Actinide and Fission Product Partitioning and Transmutation
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Pb Alloys Coolant Chemistry and Structural Materials Performance: a Review

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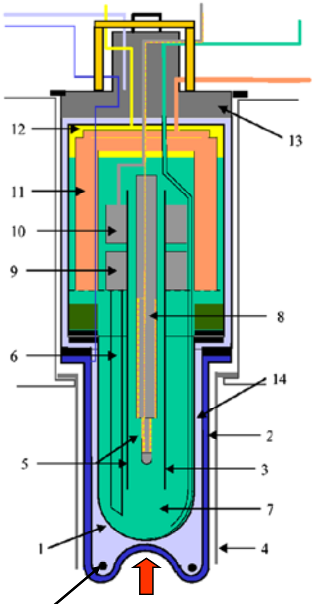
Program Nuclear Saftey Research

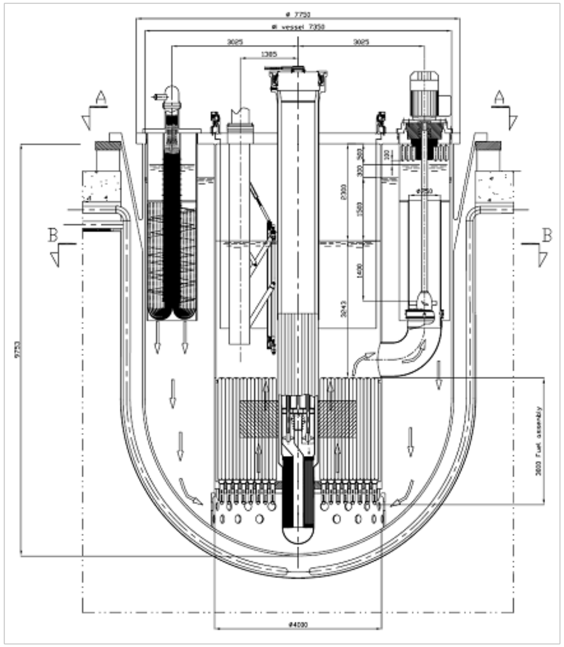
Outline

- Pb alloys cooled nuclear system
- Coolant chemistry control and Handling: some key issues
  - Solubility and Diffusivity data
  - Oxygen measurement and adjustment
  - Solid Impurities Filtering Systems
- Key Materials issues and latest results
- Summary and outlook

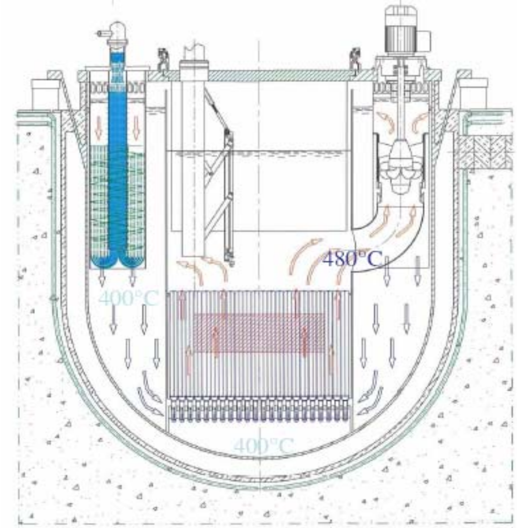
Pb alloys cooled systems



Spallation Target:
MEGAPIE



ADS: The EFIT system



LFR: The ELSY system

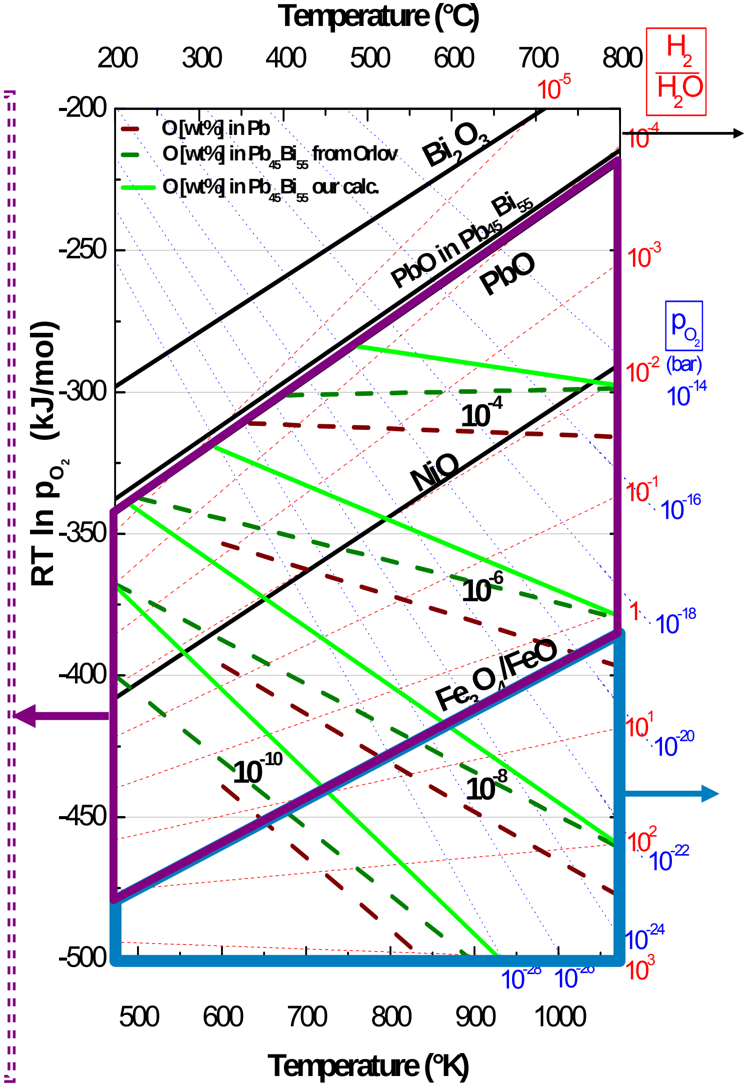
Operational conditions and materials selection

		XT-ADS (LBE)	LFR (Pb)
Core components: mechanical stresses: e.g. Hoop stress on cladding **9Cr F/M Steel**	T	300 – 500 °C	400 – 530 °C
	dpa	Up to 160	Up to 100
	flow	~ 2m/s	~ 2m/s
Reactor Vessel **Austenitic Steel**	T	300 – 400 °C	400 – 430 °C
	dpa	< 0.02	< 0.003
	flow	~ 1 m/s	~ 0.1 m/s
	stress	50-150 MPa	80-150 MPa
Heat exchanger **Austenitic or F/M Steel**	T	300 – 400 °C	400 – 480 °C
	dpa	< 0.02	< 0.03
	flow	~ 1 m/s	~ 1 m/s
	stress	~100 MPa	125-190 MPa
Spallation target **9Cr F/M Steel**	T	240 - 340 °C	-
	dpa/yr	Up to 40	-
	flow	~ 3 m/s	-
	stress	~100 MPa + 40 fatigue cycles/yr	-

LFR Pump: T= 480 °C; dpa < 0.03; flow = 10 m/s (on impeller)

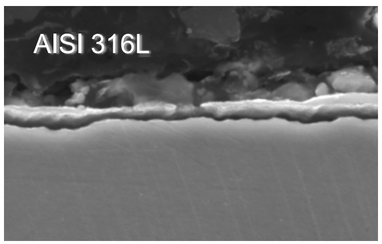
Coolant chemistry and corrosion: a key item

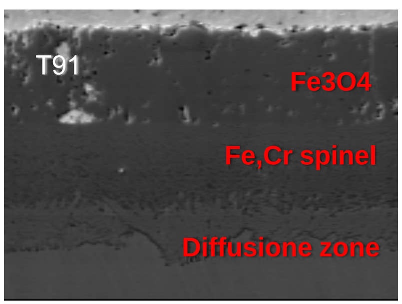
Ellingham Diagram



$[O_2]_{LBE} > 10^{-8}$ wt.% and < $\Delta G(PbO)$

400 °C < T < 550 °C

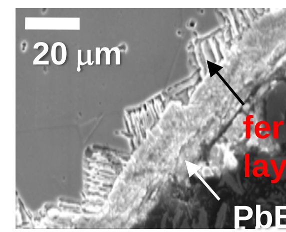


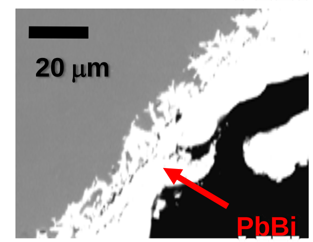


Oxidation of the steel surface The oxide layer can act as a protection barrier

HLM oxides precipitates (plugging!)

Oxygen content in LBE < 10^{-9} wt.% T=400 °C





T91 Trans/interganular dissolution

AISI 316L Leaching of Ni and ferritisation

Coolant Chemistry and Handling: key issues

- Fundamental data: Solubility and diffusivity of metallic and non metallic elements are needed.

- Oxygen measurement: Oxygen sensor's long-term reliability also in irradiation filed, and calibration

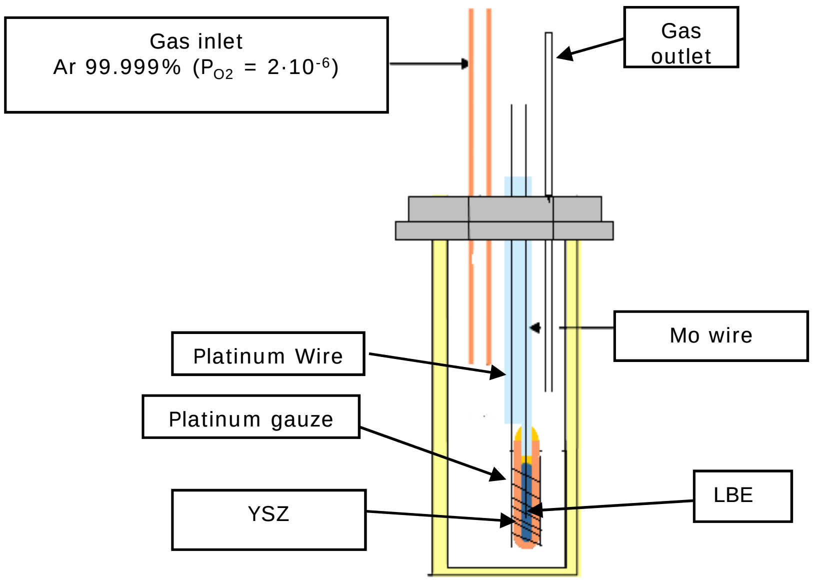
- Oxygen control systems: gaseous H_2/H_2O or solid PbO mass exchange systems

- Filtering systems: essential to remove solid impurities from the liquid and gas phase

Solubility and diffusivity data

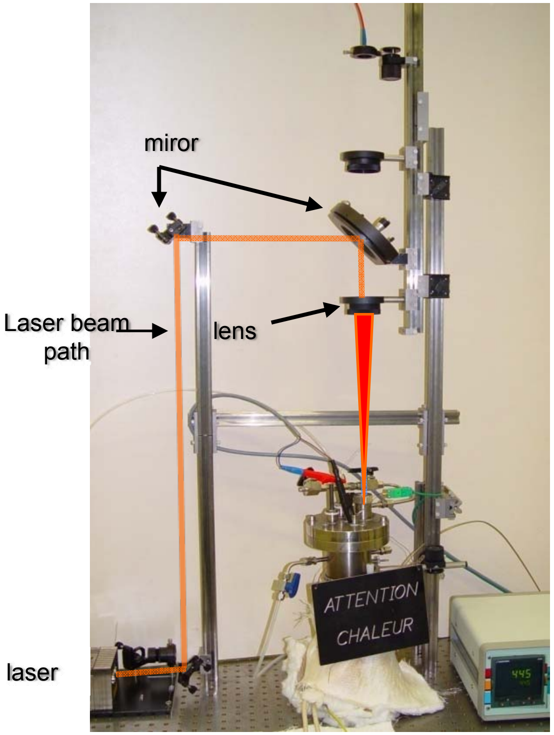
Development/adaptation of ad-hoc measurement techniques

Coulometric Oxygen Pump



Measurement of oxygen solubility

Laser-Induced Breakdown Spectroscopy

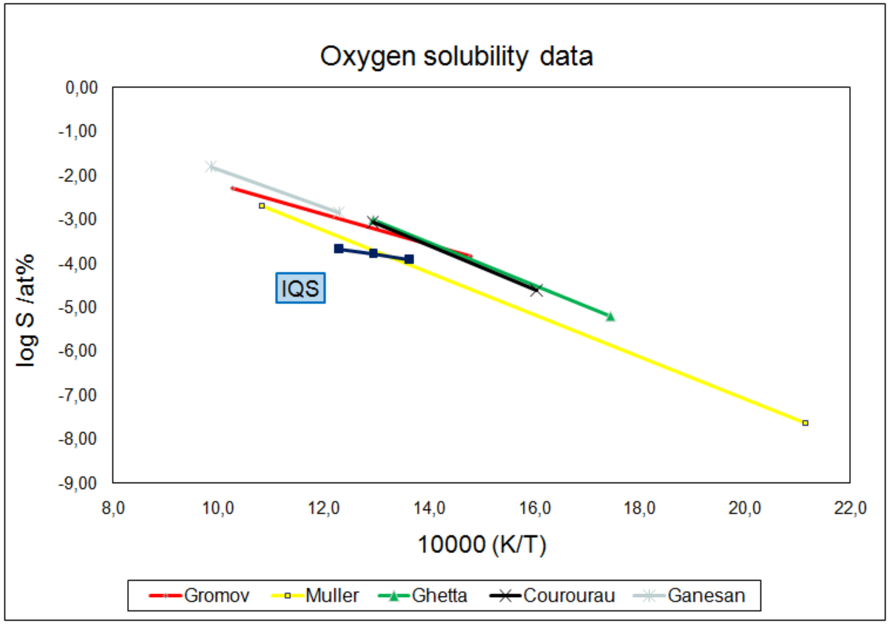


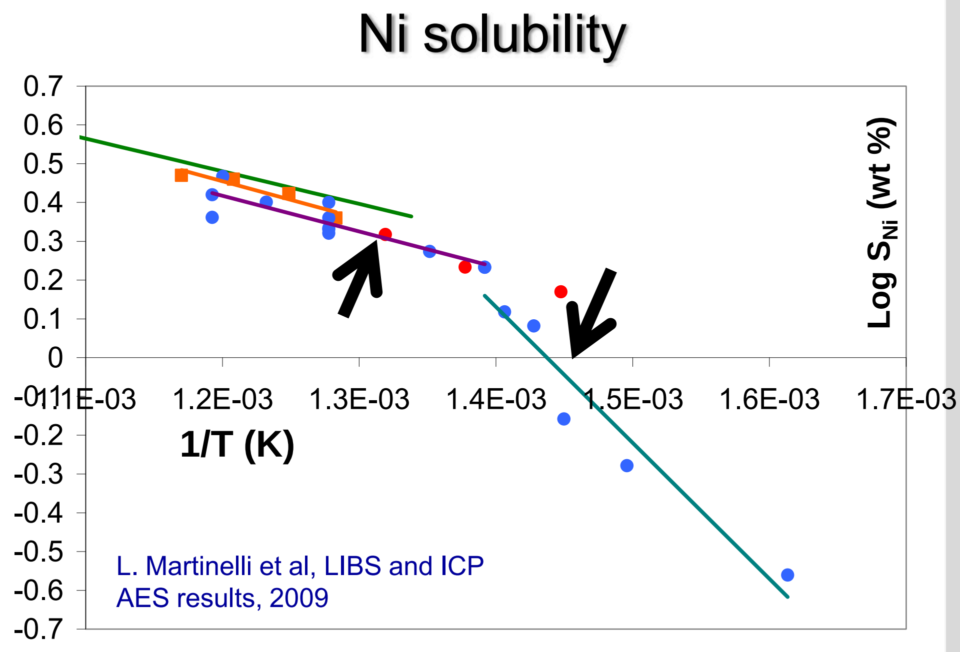
Measurement of solubility of metallic elements: e.g. Ni

Courtesy IQS

Courtesy CEA

Solubility and diffusivity data: results





Martynov, Ivanov, Proceeding of four technical meeting 1998

Rosenblatt, Wilson, Proceeding of Fall Meeting of the Metallurgical Society of AIME, 1969

Courtesy IQS

Courtesy CEA

Oxygen sensor: R&D on basic components

Solid electrolyte (YSZ)

- Optimization for mechanical strength (e.g., Al_2O_3 addition)

Reference electrode assessment

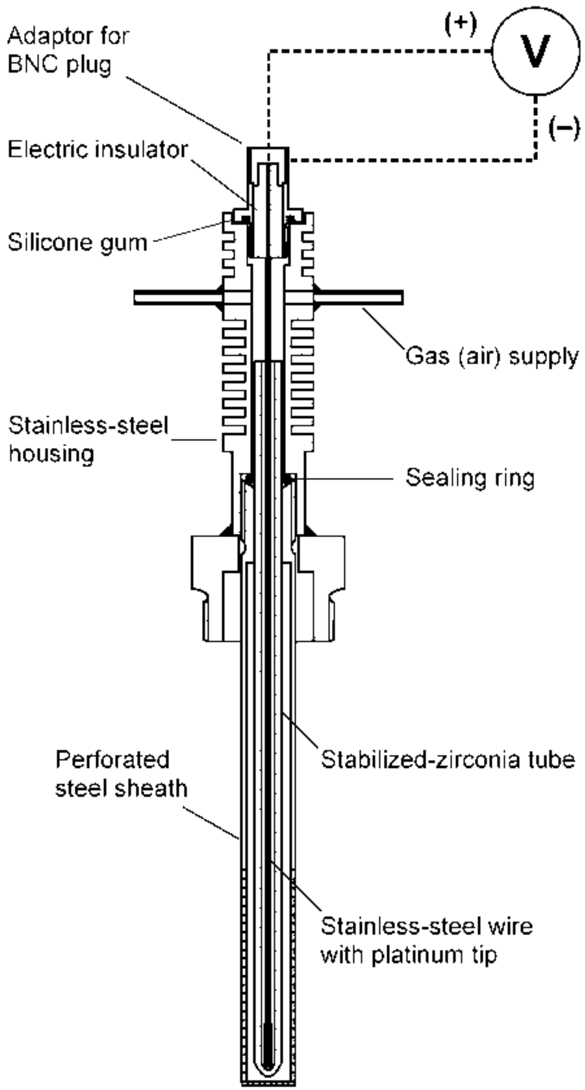
- Bi/Bi_2O_3 increases the risk of electrolyte cracking
- Use of Pt/air reduces the requirements on mechanical stability of the electrolyte

Second (working) electrode assessment

- Application of a protecting sheath around the electrolyte gives rise to sensor fouling and should be avoided

Signal transmission

- Issue to be addresses for application in pool type reactors



C. Schroer, KIT

Oxygen sensor performance

Absolute accuracy

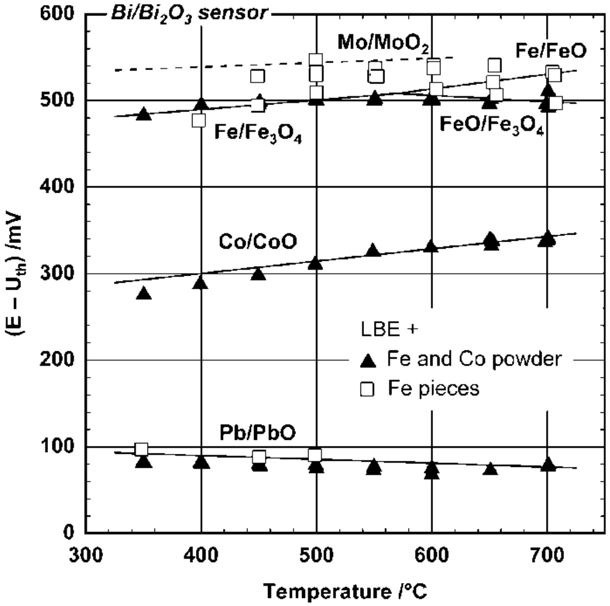
- Can be ±5 mV (±10% cO)
- Correction of thermoelectric voltages is necessary for achieving this accuracy

In-plant testing

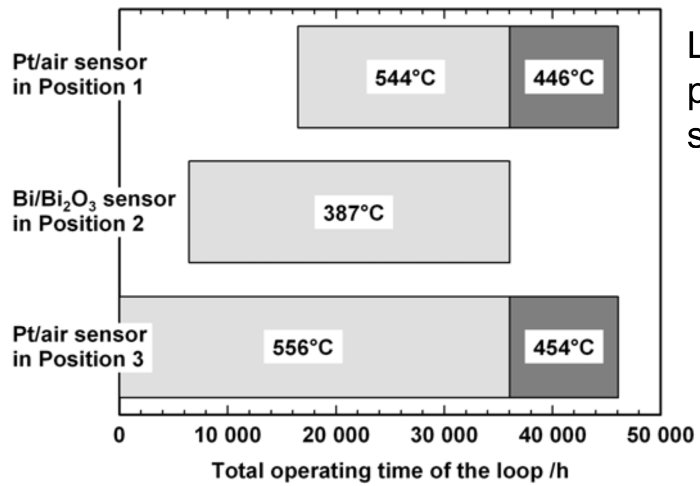
- Method to distinguish between functional and flawed sensors available

Long-term performance

- in experimental facilities is promising with respect to industrial application of electrochemical sensors in Pb alloys



Sensor accuracy by setting different oxygen potentials in LBE

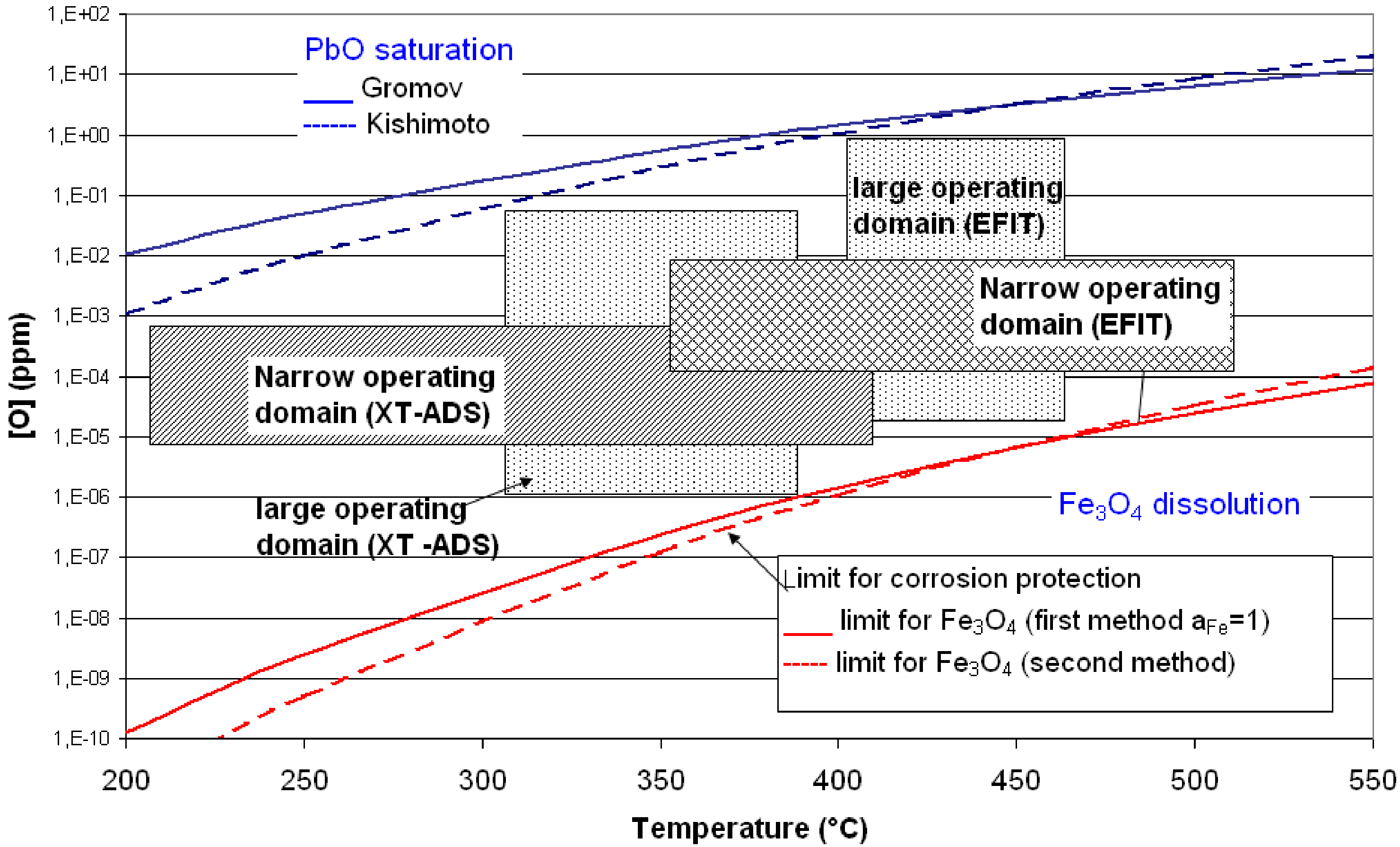


Long-term performances of sensors

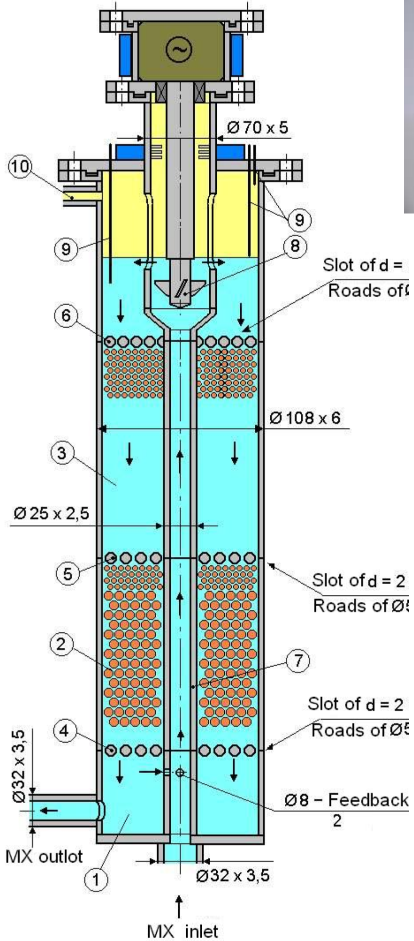
C. Schroer, KIT

Need for oxygen control

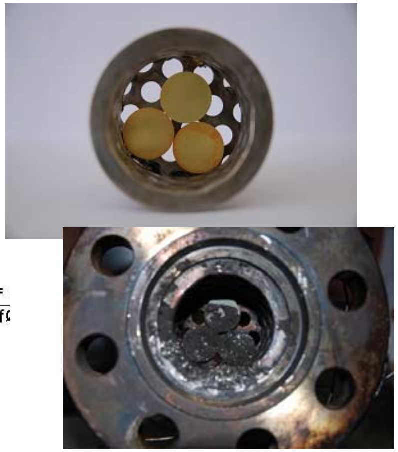
- Avoid PbO formation
- Formation of protective oxide layers



Oxygen control technologies: Solid Phase mass exchange



IPPE MX, Martynov, ICONE 17



F. Beauchamp, CEA

Advantages

- No gas management
- No risks of plugging (oxide formation)
- Quite easy control by flow rate and temperature

Drawbacks

- More complex design for MXp
- More maintenance: pellets filling
  - Personal exposure
- Risks of oxide precipitation on pellets
  - Sluggish kinetic for dissolution

L. Brissonneau, CEA

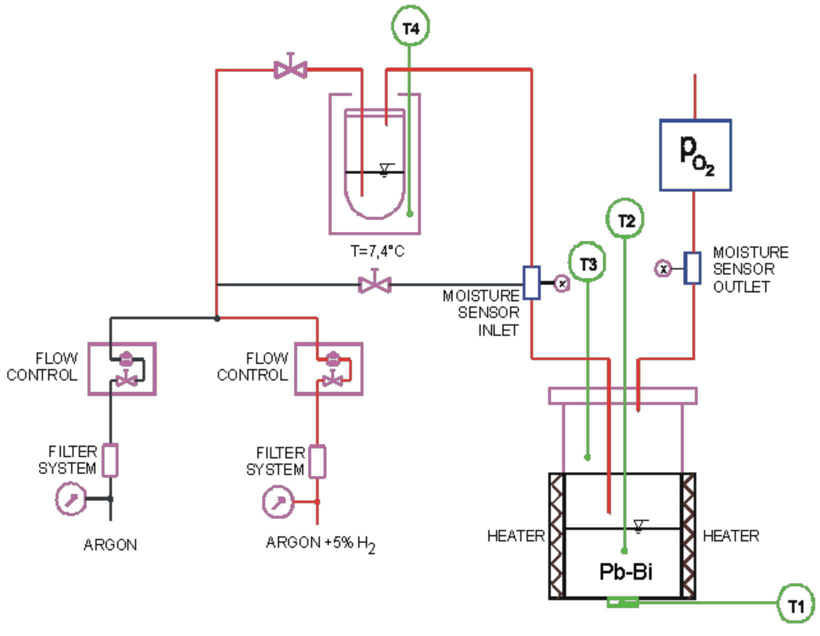
Oxygen control technologies: Gas Phase mass exchange

Advantages

- Same device for O_2 control and purification by H_2.
- No intervention on the device in normal operation
- Quite easy to control automatically

Drawbacks

- Rely on sensors if non equilibrium gases are used
- Need for exchange coefficient if equilibrium gases are used
- Large surface exchange
- Risks of oxide formation
- Large flow rates
- Risk of contamination exposure for operators



G. Müller, A. Weisenburger KIT

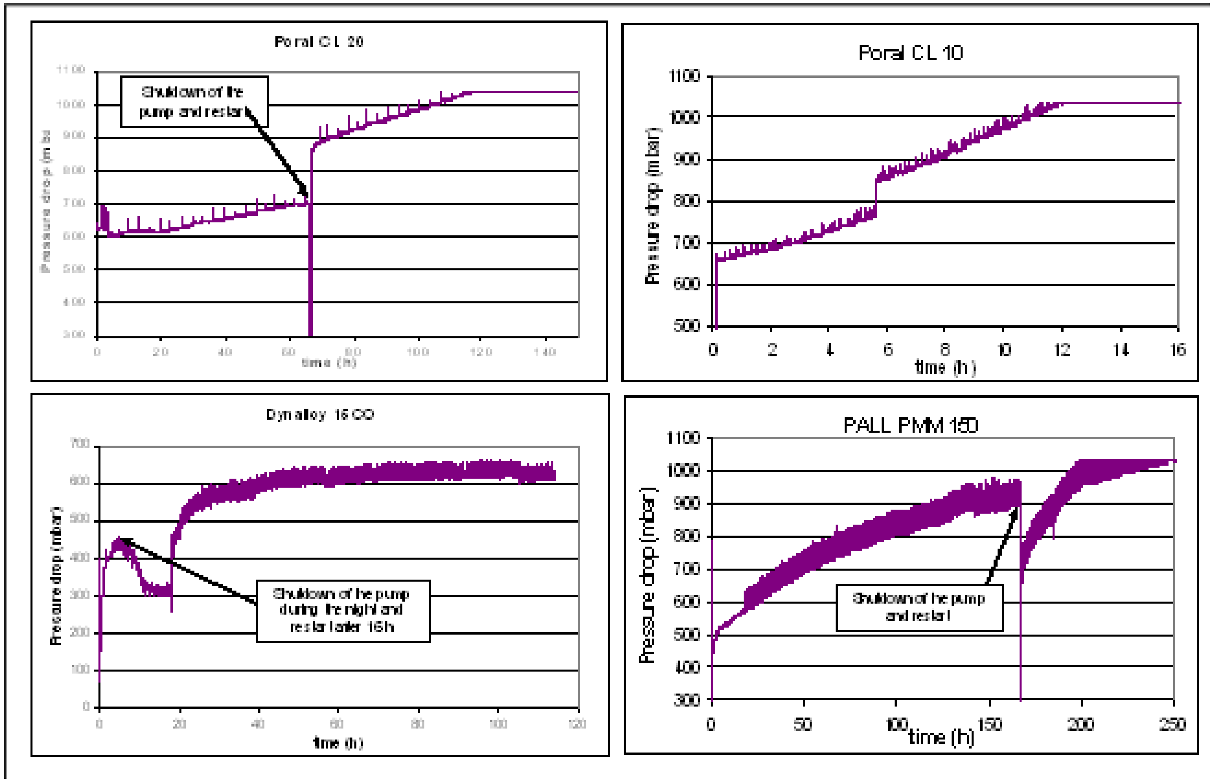
Impurities removal technologies

Poral

Dynalloy

Pall cartridge

Pressure drop vs. time



Filters have been tested:

- Maintenance problem have been encountered
- For assessment longer experiments are needed

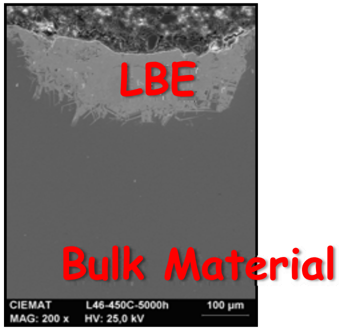
L. Brissonneau, CEA

Key materials issues for HLM systems

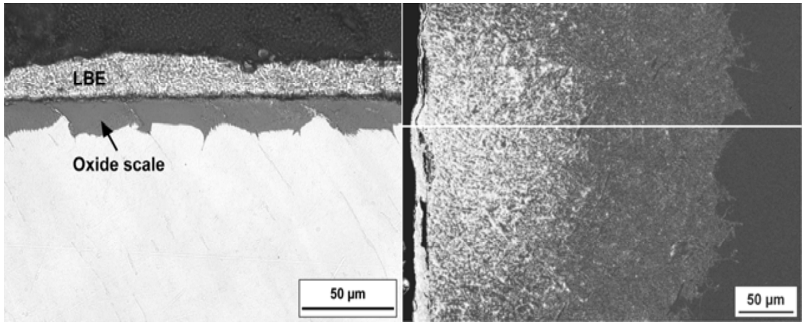
- Compatibility with Pb and LBE
  - Corrosion / oxidation resistance
  - Environmental assisted degradation of mechanical properties

- Irradiation in a fast neutron and for ADS in a proton/neutron field
  - High dpa (cladding)
  - High H and He (spallation target)
  - coolant / irradiation synergetic effects

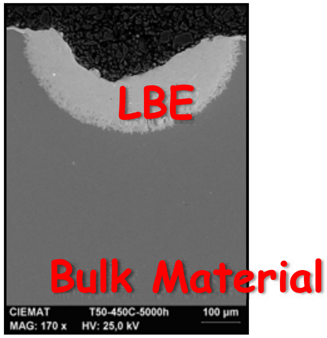
Corrosion / oxidation resistance



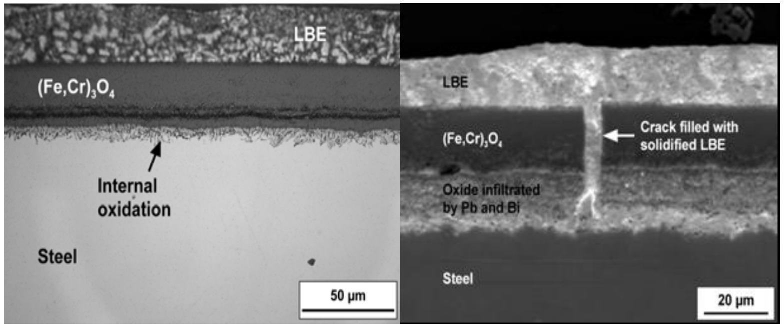
AISI 316L at 450 °C and low oxygen *Courtesy CIEMAT*



AISI 316L at 550 °C and 10-6 wt.% oxygen (left low exposure time; right high exposure time) *Courtesy KIT*

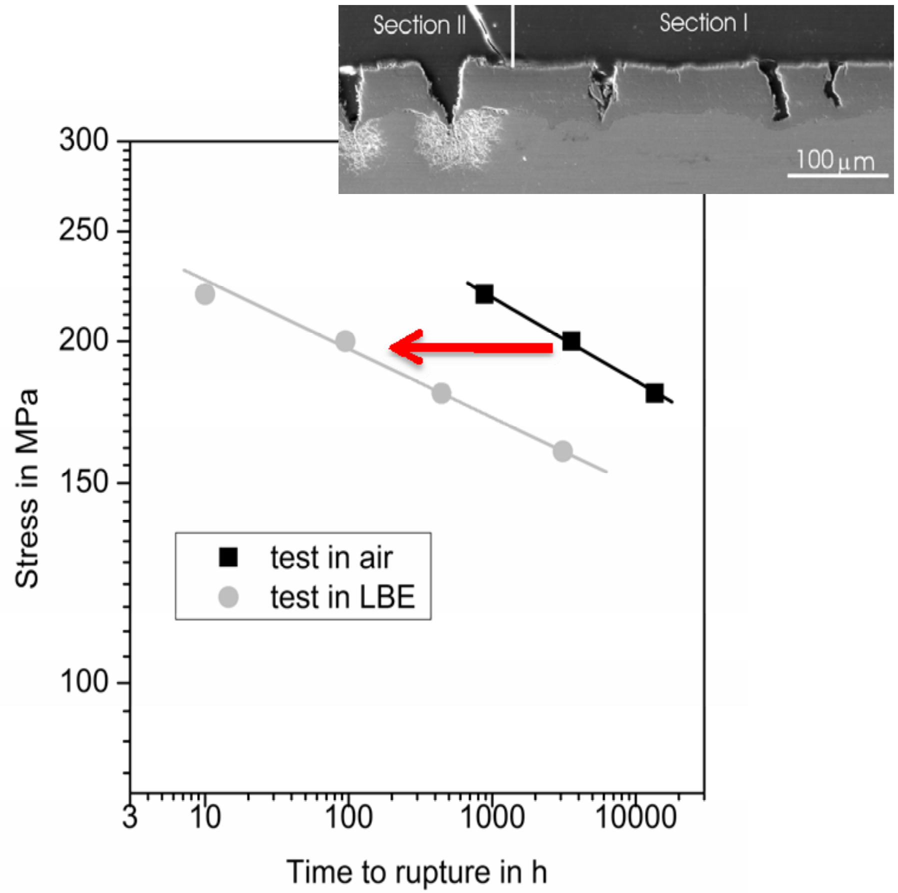


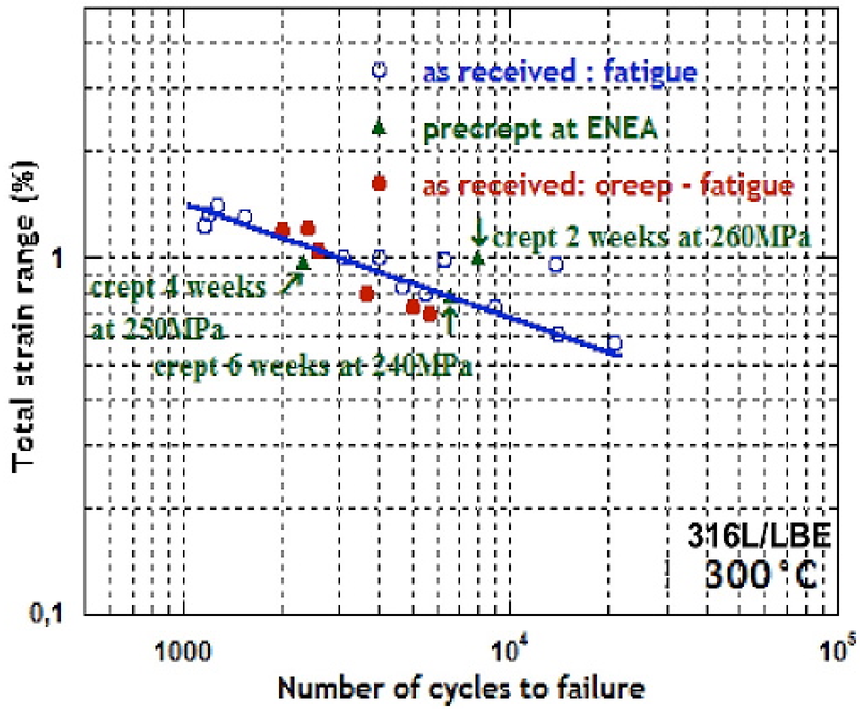
T91 at 450 °C and low oxygen *Courtesy CIEMAT*



T91 at 550 °C and 10-6 wt.% oxygen (left low exposure time; right high exposure time) *Courtesy KIT*

Mechanical behaviour in HLM





Creep-ruture test **T91**. Impact on LCF, fracture toughness and tensile have been observed as well

LCF test **AISI316L**. Tensile and fracture toughness test have shown as well no effect

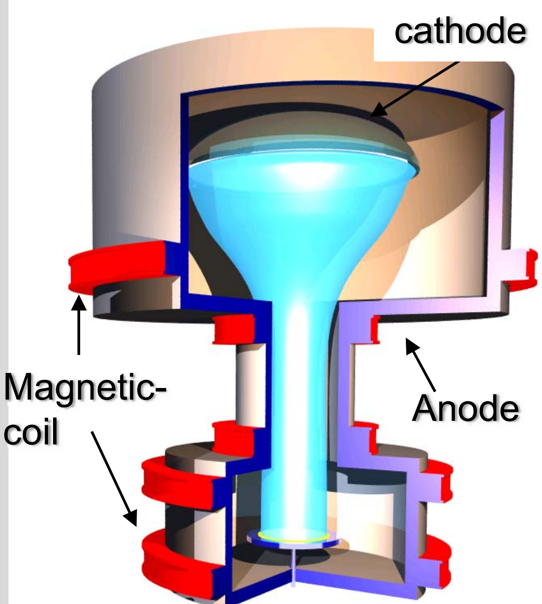
Summary T91 and AISI316L

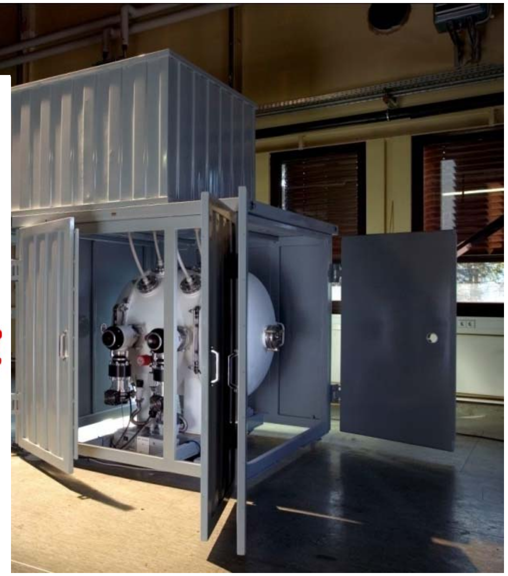
T	T91	AISI 316L
Low (< ~ 400 °C)	• Irradiation H & E • Corrosion low • Impact on mechanical properties if wetting and stress above certain values	• Irradiation H • Corrosion low • No Impact on mechanical properties
Medium (≤ ~ 450 °C)	• Slight Irradiation H & E • Oxygen control stringent • Impact on mechanical properties (see low T)	• No Irradiation H & E • Oxygen control stringent • No Impact on mechanical properties
High (> 450 °C)	• No irradiation H & E • Oxygen control very stringent (oxide layer thickness) • Impact on mechanical prop if oxide layer fails	• No irradiation H & E (high dose swelling) • Dissolution attack T> 500°C • No impact on mechanical properties

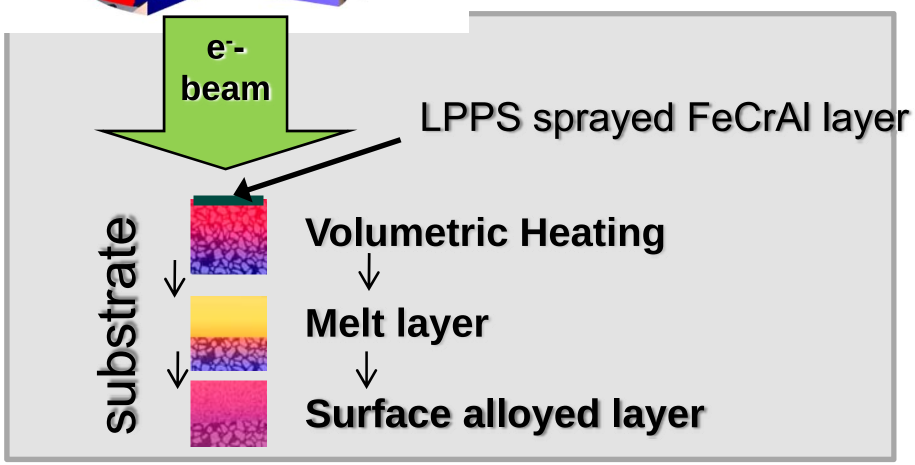
In the high temperature range for both material corrosion protection would be mandatory

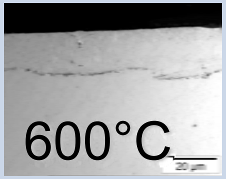
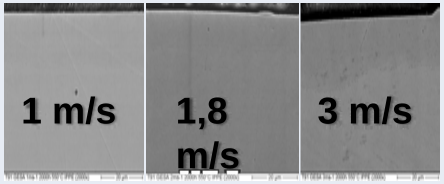
GESA for corrosion protection

GESA facility







Tests on GESA	Results
Corrosion resistance	
Erosion resistance	
LCF	No reduction
Creep-to-rupture	No reduction
LISOR	No corrosion Hardening

Summary and outlook

HLM Chemistry and quality control

- Basic phenomena have been understood
- Technologies have been tested on laboratory scale and in loop systems
- Selection of best performing technology for large scale and pool type is needed
- Testing of these technologies in large scale pool type is needed

Materials in HLM

- Basic corrosion mechanism have been understood
- Basic mechanical properties degradation mechanism have been understood
- Positive impact of corrosion-protection barrier (e.g. GESA) has been assessed.
- Materials operational window have been identified
- Strategies on materials performance assessment for component lifetime estimation have to be defined

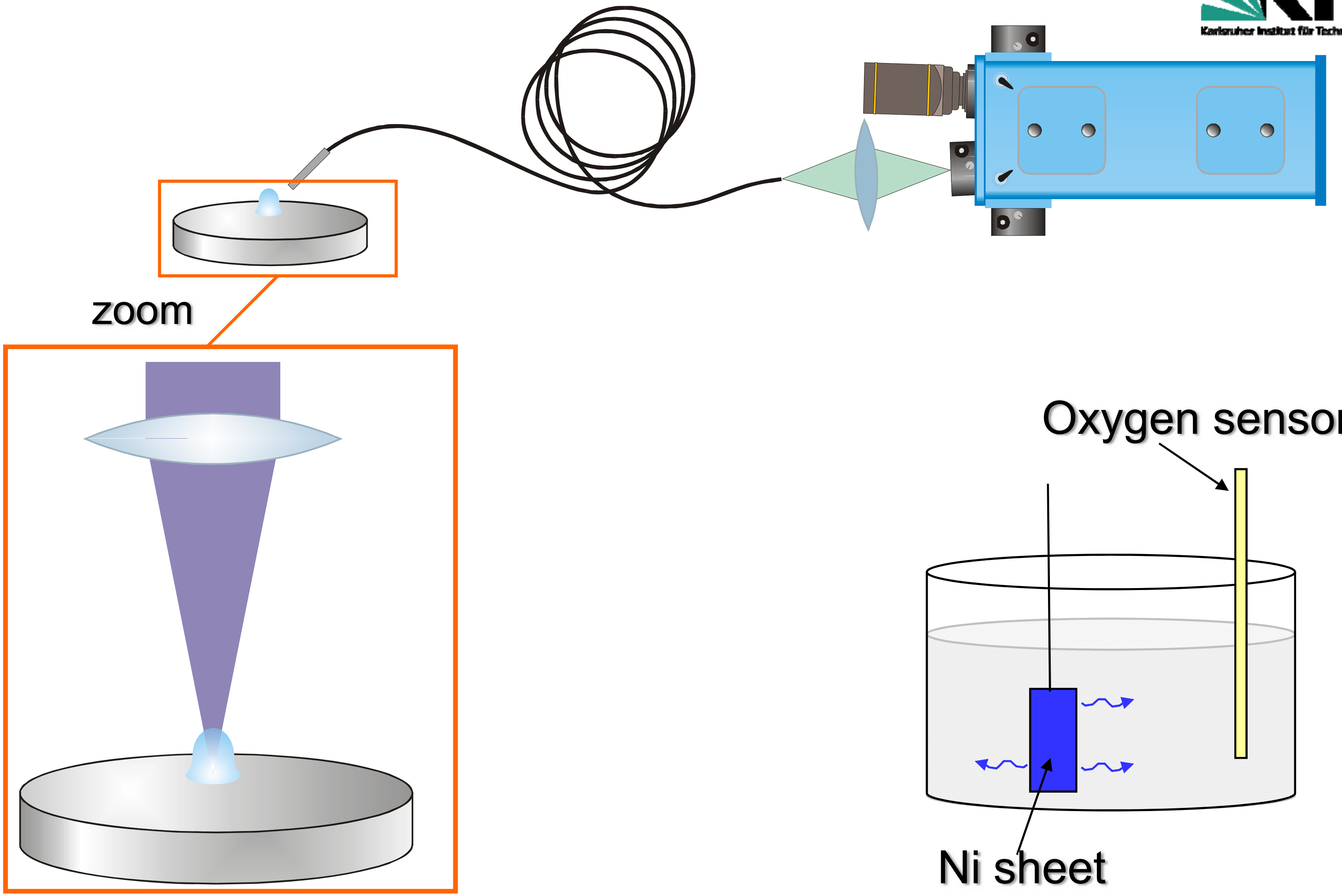
Acknowledgments: DEMETRA Partners

KIT	Germany
AAA	France
Ansaldo	Italy
CEA	France
CIEMAT	Spain
CNRS	France
CRS4	Italy
ENEA	Italy
ENEN: IQS KTH RUB-LEE UCL	Spain Sweden Germany Belgium
FZR	Germany
NRG	Netherland
NRI	Czech Republic
PSI	Switzerland
SCK-CEN	Belgium

Thank you for your attention

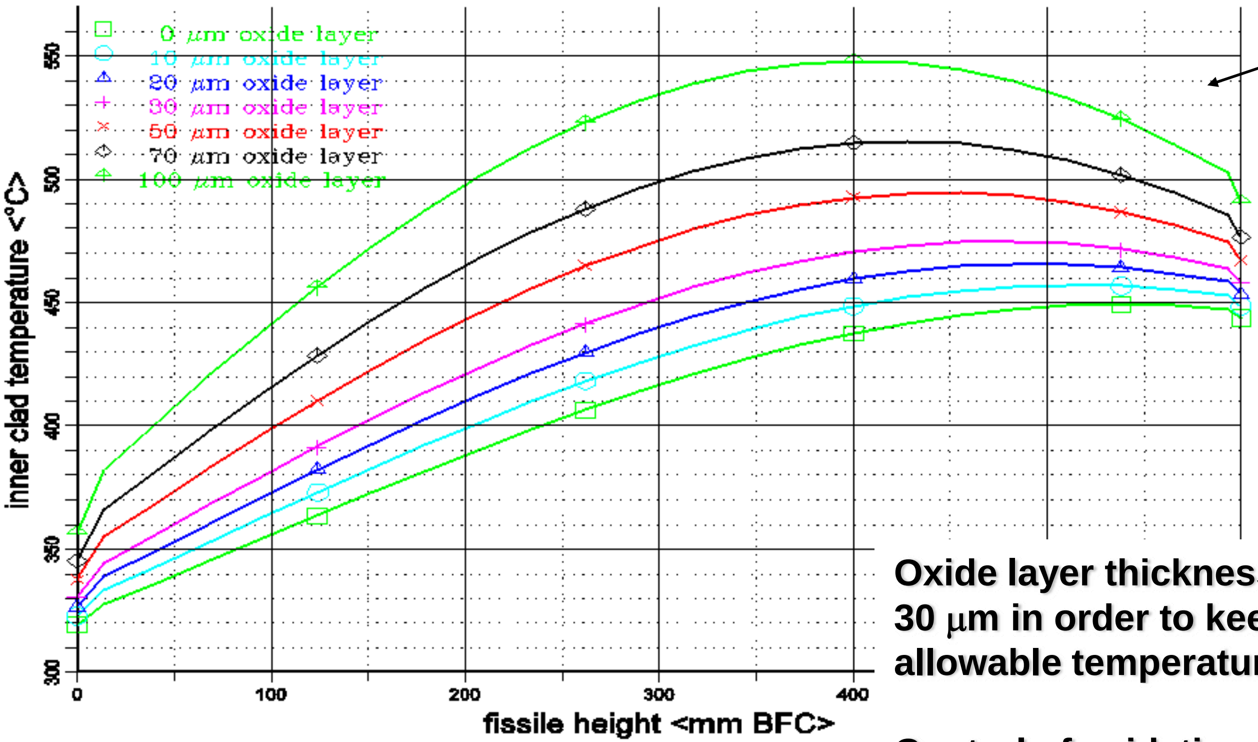
Back-up

Laser-Induced Breakdown Spectroscopy: principle



Example of practical application: importance of oxide thickness

Axial profiles of clad inner temperature modified calculation with different additional oxide layers



Increase of clad temperature

Shift of the maximum temperature

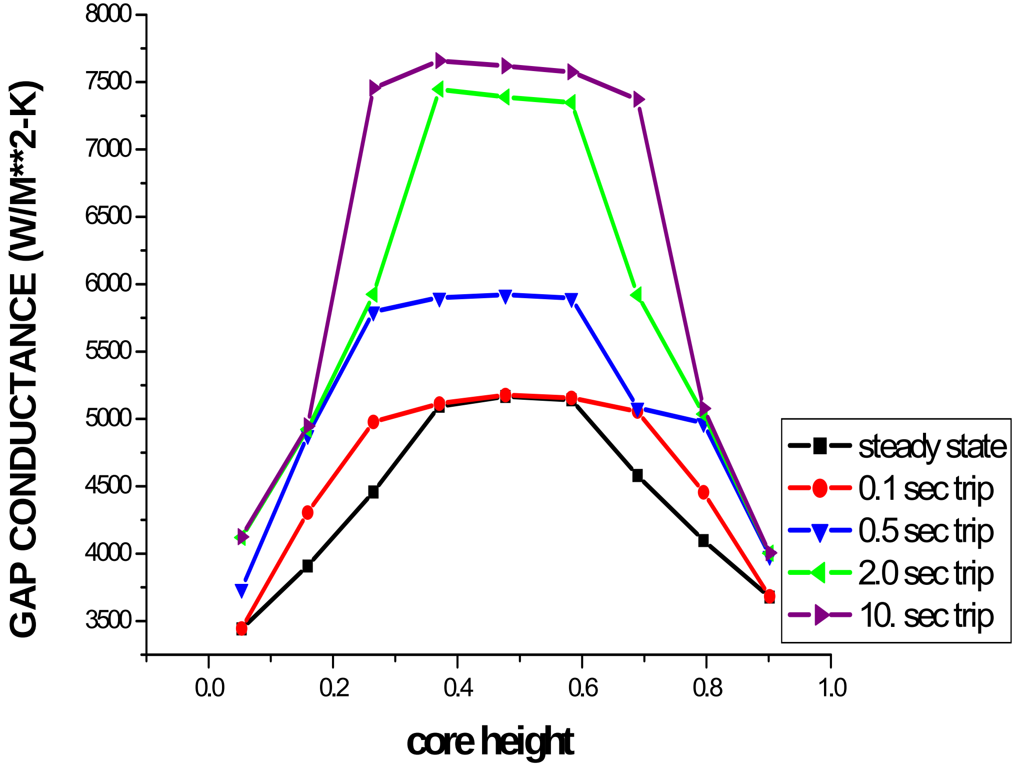
Oxide layer thickness should be limited to < 20-30 μm in order to keep margin on the maximum allowable temperature for the T91 steel.

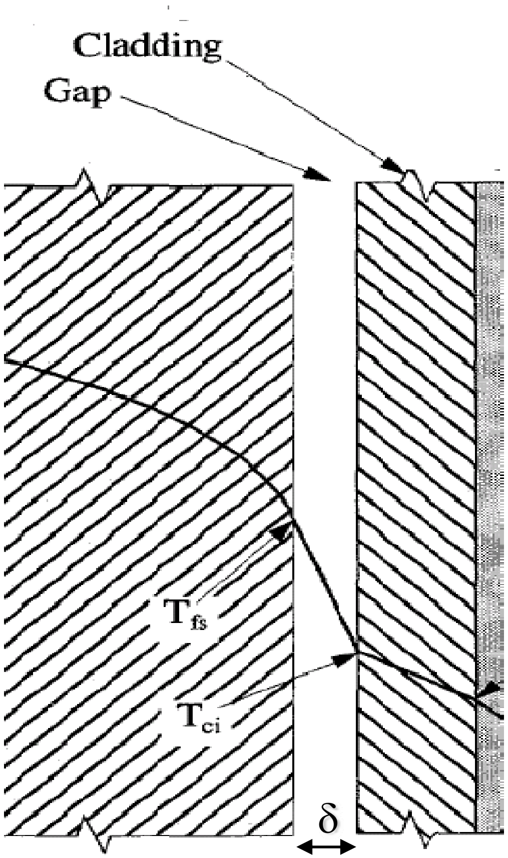
Control of oxidation process in a reactor system might not be applicable

GESA surface alloyed steel can be seen as a solution

(D. Struwe, W. Pfrang, IRS/FZK)

Example of practical application: Importance of mechanical features





Mechanical properties of materials:

- **Fast Closure of gap between fuel and clad due to beam trips could lead to enhanced stress on the clad.**
- **Thermal-shock could affect the oxide integrity**