± 4	Ductile with quasi-cleavage side cracks
LBE	350	LBE	63 ± 14	Quasi-cleavage



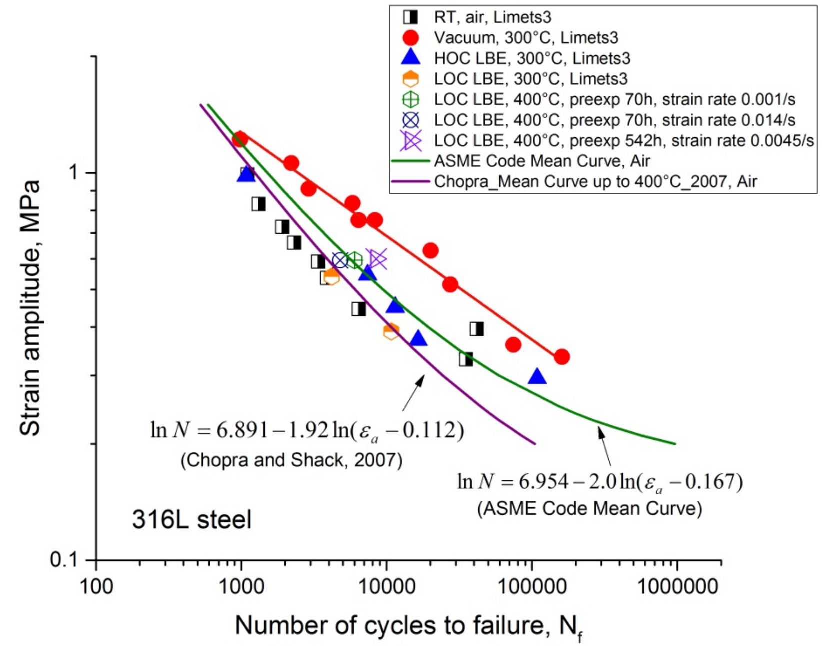
85 % reduction in fracture toughness in LBE

Ersoy, F.; Gavrilov, S. & Verbeken, K. Investigating liquid-metal embrittlement of T91 steel by fracture toughness tests, *Journal of Nuclear Materials*, **2016**, *472*, 171-177

Investigation of susceptibility of 316L

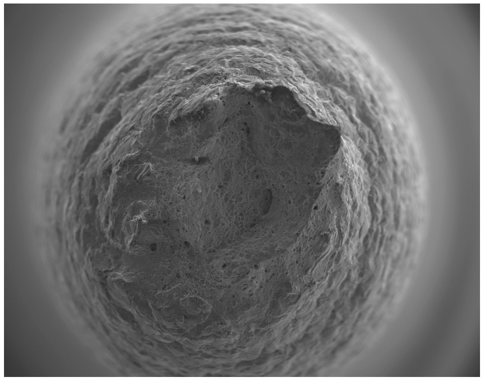


SSRT



Fatigue

Fractography



⊢ 600 µm ⊣

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
  - Challenges: to define and justify mitigation strategy

Options to handle LME for design

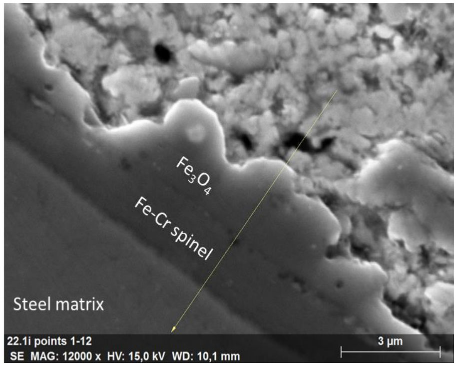
- To use materials, which are not susceptible to LME
  - Pro: readily available materials & data (ideally in construction codes)
  - Con: significant reduction of candidate materials
  - Challenges: demonstration of immunity
- Incorporation of LME by reduction of mechanical properties
  - Pro: widening 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
  - Challenges: to define and justify mitigation strategy

Materials degradation effects to be investigated

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

Liquid metal corrosion

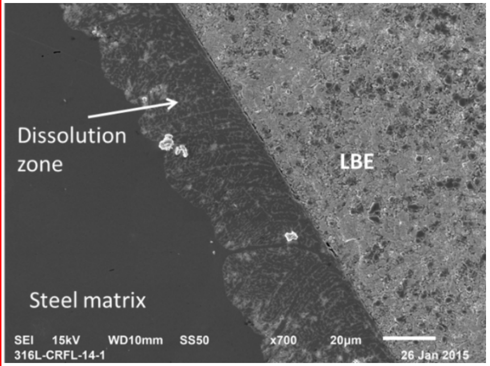
1. Oxidation



- 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*)

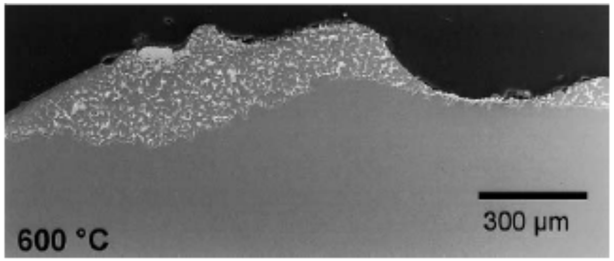
2. Dissolution



- 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, 7×10^{-7} wt%, 2m/s LBE
(S. Gavrilov, SCK•CEN data)

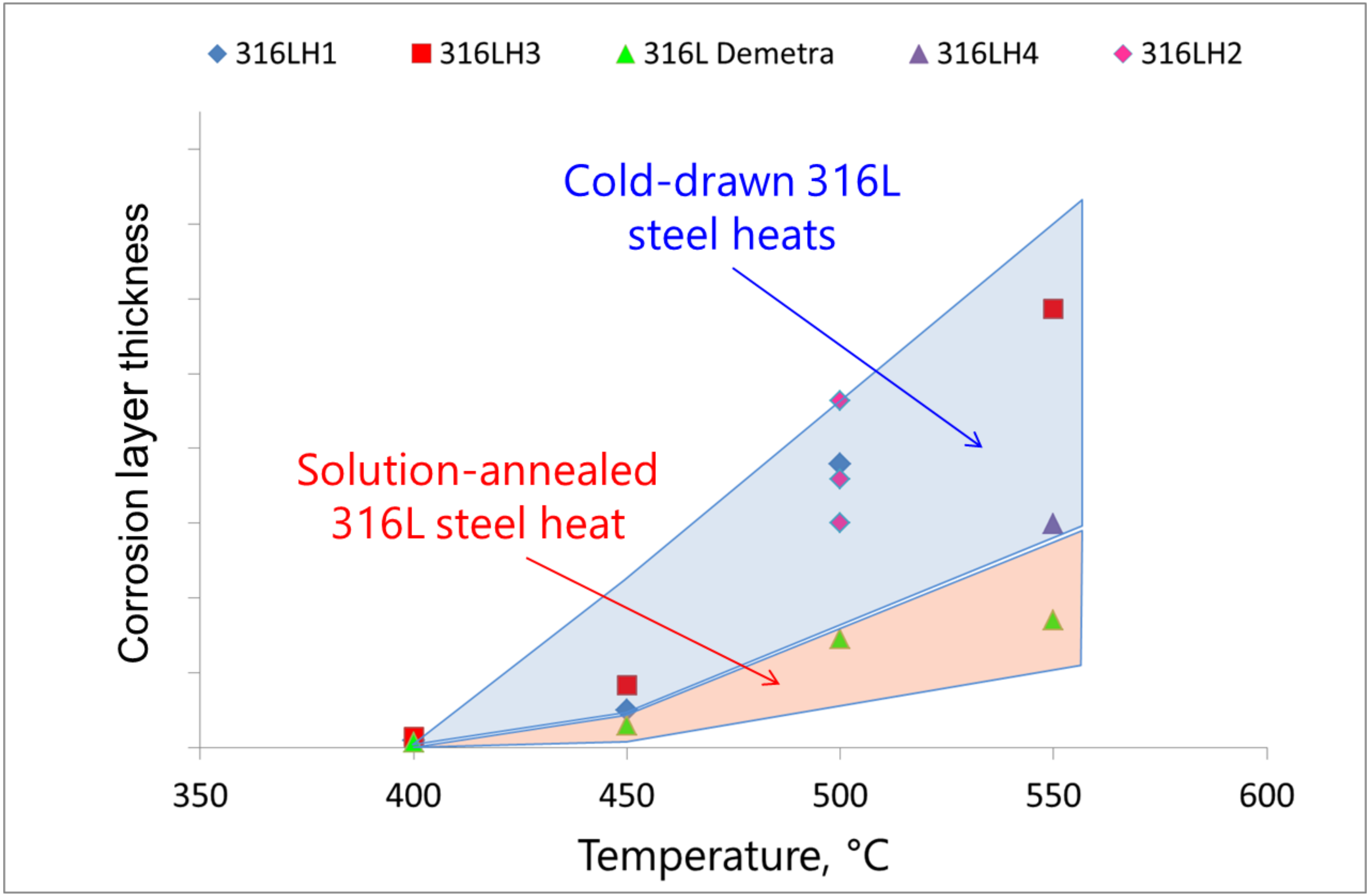
3. Erosion



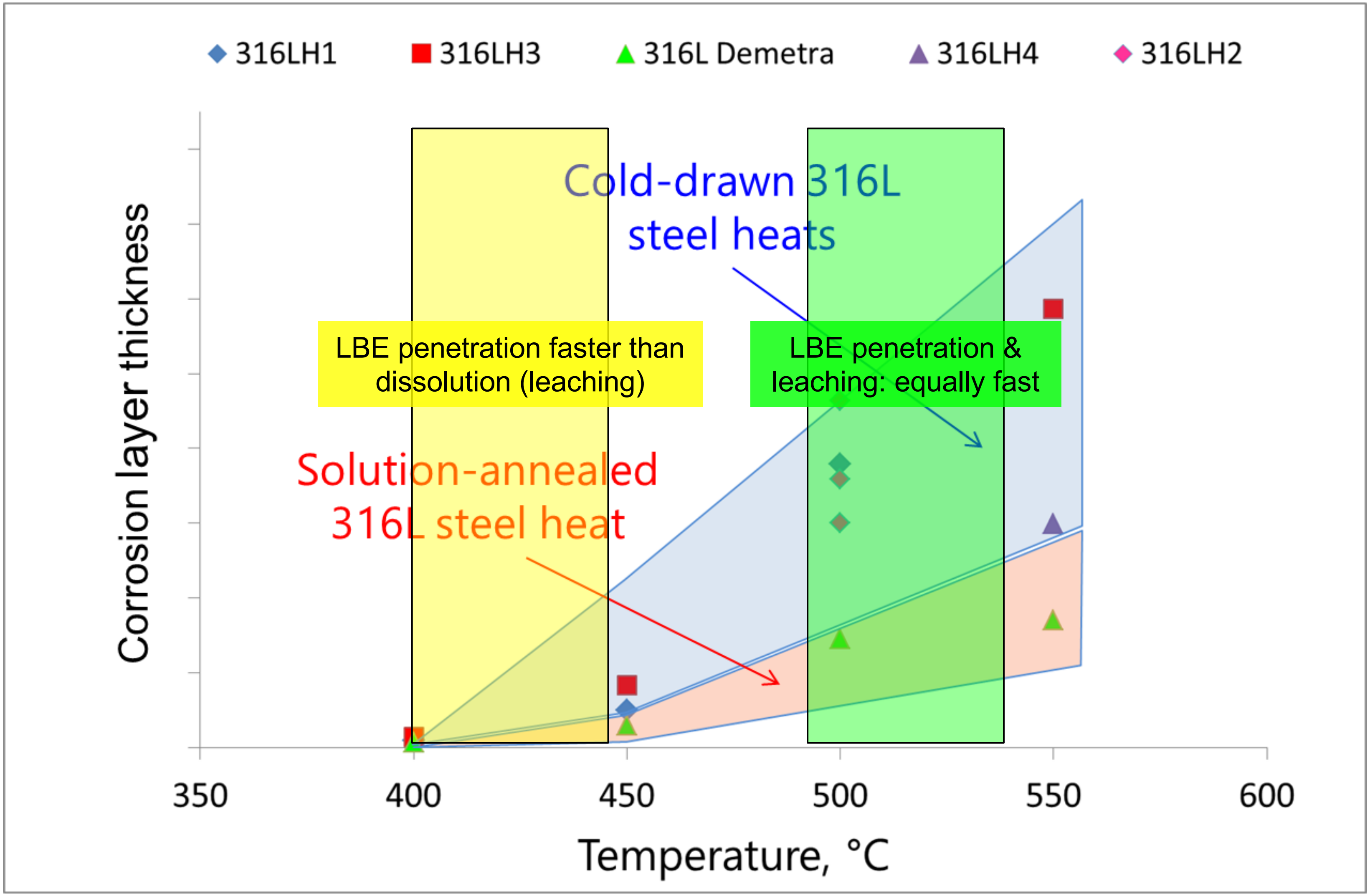
- Severe material loss & compromise of structural integrity
- Observed at high LBE flow velocities, two-phase flow, and sites of flow diversion

316L: 600°C, 2000 h, $C_O \approx 10^{-6}$ wt%, flowing LBE (v ≈ 2 m/s)
*(Müller et al., Journal Nuclear Materials, **301** (2002) 40-46)*

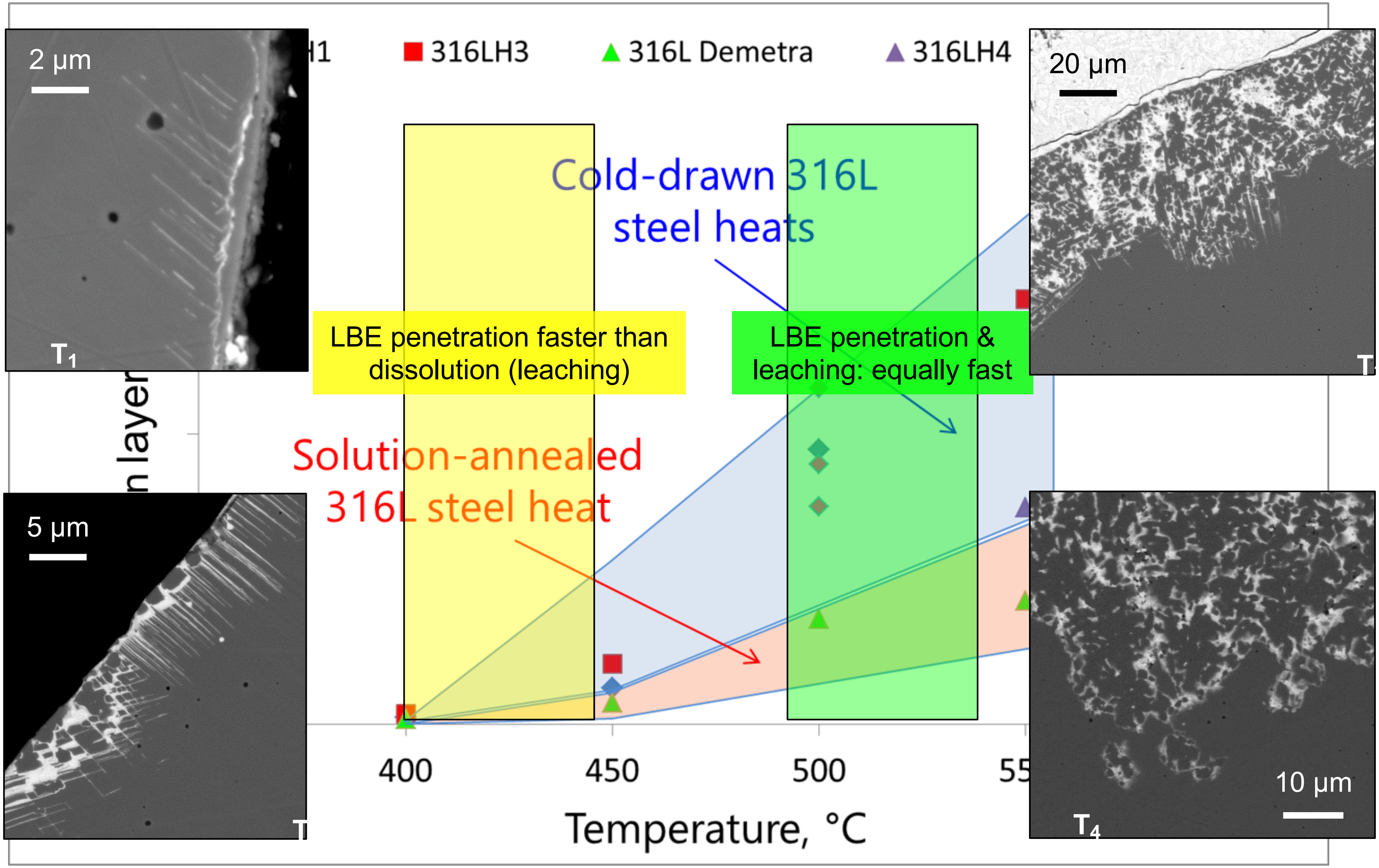
Temperature Dependence of 316L Dissolution Corrosion



Temperature Dependence of 316L Dissolution Corrosion



Temperature Dependence of 316L Dissolution Corrosion



SCK•CEN corrosion data base

- 316L -> tentative design correlation
  - solution annealed, cold drawn, controlled deformation (20, 40, 60 %), components
  - **T**: 350 ÷ 550 °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 ÷ 1000 °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

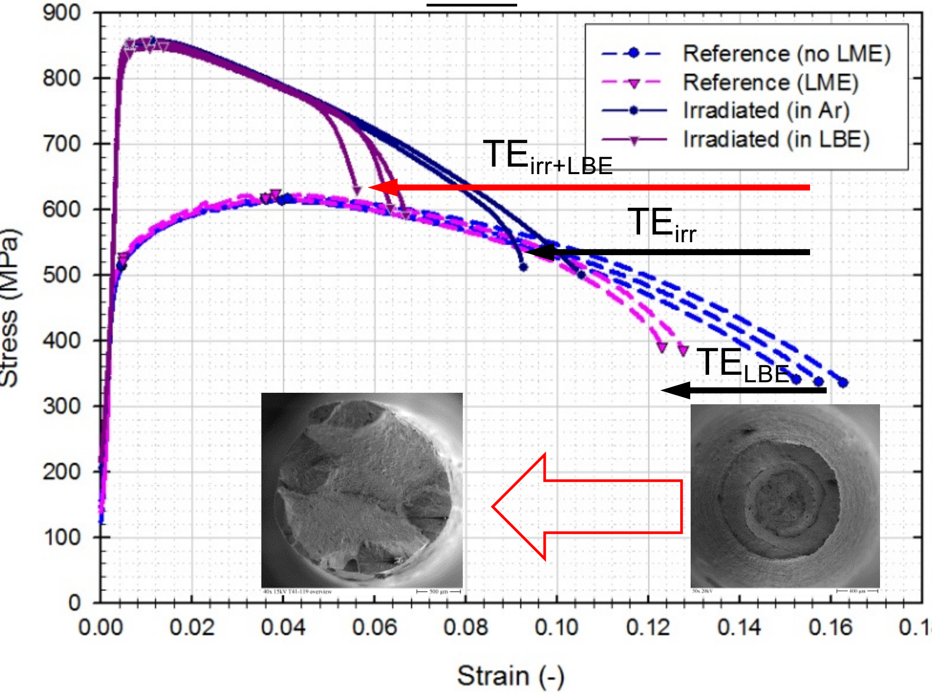
- Liquid Metal Embrittlement (LME)
- Liquid Metal Corrosion (LMC)
- Irradiation effects/synergetic effects

Irradiation experiments

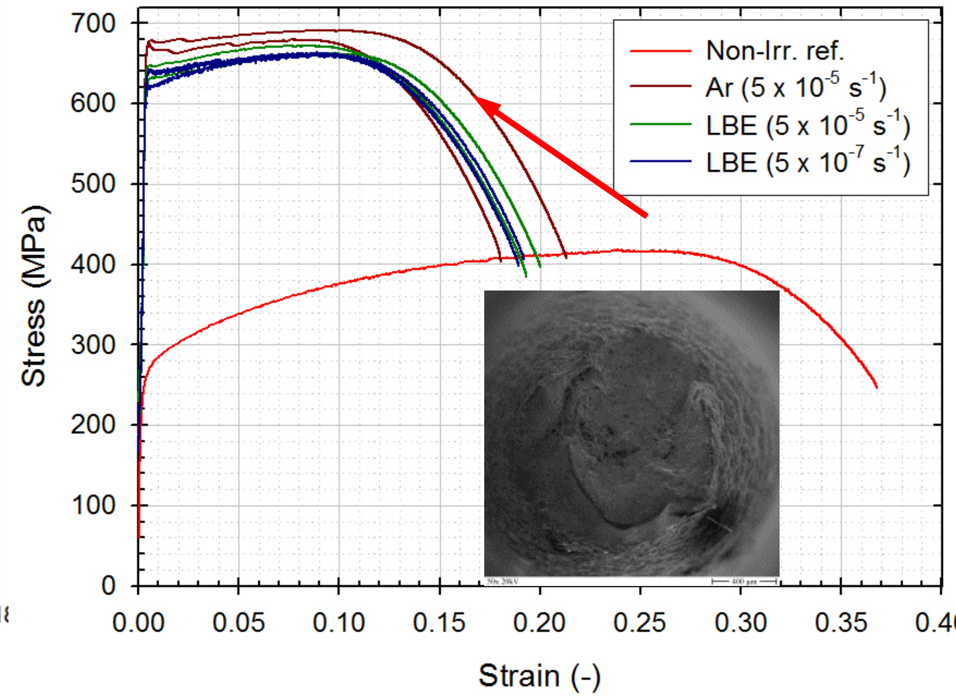
- TWIN-ASTIR
  - Irradiation experiment in BR2 reactor (SCK•CEN, Belgium)
  - Materials: T91, 316L, High Silicon Steels, welds
  - Doses: 0, 1.5 and 2.5 dpa
  - Environment: LBE & PWR water H_2O
  - Temperatures: 300-320°C (H_2O), 350-370°C & 460-490°C (LBE)
  - Specimens: Tensile, DCT, corrosion plates
- 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

Irradiation in LBE

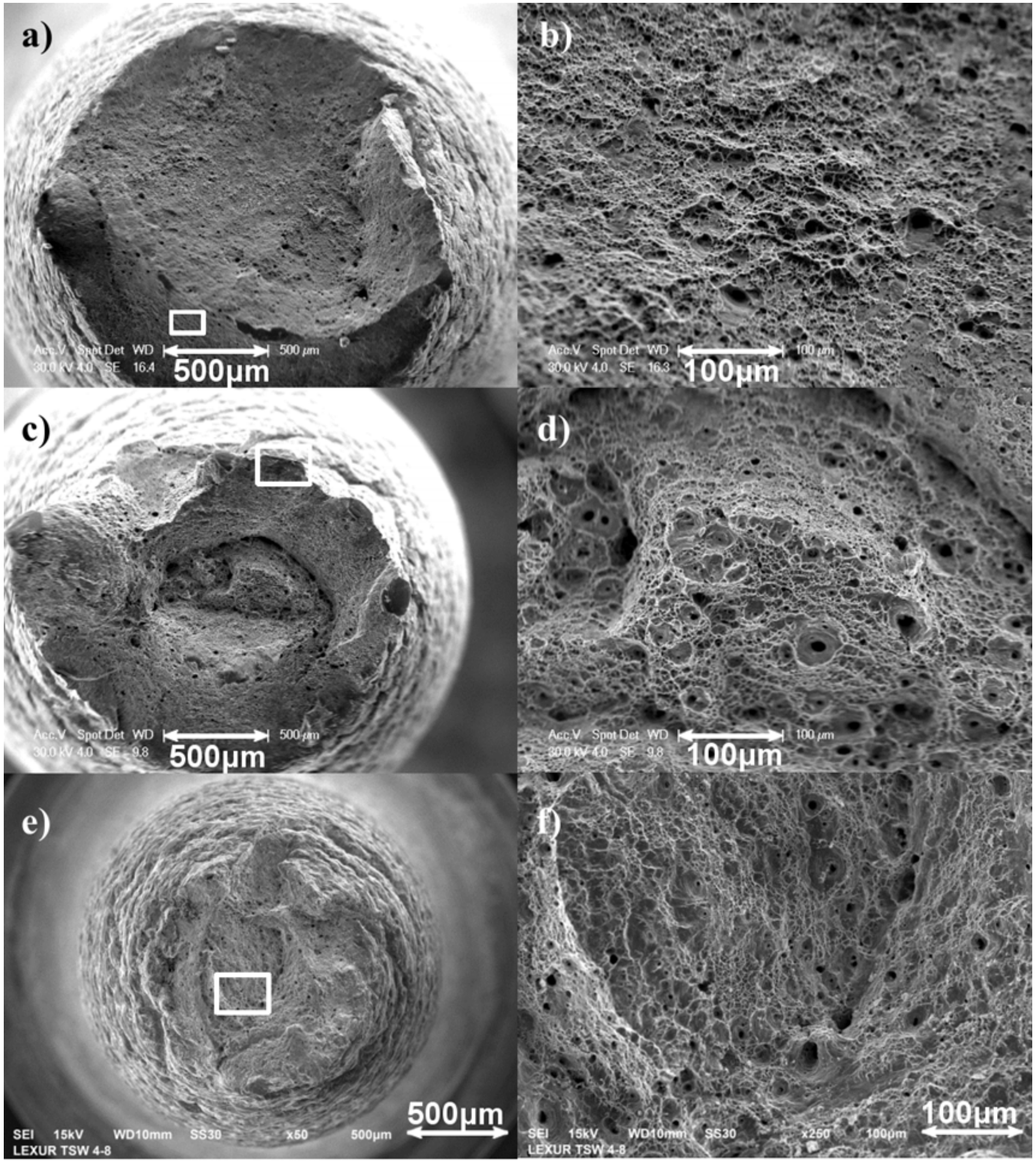
T91



316L



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