Chapter 12
EXISTING HLM FACILITIES FOR EXPERIMENTAL APPLICATIONS*

12.1 Introduction

The use of the heavy liquid metals (HLM) lead-bismuth eutectic (LBE) and lead (Pb), as cooling medium and spallation material has been envisaged in the field of accelerator-driven systems (ADS), which are devoted to transmute and reduce the radiotoxicity of nuclear waste. An increasing interest on HLM can be identified also in other research and industrial fields, as for instance the energy production with advanced nuclear systems, the hydrogen production with nuclear power and the development of spallation neutron sources for medical applications and materials studies. Therefore, scientific and technological activities focused on materials compatibility, thermal fluid dynamics characterisation and technology issues have been launched. In this frame a large effort has been made to built and operate HLM test facilities in support to the previously mentioned applications. In the following paragraphs the descriptions of the HLM facilities available at the laboratories of the expert groups participating to the realisation of this handbook are given. A list of the facilities is given also in Table 12.1 at the end of this chapter.

The available facilities covers almost all basic studies needed to design HLM nuclear systems working at temperatures up to 550°C. However, further needs can be envisaged for applications at temperature ranges above 600°C and for specific analysis concerning safety aspects in representative conditions (i.e. interaction with secondary coolants, loss of coolant, etc.), specific component testing in prototypical conditions (i.e. dedicated heat exchanger, pump, etc.) and in-service inspection and repair (ISI&R).

In addition the need to characterise and validate for the reactor applications specific measurement techniques (e.g. oxygen sensors) and operational techniques (e.g. pumps, flow meters) in a combined neutron field and HLM environment can be also envisaged.

In the sections that follow the available facilities are listed, and the objectives and the operational parameters are reported. As can be seen, some facilities have been built to provide data for the three fields of investigation previously mentioned.

12.2 Technological facilities and their applications

Technological and liquid metal chemistry, experiments performed in this field are aimed at the development of measurement tools and device to realise and execute thermal-hydraulics benchmark experiments with well known and measurable initial and boundary conditions. Moreover, these facilities are aimed to validate specific procedures for large circuit operation. The relevant measurement tools and devices to be applied for thermal-hydraulics experiments are:

* Chapter lead: Concetta Fazio (FZK, Germany).
heat flux simulation tools;
flow meter devices;
pressure measuring systems;
local velocity measurement systems;
development of tools to measure locally and globally free surfaces.

A second item is the study of liquid metal chemistry, where the development and validation oxygen monitoring and control systems is one of the most important task. Three types of oxygen control methods are currently analysed, which make use of a mixture of hydrogen/moisture; oxygen and hydrogen gases and PbO pellets respectively. Concerning the measurement of the oxygen content in the liquid metal, electrochemical oxygen probes are presently developed. Activities are focused on the definition of a standardised calibration procedure to assess the probes for reliability in conformity to nuclear use. Key variables include dose, dose rate, thermal transients, pressure variations, etc.

Facility: Technologies of heavy liquid metal systems (THESYS) loop – Figure 12.2.1
FZK, Germany

Objectives:
- Optimisation of Karlsruhe OCS for loop applications.
- Development of thermal-hydraulic measurement techniques.
- Heat transfer and turbulence experiments.
- Development of high performance INCONEL heaters (fuel rod simulator).
- Set-up of thermal-hydraulic data base for physical model development and code validation.

Operational parameters:
- Maximum temperature: 550°C.
- Maximum flow rate: 3.5 m³/h.
- LBE volume: 100 l.
- The loop was operated originally with LBE, but it is presently under modification to enable the use of Pb. The relevant of the loop are:

Facility: Karlsruhe Oxygen Control System (KOCOS) – Figure 12.2.2
FZK, Germany

Objectives:
- Development of the Karlsruhe Oxygen Control System OCS.
- Measurement of diffusion coefficients of oxygen in Pb-Bi.
- Measurement of oxygen mass exchange rates.

Facility: Karlsruhe Oxygen Sensor in Molten Alloys (KOSIMA) – Figure 12.2.3
FZK, Germany

Objectives:
- Development of oxygen sensors.
- Optimisation of oxygen sensor performance as for reference system, reproducibility and long-term stability.
- Calibration of oxygen sensors.
Figure 12.2.1. Scheme and photo of THESYS

![Scheme and photo of THESYS]

Figure 12.2.2. Diagrammatic sketch of KOCOS experiment

![Diagrammatic sketch of KOCOS experiment]
Figure 12.2.3. Diagrammatic sketch of KOSIMA experiment

**Facility: Chemistry and Operation (CHEOPE) – Figure 12.2.4**

**ENEAA, Italy**

The device consists of three different loops:
- CHEOPE I for thermal-hydraulic activities.
- CHEOPE II for liquid metal chemistry studies.
- CHEOPE III for corrosion studies at high oxygen content.

**Objectives:**
- Corrosion investigation in lead alloys at high oxygen content.
- Component test and development.
- Physico-chemistry.
- Thermal-hydraulic experiments: heat transfer characteristics, target development, pumping systems, etc.

**Operational parameters:**
- Maximum temperature (Cheope III): 500°C.
- Maximum flow rate (Cheope III): 1.2 m³/h.
- Volume Cheope I: 900 l.
- Volume Cheope II: 50 l.
- Volume Cheope III: 50 l.
- Oxygen meter: Yes.
- Oxygen control: Yes.
- Heavy liquid metal: Pb-Bi.

**Facility: SOLDIF – Figure 12.2.5**

**CEA, France**

**Objectives:**
- Determination of solubility and diffusivity of dissolved species in molten lead or lead alloys by means of electrochemical techniques using a molten salt electrolyte.
- Characterisation of the oxide layer on a metallic material immersed in molten lead or lead alloys by means of electrochemical techniques.

**Operational parameters:**
- Maximum temperature: 500°C.
- Maximum flow rate: Static.
- Number of electrochemical cell: One.
- Heavy liquid metal: Pb-Bi or Pb.
Figure 12.2.4. Scheme and photograph of CHEOPE
Figure 12.2.5. Scheme and photograph of SOLDIF
**Facility: Standard Technology Loop for Lead Alloy (STELLA) – Figure 12.2.6**

**CEA, France**

**Objectives:**
- Lead alloys chemistry monitoring and control.
- Oxygen sensors validation.
- Purification process development and qualification.
- Oxygen control process development and qualification based on mass exchange unit (PbO).
- Dip sampling system qualification on loop.

**Operational parameters:**
- Maximum temperature: 550°C.
- Temperature gradient: 150°C max.
- Volume: 32 litres.
- Max flow rate: 1 m³/h at 3 m NPSH.
- Number of test sections: 1.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi.
- Corrosion protection: Aluminisation by pack cementation.

**Facility: Vacuum Interface Compatibility Experiment (VICE)**

**SCK•CEN, Belgium**

**Objectives:**
- Study of gas transport in the proton beam line and possible compound formation in a realistic 1-1 pumping geometry mock-up.
- Detailed investigation of initial and long-term out-gassing of Pb-Bi including component identification.
- Study of metal evaporation.
- Simulation of emanation behaviour of volatile spallation products.

**Operational parameters:**
- Beam-line geometry (5 m).
- Maximum temperature: 500°C.
- Minimum operating pressure: $10^{-7}$ mbar – UHV technique.
- Heavy liquid metal: Pb-Bi.
- Useful Pb-load: 100 kg.
- Vacuum pressure controller: $10^{-7}$ mbar – 1 bar.
- High resolution rest gas analyser.
- Gas flow rate differential calibration system.
- Magneto-hydrodynamic stirring.
- Plasma cleaning system (10 kW).
Figure 12.2.6. Scheme and photograph of STELLA
Facility: Pre-conditioning Vessel (PCV) – Figure 12.2.7

SCK•CEN, Belgium

Objectives:
- Investigation of conditioning and cleaning procedures of Pb-Bi eutectic to a suitable level for use in a windowless spallation target loop.
- Outgassing studies of Pb-Bi eutectic (stage 1).

Operational parameters:
- Maximum temperature: 500°C.
- Maximum pressure: 10 bar.
- Minimum operating pressure: $10^{-7}$ mbar – UHV technique.
- Heavy liquid metal: Pb-Bi.
- Useful Pb-load: 100 kg.
- Oxygen control system: H₂/H₂O gas.
- Plasma cleaning system: 10 kW.
- Rest gas analyser: Hi-tech quadrupole.
- Magneto-hydrodynamic stirring.

Facility: Target Complex 1 (TC-1) – Figure 12.2.8

University of Nevada, Las Vegas, USA

Objectives:
- Demonstrate long-term, sustained operation of MHD pump for LBE loop.
- Complete prototype evaluation for TC-1 complex on behalf of ISTC partners.
- Train students in the operation of molten metal engineering scale systems.
- Examine long-term performance of target systems under non-irradiation conditions.

Operational parameters:
- Maximum temperature: TBD (not to exceed 300°C at pump inlet).
- Minimum temperature: 200°C.
- Maximum (typical) flow rate: 15 (TBD) m³/hr.
- Electrical power: TBD (70 kW max.).
- Number of test sections: 0.
- Number of samples: 0.
- Oxygen control system (OCS): None.
- Oxygen sensors: None.
- Heavy liquid metal: Pb-Bi.

Figure 12.2.7. Photograph of inside PCV
Figure 12.2.8. Schematic/components arrangement of TC-1
Facility: Steam Injection and Oxygen Concentration Control Apparatus – Figure 12.2.9

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Japan

Objectives:
- Performance of oxygen sensor.
- Control of oxygen potentials in Pb-Bi.
- Material corrosion and corrosion product in Pb-Bi.
- Carry-over of Pb-Bi mist and impurities into steam flow.
- Dissolved H₂ in steam and water.
- Chemistry and transport of metal elements in Pb-Bi.

Operational parameters:
- Maximum temperature: 500°C.
- Maximum pressure: 0.5 MPa.
- Pb-Bi inventory: 70 kg.
- Water/steam inventory: 30 kg.
- Maximum water/steam flow rate: 25 g/min., 250°C.
- Pb-Bi flow system: Steam gas lift pump.
- Maximum electrical power Pb-Bi: 6 KW.
  - Maximum electrical power water/steam: 4 KW.
- Pb-Bi test vessel number: 1.
  - Size: φ260 × 760 mm.
  - Material: Cr-Mo steel.
- Maximum apparatus height: 3.2 m.
- Oxygen control system (OCS): Yes (hydrogen-dissolved water).
- Heavy liquid metal: Pb-Bi eutectic.
Figure 12.2.9. Flow diagram and photo of the Steam Injection and Oxygen Concentration Control Apparatus

Steam Supply Sub-system

Pb-Bi Test Sub-system
12.3 Materials testing facilities and their applications

Materials testing, the facilities used to characterise the materials behaviour in the liquid metal are principally of two types. One are static tests facilities, which are used for materials screening tests and for basic corrosion mechanism investigations. Usually on these static devices an oxygen control and monitoring system is installed in order to evaluate the basic corrosion mechanism in well controlled oxygen conditions. Some of these static devices are also devoted to the mechanical testing of not irradiated and irradiated materials in the liquid metal. The second type of materials testing facilities are loops. The tests performed with the loops are of importance for the evaluation of the long-term corrosion resistance of the materials. The tests were typically performed under well known conditions in terms of oxygen concentration, temperature, HLM flow rate. The database produced with the loop tests can be employed for the development and validation of corrosion prediction models.

**Facility: Corrosion Test Stand for Stagnant Liquid Lead Alloys (COSTA) – Figure 12.3.1**

FZK, Germany

*Objectives:*
- Investigation of corrosion mechanisms.
- Influence of protection layers and coatings on corrosion.
- Investigation of GESA treated surfaces.
- Influence of surface alloying on corrosion.

**Facility: Corrosion in Dynamic Alloys (CORRIDA) – Figure 12.3.2**

FZK, Germany

*Objectives:*
- Long-term corrosion investigations of structural materials in flowing LBE.
- Long-term corrosion investigations of coated materials in flowing LBE.
- Investigations on the mechanisms and the kinetics of material/LBE interactions.
- Modelling of corrosion/precipitation behaviour in LBE.
- Investigations on the applicability of “Oxygen Control System (OCS)” in large LBE loops.
- Testing of appropriate zirconia-based oxygen sensors in LBE as part of the OCS.

*Operational parameters:*
- Maximum temperature: 550°C.
- Minimum temperature: 400°C.
- Maximum (typical) flow rate: 4 (2) m/s.
- Electrical power: 170 kW.
- Number of test sections: 2.
- Number of samples: Ca. 32.
- Oxygen control system (OCS): Via H₂/H₂O ratio in gas phase.
- Oxygen sensors: 3 in LBE, 1 in gas phase.
- Heavy liquid metal: PbBi.
Figure 12.3.1. Sketch and photo of the COSTA facility
Figure 12.3.2. Scheme and photo of CORRIDA
**Facility: Lead Corrosion (LECOR) – Figure 12.3.3**

**ENEA, Italy**

*Objectives:*
- Corrosion investigation in lead alloys.
- Component test and development.
- Physico-chemistry.

*Operational parameters:*
- Maximum temperature hot leg: 500°C.
- Maximum flow rate: 4.5 m³/h.
- Maximum electrical power: 4 MW.
- Number of test sections: 3.
- Oxygen meter: Yes.
- Oxygen control: Separate addition of hydrogen and oxygen.
- Heavy liquid metal: Pb-Bi.

**Facility: Development of Lead-alloy Technology and Applications (DELTA) – Figure 12.3.4**

**LANL, USA**

*Objectives:*
- Corrosion tests of structural and surface treated materials in flowing LBE.
- Investigations on mechanisms of material/LBE interactions.
- Investigations and benchmarking of corrosion/precipitation and system kinetics models.
- Implementation, testing and improvement oxygen sensors and control systems in large LBE loops.
- Thermal hydraulics experiments (e.g. natural convection) and system modelling (e.g. TRAC) and benchmarking.
- Development and testing of components, data acquisition and control systems.

*Operational parameters:*
- Maximum temperature: 550°C.
- Minimum temperature: 400°C.
- Maximum (typical) flow rate: 5 (2) m/s.
- Electrical power: 65 kW (main heater).
- Number of test sections: 2 (corrosion, scc).
- Number of samples: 186 (in 32/holder batches).
- Oxygen control system (OCS): Direct injection of O₂/He and H₂/He.
- Oxygen sensors: 4 in LBE, 1 in gas phase.
- Heavy liquid metal: PbBi.
Figure 12.3.3. Scheme and photo of LECOR

Flow-rate = 1.2 l/s
Max. Temp. = 550°C
Pressure = 400 kPa
Figure 12.3.4. Scheme and photo of DELTA loop
**Facility: Lead Correlation Stand (LCS) – Figure 12.3.5**

LANL/UNLV, USA

**Objectives:**
- Transfer and extend LBE coolant technology to high temperature Pb systems.
- Corrosion tests of structural and surface treated materials in flowing Pb.
- Thermal-hydraulics experiments (e.g. natural convection and flow stability).
- Adapting and testing of sensors, components, data acquisition and control systems to in-Pb use at higher temperatures.
- Test ODS steel (MA956) welding and construction for the loop.

**Operational parameters:**
- Maximum temperature: 700°C.
- Minimum temperature: 400°C.
- Maximum flow rate: 0.25 m/s.
- Electrical power: 15 kW (main heater).
- Number of test sections: 1 (corrosion).
- Number of samples: TBD.
- Oxygen control system (OCS): Direct injection of O₂/He and H₂/He.
- Oxygen sensors: 2.
- Heavy liquid metal: Pb.

**Facility: COLIMESTA – Figure 12.3.6**

CEA, France

**Objectives:**
- Corrosion studies of materials (including welds) and coatings.
- Corrosion mechanisms.
- Effect of oxygen content on corrosion processes.
- Corrosion kinetics.
- Development of corrosion models.

**Operational parameters:**
- Maximum temperature: 500°C.
- Maximum flow rate: Static.
- Number of test sections: 2.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi.
- Corrosion protection: Aluminisation by pack cementation max.
Figure 12.3.5. Schematic of the Lead Correlation Stand (LCS)
Figure 12.3.6. Scheme and photo of COLIMESTA
Facility: CICLAD – Figure 12.3.7

CEA, France

Objectives:
- Corrosion studies of materials (including welds) and coatings.
- Effect of hydrodynamic on corrosion by means of a rotating cylinder (especially at high velocity and including erosion phenomena).
- Effect of oxygen content on corrosion processes.
- Corrosion kinetics.
- Development of corrosion models.

Operational parameters:
- Maximum temperature: 500°C.
- Maximum flow rate: 5 m s⁻¹ corresponding to 5000 rev.min⁻¹.
- Number of test sections: One with the rotating specimens, one with in-pipe specimens.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi.
- Corrosion protection: Aluminisation by pack cementation max.
- Oxygen control system (OCS): Yes.

Facility: Liquid Solid Reaction (LiSoR) – Figure 12.3.8

PSI, Switzerland

Objectives:
- Investigation of the effect of simultaneous interaction of irradiation, LBE and mechanical stresses with structural materials.

Operational parameters:
- Maximum temperature: 350°C.
- Maximum flow rate: 1 m/s in the test section.
- Maximum electrical power: 30 kW.
- Number of test sections: 1.
- Oxygen control system (OCS): No.
- Heavy liquid metal: Pb-55.5Bi.

Irradiation parameter:
- Beam energy on target: 72 MeV.
- Beam current: Minimum 15 μA, maximum 40 μA.
- Beam profile on target (Gaussian) : \( \sigma_x = \sigma_y = 1.6 \text{ mm} \).
- Beam wobbling max frequency: 14.3 Hz in X, 2.38 Hz in Y (6:1).
- Beam structure: Wobbling horizontal \( x_{\text{max}} = \pm 2.75 \text{ mm} \), wobbling vertical \( y_{\text{max}} = \pm 7 \text{ mm} \).
Figure 12.3.7. Scheme and photo of CICLAD

![Scheme and photo of CICLAD](image-url)
Figure 12.3.8. Scheme and photo of LISOR

1 – LBE tank, 2 – induction pump, 3 – electromagnetic flow meter, 4 – thermostat (4-1 – LBE-DIPHYL heat exchanger, 4-2 – DIPHYL-WATER heat exchanger, 4-3 – oil pump, 4-4 – ventury tube, 4-5 – bypass, 4-6 – oil expansion tank, 4-7 – valves for oil loop filling and draining), 5-12 – automatic valves, 13 – expansion tank, 14 and 15 – inlet and outlet pipe
Facility: Corrosion and Wetting Investigation (CorrWett) – Figure 12.3.9

PSI, Switzerland

Objectives:
- Corrosion.
- Thermal cycling.
- Investigation of stressed coated specimens.

Operational parameters:
- Maximum temperature: 350°C.
- Maximum flow rate: 0.8 m/s in the test section.
- Maximum electrical power: 8.6 kW.
- Number of test sections: 1.
- Oxygen control system (OCS): No.
- Heavy liquid metal: Pb-55.5Bi.

Facility: SSRT/stagnant experimental set-up – Figure 12.3.10

SCK•CEN, Belgium

Objectives:
- Effects of Pb-Bi on the mechanical properties of the structural materials.
- Mutual effect of Pb-Bi and irradiation (mechanical tests on pre irradiated materials).
- Oxygen control and measurements of the dissolved oxygen concentration.

Operational parameters:
- Maximum temperature: 500°C.
- Maximum electrical power: 3.5 KW.
- Number of test sections: 1 (autoclave).
- Volume of the liquid metal: ~2.5 litre.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi
Figure 12.3.9. Scheme and photo of CorrWett
Figure 12.3.10. Scheme and photo of SSRT/stagnant experimental set-up
Facility: FELIX/FEDE – Figure 12.3.11

CIEMAT, Spain

Objectives:
- Materials screening test in stagnant conditions.

Operational parameters:
- Different gas atmospheres are used.
- Oxygen content is measured.
- Maximum temperature 600°C.

Facility: CIRCO (natural convection loop) – Figure 12.3.12

CIEMAT, Spain

Objectives:
- Long-term corrosion experiments in quasi-static LBE.
- Testing of oxygen sensors.
- Destructive examination of the loop after the test.

Operational parameters:
- Structural material: AISI316L.
- LBE inventory: 1 L.
- Max temperature: 550°C.
- Temperature gradient: 150°C.

Facility: LINCE (forced convection loop) – Figure 12.3.13

CIEMAT, Spain

Objectives:
- Long-term corrosion experiments in LBE.
- Oxygen control systems in flowing LBE.

Operational parameters:
- Maximum temperature: 500°C.
- Maximum flow rate: 2.5 m³/h.
- Number of test sections: 2.
- Lead-bismuth inventory: 170 L.
- Electrical power: 80 kW.
- Oxygen control system installed.
Figure 12.3.11. Scheme and photo of FEDE and FELIX

Figure 12.3.12. Photo of CIRCO
Figure 12.3.13. Scheme of LINCE
**Facility: JAERI Lead-bismuth Static Corrosion Facility (JLBS) – Figure 12.3.14**

JAERI, Japan

**Objectives:**
- Corrosion of materials for ADS components under static condition.
- Screening tests of materials for ADS components.
- Corrosion mechanism of various materials in Pb-Bi.
- Corrosion of surface-treated materials.
- Effect of alloying elements and stress on corrosion in Pb-Bi.
- Effect of impurities in Pb-Bi.

**Operational parameters:**
- Maximum temperature: 600°C.
- Number of pots: 4.
- Number of test pieces: 10/pot.
- Diameter of pot: 100 mm.
- Heavy metal weight: 7 kg/pot.
- Oxygen control system (OCS): Yes (partially).
- Heavy liquid metal: Pb-Bi.

**Facility: JAERI Lead-bismuth Flow Loop (JLBL-1) – Figure 12.3.15**

JAERI, Japan

**Objectives:**
- Corrosion study of ADS components in flowing Pb-Bi.
- Development of Pb-Bi flow control.
- Material corrosion-proof test for ADS target test facility at JAERI.

**Operational parameters:**
- Maximum temperature: 450°C.
- Maximum pressure: 5 bar.
- Maximum flow rate: 18 L/min.
- Maximum electrical power: 15 kW heaters.
- Number of test sections: 2.
- Heavy liquid metal: Pb-Bi.

**Facility: CRIEPI Static Corrosion Test Facility – Figure 12.3.16**

CRIEPI, Japan

**Objectives:**
- Behaviour of static corrosion in Pb-Bi.

**Operational parameters:**
- Maximum temperature: 700°C.
- Number of pots: 2.
- Number of test piece: 8 / pot.
- Diameter of the pot: 100 mm.
- Step extraction of pieces: Yes.
- Oxygen control system: Yes.
Figure 12.3.14. Photo of JLBS

Figure 12.3.15. Scheme and photo of JLBL-1
Figure 12.3.16. Photo of CRIEPI static corrosion test facility
Facility: KPAL-1 – Figure 12.3.17

KAERI, Korea

Objectives:
- Database for Pb-Bi corrosion.
- Development of oxygen control technique.
- Development of oxygen sensor.
- Development of thermal-hydraulic device for Pb-Bi loop.
- Enhancement of Pb-Bi Loop operation technique.

Operational parameters:
- Maximum temperature: 550°C.
- Maximum flow rate: 3.6 m³/h at 4.0 m NPSH.
- Maximum electrical power: 120 kW.
- Number of test sections: 1.
- Maximum test section height: 0.9 m.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi.

Facility: Convectional Loop, COLONRI I – Figure 12.3.18

Nuclear Research Institute Řež, Czech Republic

Objectives:
- Evaluation of corrosion resistance of structural materials in lead-bismuth at different conditions.
- Impact of oxygen content (oxygen technology).

Operational parameters:
- Maximum temperature: 700°C.
- Maximum flow rate: 1-2 cm/s.
- Maximum electrical power: 4 KW.
- Number of test sections: 2.
- Maximum test section height: 2.5 m.
- Oxygen control system (OCS): Yes – indirectly.
- Heavy liquid metal: Pb-Bi.
Figure 12.3.17. KAERI Pb-Bi loop
Figure 12.3.18. Scheme and photo of COLONRI I

- Oxidizing mixture generator
- Equalizing tank
- Heating
- Demineralised water
- Gaseous mixture $Ar + H_2$
- Low-temperature part with sample holders
- High-temperature part with sample holders
- Oxygen sensor
- Heating
- Filling tank
- Direct ion of media flow
- V1, V2, V3
- Oxygen sensor

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Facility: H.H. Uhlig Corrosion Laboratory – Figure 12.3.20

MIT, US

Objectives:
- Corrosion tests of structural and surface treated materials in LBE.
- Investigations on fundamental mechanisms of material/LBE interactions.
- Investigations and benchmarking of corrosion/precipitation and system kinetics models.
- Implementation, testing and improvement oxygen sensors.

Operational parameters:
- Maximum temperature: 800°C.
- Minimum temperature: 400°C.
- Maximum/minimum flow velocity: 3/0 m/s.
- Electrical power: 15 kW/test station (heater).
- Number of test stations: 2 (corrosion, scc, rotating electrode).
- Number of samples (immersion): 15/test station (individual crucibles).
- Number of samples (rotating): 1/test station.
- Oxygen control system (OCS): Direct injection of O₂/He and H₂/He, H₂/H₂O.
- Oxygen sensors: 1 in LBE, 1 in gas phase.
- Heavy liquid metal: PbBi/Pb.

Facility: ANL, USA

Objectives:
- Long-term corrosion investigations of structural materials in flowing Pb or LBE.
- Long-term corrosion investigations of coated materials in flowing Pb or LBE.
- Investigations regarding corrosion mechanisms and thermo-mechanical behaviour between materials and Pb or LBE.

Operational parameters:
- Maximum temperature: 800°C.
- Minimum temperature: 375°C (LBE), 500°C (Pb).
- Typical flow rate: ~0.01 m/s.
- Electrical power: Low.
- Number of test sections: 2.
- Number of samples: 2.
- Oxygen control system: Via H₂/H₂O ratio in gas phase.
- Oxygen sensors: –.
- Heavy liquid metal: Pb or LBE.
Figure 12.3.19. Schematic and photo of quartz convection harp

Figure 12.3.20. Schematic of rotating electrode system and photograph of various components of the system
**Facility: Mechanical Properties in Liquid Metals – Figure 12.3.21**

University of Lille – UMR CNRS 8517, France

**Objectives:**
Determination of mechanical behaviour and mechanical resistance of structural metallic alloys in liquid metals.

- Monotonic tensile behaviour:
  - standard tensile test (STT) using cylindrical specimen;
  - small punch test (SPT) using 9 mm diameter, 0.5 mm thickness disk.
- Cyclic behaviour:
  - low cycle fatigue (LCF) on smooth specimen;
  - fatigue crack growth gate (FCGR) on notched specimen.

**Operational parameters:**
- Maximum temperature: 350°C for LCF, FCGR and SPT, 600°C for STT.
- Maximum flow rate: Static.
- Oxygen control system: No.
- Heavy liquid metals: Pb, Bi, Sn …
- Machine for STT and SPT: 20 kN load capacity strain rate 10^{-2} to 10^{-5} s^{-1}.
- Machine for LCF: 100 kN load capacity – strain control, strain range Δε: 0.5 \times 10^{-2} to 2.5 \times 10^{-2} strain rate 10^{-2} to 10^{-4} s^{-1}.
- Machine for FCGR: 100 kN load capacity – load control, four-point bending specimen frequency 15 Hz maxi COD measurement.

**Facility: Lead-bismuth Corrosion Test Loop – Figure 12.3.22**

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Japan

**Objectives:**
- Material corrosion in flowing Pb-Bi.
- Oxygen control technique.
- Performance of oxygen sensor.
- Performance of electromagnetic flow meter.
- Performance of ultrasonic flow meter.

**Operational parameters:**
- Maximum temperature: 550°C.
- Maximum system pressure: 0.4 MPa.
- Maximum flow rate: 0.36 m³/h.
- Maximum electrical power: 22 kW.
- Number of test sections: 1.
- Maximum test section height: 1.5 m.
- Oxygen control system (OCS): Yes (PbO tablets).
- Heavy liquid metal: Pb-Bi eutectic.
- Pb-Bi inventory: 450 kg.
Figure 12.3.21. Photo of fatigue propagation set-up

![Fatigue propagation set-up](image1)

Figure 12.3.22. Flow diagram and photo of the Lead-bismuth Corrosion Test Loop at TIT

![Flow diagram of Lead-bismuth Corrosion Test Loop](image2)
Facility: Liquid Metal Embrittlement Testing Station 1 (LIMETS1) – Figure 12.3.23
In operation: August 2004

SCK•CEN, Belgium

Objectives:
- Effects of Pb-Bi on the mechanical properties of the structural materials.
- Calibration of oxygen sensors.
- Effects of oxide layers on the mechanical properties of the structural materials.

Operational parameters:
- Maximum temperature: 500°C.
- Maximum electrical power: 3.5 KW.
- Number of test sections: 1 (autoclave).
- Volume of the liquid metal: ~3.5 litre.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi.

Facility: Liquid Metal Embrittlement Testing Station 2 (LIMETS2) – Figure 12.3.24
Planned operation: January 2006

SCK•CEN, Belgium

Objectives:
- To test radioactive materials in a controlled lead-bismuth environment.
- Tests that can be carried out are:
  - slow strain rate tests (SSRT);
  - constant load;
  - rising load;
  - crack growth rate (fracture mechanics).

Operational parameters:
- Maximum temperature: 500°C.
- Maximum pressure: 4 Bar.
- Maximum load: 20 kN.
- Displacement rates: $9 \times 10^{-2}$ to $3 \times 10^{-6}$ mm.s$^{-1}$.
- Strain rates (gage length 10 mm): $9 \times 10^{-3}$ to $3 \times 10^{-7}$ s$^{-1}$.
- Maximum displacement: 30 mm.
- Specimens to be tested: Tensile specimen, small size CT.
- Number of autoclaves and loading units: 1.
- Autoclave volume: 3.6 L.
- Autoclave materials: 316L.
- Material conditioning system: 316L.
- Conditioning gasses: Hydrogen, argon.
Figure 12.3.23. Schematic and photo of the LIMETS 1 facility
Figure 12.3.24. Flow sheet of the LIMEST II and photo of instrumentation panel for temperature control of LIMESTII
12.4 Thermal-hydraulics facilities and their applications

Thermal-hydraulics, the facilities are aimed at the study of basic phenomena as for instance the turbulent heat transfer, the free surface flow and two-phase flows. These phenomena can be studied by performing experiments with simple geometries. In addition, a very challenging activity is the execution of design oriented experiments as for instances experiments devoted to the characterisation of a spallation target or a fuel bundle. The experimental activities are normally prepared with the help of computational analysis (CFD calculations). One of the most important aims of thermal-hydraulics experiments is to improve physical models and to validated the CFD codes. The importance of these activities can be recognised in the fact that CFD codes are regularly used for the layout of the design of an HLM system.

**Facility: Thermal-hydraulics and ADS Design (THEADES) – Figure 12.4.1**

**FZK, Germany**

**Objectives:**
- Thermal-hydraulic single-effect investigations of ADS components.
- Cooling of the beam window.
- Flow field of a windowless target configuration.
- Cooling of fuel element(s).
- Heat transfer characteristics of a Pb-Bi/Pb-Bi heat exchanger.
- Heat transfer characteristics of a steam generator.
- Heat transfer characteristics of a Pb-Bi/air heat exchanger.
- Set-up of thermal-hydraulic data base for physical model and code validation.

**Operational parameters:**
- Maximum temperature: 450°C.
- Maximum flow rate: 100 m³/h at 4.5 m NPSH.
- Maximum electrical power: 4 MW.
- Number of test sections: 4.
- Maximum test section height: 3.4 m.
- Oxygen control system (OCS): Yes.
- Heavy liquid metal: Pb-Bi.

**Facility: Circolazione Eutettico (CIRCE) – Figure 12.4.2**

**ENEA, Italy**

**Objectives:**
- Thermal-hydraulic experiments.
- Component development.
- Large scale experiments in pool configuration.
- Liquid metal chemistry in pool configuration.

**Operational parameters:**
- Maximum temperature: 450°C.
- Volume test section: 9480 l.
- Volume storage tank: 9250 l.
- Volume pumping tank: 924 l.
- Oxygen meter: No.
- Oxygen control: Yes (controlling the cover gas).
- Heavy liquid metal: Pb-Bi.
Figure 12.4.1. Scheme and photo of THEADES
Figure 12.4.2. Schematic and photo of CIRCE
**Facility: Thermal-hydraulic ADS Lead-bismuth Loop (TALL) – Figure 12.4.3**

**RIT (KTH), Sweden**

**Objectives:**
- To perform medium-scale heat transfer experiments of TECLA on different heat exchangers.
- Investigation on LBE flow and heat transfer with prototypic thermal-hydraulic conditions (as in conceptual ADS design).
- Thermal-hydraulic characteristics of natural and forced circulation under steady and transient conditions.
- To perform tests representative for accident scenarios and to strengthen the database for code validation in support of EU’s project PDS-XADS.
- Set-up of thermal-hydraulic data base for physical model and code validation.

**Operational Parameters:**
- Maximum temperature: 500°C.
- Maximum flow rate: 2.5 m³/h.
- Maximum electrical power: 55 kW.
- Electro-magnetic pump: 5.5 kW
- Maximum test section height: 6.8 m.
- Oxygen control system (OCS): No.
- Oxygen control sensors: Yes.
- Heavy liquid metal: Pb-Bi.
- Secondary loop coolant: Glycerol.

**Facility: JAERI Lead-bismuth Flow Loop (JLBL-2) – Figure 12.2.4**

**JAERI, Japan**

**Objectives:**
- Flow study in horizontal Pb-Bi target.
- Proof test of I-target.

**Operational parameters:**
- Maximum temperature: <450°C.
- Maximum pressure: 2 bar.
- Maximum flow rate: 50 L/min.
- Maximum electrical power: 5 kW heaters.
- Number of test sections: –.
- Oxygen control system (OCS): No.
- Heavy liquid metal: Pb-Bi.
Figure 12.4.3. Schematic and photo of TALL

Figure 12.4.4. Schematic and photo of JLBL-2
Facility: JAERI Lead-Bismuth flow Loop-3 (JLBL-3) – Figure 12.4.5
JAERI, Japan

Objectives:
- Thermal fluid test of beam window.
- Proof test of mechanical pump and massive Pb-Bi flow.

Operational parameters:
- Maximum temperature: 450°C
- Maximum pressure: 7 bar.
- Maximum flow rate: 500 L/min.
- Maximum electrical power: 6 kW heaters.
- Number of test sections: 1.
- Oxygen control system (OCS): Yes
- Heavy liquid metal: Pb-Bi.
- Total inventory: 450 litres.

Facility: Mitsui Engineering and Shipbuilding Test LOOP 2001 (MES-LOOP2001) – Figure 12.4.6
MES, Japan

Objectives:
- Coolant purification control test.
- Structural materials corrosion test.
- Thermal-hydraulic test.
- Static/transient operation test.

Operational parameters:
- Maximum temperature: 550°C
- Maximum flow rate: 15 L/min
- Maximum electrical power: 6 kW
- Number of test sections: 1.
- Number of test pieces: 1–10.
- Maximum test section height: 1 m.
- Oxygen control system: Yes.
- Heavy liquid metal: Pb-Bi.
Figure 12.4.5. Flow diagram and photo of JBL3 loop
Figure 12.4.6. Scheme and photo of MES
Facility: CRIEPI Pb-Bi Test Loop on Thermal-hydraulics – Figure 12.4.7

CRIEPI, Japan

Objectives:
- Heat transfer characteristics of Pb-Bi.
- Gas lift pump performance in Pb-Bi.
- Flow characteristics of Pb-Bi/gas two phase flow.

Operational parameters:
- Maximum temperature: 300°C.
- Maximum pressure: 0.5 MPa.
- Maximum flow rate: 6 m³/h.
- Total electric power supply: 160 KVA.
- Number of heaters and control: 30 (PID controlled).
- Maximum heater power: 5 KVA.
- Diameter of main piping: 2 inches.
- Oxygen control system: No.

Facility: Wisconsin Tantalus Facility – Figure 12.4.8

UW, USA

Objectives:
- Multi-phase flow, heat transfer and flow stability/oscillations of steam/water injection into liquid metal.

Operational parameters:
- Maximum temperature: 550°C.
- Minimum temperature: 400°C.
- Maximum (typical) flow rate: 1-10 gram/sec.
- Electrical power: 30 kW.
- Number of test sections: 2 with multiple injectors.
- Heavy liquid metal: Pb and PbBi.
Figure 12.4.7. Schematic and photo of CRIEPI Pb-Bi Test Loop on Thermal-hydraulics

Figure 12.4.8. Schematic and photo of the Wisconsin Tantalus Facility
Facility: Heavy Eutectic Liquid Metal Loop for Investigation of Operability and Safety (HELIOS)  
Figure 12.4.9

Seoul National University (SNU), Korea

Objectives:
- Verification of the natural circulation capability in PEACER-300 (transmutation reactor), corrosion testing and oxygen sensor development.

HELIOS is going to be completed at the end of 2004. Materials corrosion tests are planned for 2005 and the natural circulation tests for 2006.

Design parameters of PEACER-300/HELIOS:
- Reactor thermal power (kW): 850000/60.
- Reactor vessel height (cm): 1400/1000.
- Reactor vessel diameter (cm): 700/5.0.
- Fuel rod active length (cm): 50/50.
- Number of fuel rods: 63433/4.
- Steam generator tube height (cm): 500/500.
- Primary loop pipe inner diameter (cm): 200/5.
- Pb-Bi coolant weight (tonne): –/1.8.
- Total flow (kg/sec): 58,059/10 max.
- Maximum flow speed (cm/sec): 200/200.
- Core exit temperature (C): 400/400.
- Core inlet temperature (C): 300/300.
- Elevation difference between core centre and steam generator centre (m): 8/8.

Facility: Lead-bismuth Water Direct Contact Boiling Two-phase Flow Apparatus – Figure 12.4.10

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Japan

Objectives:
- Operation technique of steam gas lift pump type Pb-Bi-cooled fast reactor.
- Thermal-hydraulics of Pb-Bi-water direct contact boiling flow.

Operational parameters:
- Maximum Pb-Bi temperature: 460°C.
- Steam temperature: 296°C.
- System pressure: 7 MPa.
- Pb-Bi flow rate: 33840 kg/h.
- Steam-water flow rate: 250 kg/h.
- Heater bundle power: 133 kW.
- Number of test sections: 1.
- Length of test section: 7 m.
- Oxygen control system (OCS): Yes (hydrogen-dissolved water).
- Heavy liquid metal: Pb-Bi eutectic.
- Pb-Bi inventory: 1000 kg.
- Water inventory: 50 kg.
Figure 12.4.9. 3-D CAD drawing (a), side-view photograph (b) and design schematic (c) of HELIOS at Seoul National University.

(a) 3-D CAD drawing of HELIOS.
(b) Side-view photograph of HELIOS.
(c) Design schematic of HELIOS.
Figure 12.4.10. Flow diagram and photo of the Lead-bismuth-Water Direct Contact Boiling Two-phase Flow Apparatus at TIT
Table 12.1. Summary of the international heavy liquid metal test facilities

<table>
<thead>
<tr>
<th>Association/country</th>
<th>Name of the facility</th>
<th>Type of facility</th>
<th>Objectives</th>
<th>OCS – O&lt;sub&gt;2&lt;/sub&gt; probe</th>
<th>Tmax</th>
<th>Flow rate</th>
<th>Other information</th>
<th>CP*</th>
</tr>
</thead>
<tbody>
<tr>
<td>FZK/D</td>
<td>THESYS</td>
<td>Loop</td>
<td>Development and testing of measurement techniques</td>
<td>H₂/H₂O – yes</td>
<td>550°C</td>
<td>3.5 m³/h</td>
<td>Heated pipe experiment Heated rod experiment</td>
<td>1</td>
</tr>
<tr>
<td>FZK/D</td>
<td>KOKOS</td>
<td>Loop</td>
<td>OCS development</td>
<td>H₂/H₂O – yes</td>
<td>550°C</td>
<td>–</td>
<td>Diffusion coefficient measurement of oxygen in LBE</td>
<td>3</td>
</tr>
<tr>
<td>FZK/D</td>
<td>KOSIMA</td>
<td>Static</td>
<td>Oxygen sensor development and calibration</td>
<td>H₂/H₂O – yes</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>ENEA/I</td>
<td>CHEOPE II</td>
<td>Loop</td>
<td>Liquid metal chemistry</td>
<td>–</td>
<td>500°C</td>
<td>50 l of LBE</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>CEA/F</td>
<td>SOLDIF</td>
<td>Static</td>
<td>Solubilities, diffusivities, oxide layer characterisation</td>
<td>? – yes</td>
<td>500°C</td>
<td>–</td>
<td>–</td>
<td>5</td>
</tr>
<tr>
<td>CEA/F</td>
<td>STELLA</td>
<td>Loop</td>
<td>Oxygen sensor and dip sampling system validation, OCS development</td>
<td>PbO – yes</td>
<td>550°C</td>
<td>1 m³/h</td>
<td>–</td>
<td>6</td>
</tr>
<tr>
<td>SCK&gt;CEN/B&amp;F</td>
<td>PCV</td>
<td>Stirring</td>
<td>Conditioning and cleaning procedures of LBE and LBE outgas studies</td>
<td>H₂/H₂O</td>
<td>500°C</td>
<td>–</td>
<td>Studies suitable for windowless spallation target</td>
<td>8</td>
</tr>
<tr>
<td>SCK&gt;CEN/B&amp;F</td>
<td>VICE</td>
<td>Stirring</td>
<td>Gas transport in the beam line, outgas, metal evaporation, simulation of spallation products</td>
<td>–</td>
<td>500°C</td>
<td>–</td>
<td>Main operating pressure 10&lt;sup&gt;-7&lt;/sup&gt; mbar. Studies devoted to the windowless solution</td>
<td>8</td>
</tr>
<tr>
<td>LANL/USA</td>
<td>DELTA</td>
<td>Loop</td>
<td>Corrosion tests in flowing LBE, corrosion/precipitation and system kinetics models, oxygen sensors and control systems, thermal-hydraulics experiments, components testing, data acquisition and control systems</td>
<td>Yes</td>
<td>550°C</td>
<td>2.5 m/s</td>
<td>–</td>
<td>12</td>
</tr>
<tr>
<td>LANL-UNLV/USA</td>
<td>LCS</td>
<td>Loop</td>
<td>Transfer and extend LBE technology to higher-temperature Pb</td>
<td>Yes</td>
<td>700°C</td>
<td>0.25 m/s</td>
<td>ODS steel (MA956) construction</td>
<td>12</td>
</tr>
<tr>
<td>UNL/USA</td>
<td>TC-1</td>
<td>Target</td>
<td>Long-term sustained operation of MHD pump for LBE loop; examine long-term performance of target systems under non-irradiation</td>
<td>–</td>
<td>TBD (300°C @ pump inlet)</td>
<td>TBD (15 m³/h)</td>
<td>–</td>
<td>19</td>
</tr>
<tr>
<td>JAERI/JP</td>
<td>JLBL-1</td>
<td>Loop</td>
<td>Corrosion studies and development of flow measurement techniques</td>
<td>H₂/H₂O</td>
<td>450°C</td>
<td>18 l/min</td>
<td>Two test sections</td>
<td>14</td>
</tr>
</tbody>
</table>

* CP = contact persons for the facilities. CP are listed at the end of the chapter.
Table 12.1. Summary of the international heavy liquid metal test facilities (cont.)

<table>
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<th>Type of facility</th>
<th>Objectives</th>
<th>OCS – O₂ probe</th>
<th>Tmax</th>
<th>Flow rate</th>
<th>Other information</th>
<th>CP*</th>
</tr>
</thead>
<tbody>
<tr>
<td>MES/JP</td>
<td>MES-LOOP2001</td>
<td>Loop</td>
<td>Coolant purification, thermal-hydraulic and corrosion tests</td>
<td>H₂/H₂O – yes sensor</td>
<td>550°C</td>
<td>15 l/min</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>TIT/JP</td>
<td>Steam Injection and OCC</td>
<td>Apparat.</td>
<td>Oxygen sensor, oxygen potentials in Pb-Bi, Pb-Bi mist and impurities into steam flow, dissolved H₂ in steam and water chemistry and transport of metal elements in Pb-Bi</td>
<td>H₂/H₂O – yes sensor</td>
<td>500°C</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td><strong>Materials testing facilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FZK/D</td>
<td>COSTA</td>
<td>Static</td>
<td>Corrosion mechanism investigation in controlled conditions</td>
<td>H₂/H₂O – in the gas phase</td>
<td>1000°C</td>
<td>-</td>
<td>200 specimens at 5 different T and 10 different O₂ activities in one run</td>
<td>3</td>
</tr>
<tr>
<td>FZK/D</td>
<td>CORRIDA</td>
<td>Loop</td>
<td>Corrosion rate in controlled atmosphere</td>
<td>H₂/H₂O – yes</td>
<td>550°C</td>
<td>2-4 m/s</td>
<td>Modelling of corrosion precipitation behaviour</td>
<td>2</td>
</tr>
<tr>
<td>ENEA/I</td>
<td>CHEOPE III</td>
<td>Loop</td>
<td>Corrosion at high oxygen content</td>
<td>H₂O₂ – yes</td>
<td>500°C</td>
<td>1.2 m³/h</td>
<td>50 l of LBE</td>
<td>4</td>
</tr>
<tr>
<td>ENEA/I</td>
<td>LECOR</td>
<td>Loop</td>
<td>Corrosion at low oxygen content, physico-chemistry, component testing</td>
<td>H₂O₂ – yes</td>
<td>500°C</td>
<td>4.5 m³/h</td>
<td>Three test sections</td>
<td>4</td>
</tr>
<tr>
<td>LANL/USA</td>
<td>DELTA</td>
<td>Loop</td>
<td>Corrosion tests in flowing LBE, corrosion/precipitation and system kinetics models, oxygen sensors and control systems, thermal-hydraulics experiments, components testing, data acquisition and control systems</td>
<td>Yes</td>
<td>550°C</td>
<td>2.5 m/s</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>LANL-UNLV/USA</td>
<td>LCS</td>
<td>Loop</td>
<td>Transfer and extend LBE technology to higher temperature Pb, corrosion tests in flowing Pb</td>
<td>Yes</td>
<td>700°C</td>
<td>0.25 m/s</td>
<td>ODS steel (MA956) construction</td>
<td>12</td>
</tr>
<tr>
<td>CEA/F</td>
<td>COLIMESTA</td>
<td>Static</td>
<td>Effect of oxygen content on the corrosion mechanism</td>
<td>Yes – yes</td>
<td>500°C</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>CEA/F</td>
<td>CICLAD</td>
<td>Rotating cylinder</td>
<td>Hydrodynamic effect on corrosion rate</td>
<td>H₂/H₂O – yes</td>
<td>500°C</td>
<td>5 m/s</td>
<td>Development of corrosion mechanism</td>
<td>5</td>
</tr>
<tr>
<td>PSI/CH</td>
<td>LISOR</td>
<td>Loop</td>
<td>“Stress” corrosion under irradiation</td>
<td>No</td>
<td>350°C</td>
<td>1 m/s</td>
<td>Proton beam: 72 MeV, 15-40 μA</td>
<td>7</td>
</tr>
<tr>
<td>PSI/CH</td>
<td>CorWett</td>
<td>Loop</td>
<td>Corrosion, thermal cycling</td>
<td>No</td>
<td>350°C</td>
<td>0.8 m/s</td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

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<th>Tmax</th>
<th>Flow rate</th>
<th>Other information</th>
<th>CP*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCK•CEN/BE</td>
<td>SSRT/ stagnant</td>
<td>Static</td>
<td>LBE and irradiation on mechanical properties of structural materials, studies on OCS and O₂ measurement</td>
<td>Yes</td>
<td>500°C</td>
<td>–</td>
<td>One test section in autocave with 2.5 l of LBE</td>
<td>9</td>
</tr>
<tr>
<td>CIEMAT/ES</td>
<td>FEDE</td>
<td>Static</td>
<td>Materials testing in controlled conditions and O₂ measurement</td>
<td>Yes</td>
<td>600°C</td>
<td>–</td>
<td>Different gas atmospheres and different O₂ activities, multi-specimen device</td>
<td>10</td>
</tr>
<tr>
<td>CIEMAT/ES</td>
<td>FELIX</td>
<td>Static</td>
<td>Materials testing</td>
<td>H₂/H₂O</td>
<td>600°C</td>
<td>–</td>
<td>Furnaces with controlled atmosphere</td>
<td>10</td>
</tr>
<tr>
<td>CIEMAT/ES</td>
<td>CIRCO</td>
<td>Loop</td>
<td>Long-term corrosion experiments and oxygen sensor testing</td>
<td>Yes</td>
<td>550°C</td>
<td>2.5 m³/h</td>
<td>Analysis of corrosion products deposition could be performed by destructive examination of the loop</td>
<td>10</td>
</tr>
<tr>
<td>CIEMAT/ES</td>
<td>LINCE</td>
<td>Loop</td>
<td>Long-term corrosion experiments and oxygen control system analysis</td>
<td>Yes</td>
<td>500°C</td>
<td>–</td>
<td>LBE inventory 170 l, electrical power 80 kW</td>
<td>10</td>
</tr>
<tr>
<td>JAERI/JP</td>
<td>JLB S</td>
<td>Static</td>
<td>Compatibility of materials</td>
<td>OCS partially</td>
<td>600°C</td>
<td>–</td>
<td>Analysis of corrosion products deposition could be performed by destructive examination of the loop</td>
<td>13</td>
</tr>
<tr>
<td>JAERI/JP</td>
<td>JLBS</td>
<td>Loop</td>
<td>Corrosion studies and development of flow measurement techniques</td>
<td>H₂/H₂O</td>
<td>450°C</td>
<td>18 l/min</td>
<td>Two test sections</td>
<td>14</td>
</tr>
<tr>
<td>CRIEPI/JP</td>
<td>PbBi static</td>
<td>Static</td>
<td>Behaviour of static corrosion in Pb-Bi</td>
<td>Yes</td>
<td>700°C</td>
<td>–</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>MES/JP</td>
<td>MES-LOOP2001</td>
<td>Loop</td>
<td>Coolant purification, thermal-hydraulic and corrosion tests</td>
<td>H₂/H₂O – yes sensor</td>
<td>550°C</td>
<td>15 l/min</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>KAERI/KR</td>
<td>Not named</td>
<td>Loop</td>
<td>OCS, corrosion, thermal-hydraulics</td>
<td>Yes OCS yes sensor</td>
<td>550°C</td>
<td>3.6 m³/h</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>SNU/KR</td>
<td>HELIOS</td>
<td>Loop</td>
<td>OCS, materials and thermal-hydraulics (natural circulation capabilities in PEACER-300)</td>
<td>Yes OCS</td>
<td>450°C</td>
<td>200 cm/s</td>
<td>HELIOS has been designed by thermo-hydraulics scaling of PEACER-300</td>
<td>23</td>
</tr>
<tr>
<td>ŘEŽ/CZ</td>
<td>COLONRI I</td>
<td>Loop</td>
<td>Corrosion in different conditions</td>
<td>OCS indirectly</td>
<td>700°C</td>
<td>1.2 cm/s</td>
<td></td>
<td>18</td>
</tr>
<tr>
<td>ANL/USA</td>
<td>Natural convection quartz harp</td>
<td>Loop</td>
<td>Long-term corrosion in Pb/LBE; thermo-mechanical behaviour between materials and Pb/LBE</td>
<td>H₂/H₂O</td>
<td>800°C</td>
<td>0.01 m/s</td>
<td></td>
<td>20</td>
</tr>
</tbody>
</table>

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Table 12.1. Summary of the international heavy liquid metal test facilities (cont.)

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<thead>
<tr>
<th>Association/country</th>
<th>Name of the facility</th>
<th>Type of facility</th>
<th>Objectives</th>
<th>OCS – O₂ probe</th>
<th>Tmax</th>
<th>Flow rate</th>
<th>Other information</th>
<th>CP*</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT/US</td>
<td>H.H. Uhlig Corrosion Lab</td>
<td>Static/rotating disc</td>
<td>Corrosion mechanism, benchmarking corrosion/precipitation; oxygen sensors</td>
<td>O₂/He; H₂/He; H₂/O₂</td>
<td>800°C</td>
<td>0-3 m/s</td>
<td>The liquid metal is contained in a ZrO₂ crucible, capability of the crucible is 4 L</td>
<td>21</td>
</tr>
<tr>
<td>UnivLILLE/F</td>
<td>Mechanical Properties in Liquid Metals</td>
<td>Static</td>
<td>Monotonic and cyclic properties of structural alloys in liquid metals</td>
<td>No</td>
<td>600°C</td>
<td>Static</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>TIT/JP</td>
<td>LBE Corrosion</td>
<td>Loop</td>
<td>Material corrosion in flowing Pb-Bi, oxygen control technique, oxygen sensor, electromagnetic flow meter, ultrasonic flow meter</td>
<td>PbO Yes sensor</td>
<td>550°C</td>
<td>0.36 m³/h</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>SCK/CEN/B</td>
<td>LIMEST 1</td>
<td>Static</td>
<td>Mechanical testing of materials and oxide layers in LBE</td>
<td>Ar/H₂</td>
<td>500°C</td>
<td>Static</td>
<td>Calibration of oxygen sensors also foreseen</td>
<td>26</td>
</tr>
<tr>
<td>SCK/CEN/B</td>
<td>LIMEST 2</td>
<td>Static</td>
<td>Mechanical testing of irradiated materials in LBE</td>
<td>Ar/H₂</td>
<td>500°C</td>
<td>Static</td>
<td>SSRT, constant and raising load, CGR</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Thermal-hydraulics facilities</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FZK/D</td>
<td>THEADES</td>
<td>Loop</td>
<td>Single effects, beam window, window less, fuel elements, heat transfer</td>
<td>H₂/H₂O – yes</td>
<td>450°C</td>
<td>100 m³/h</td>
<td>Height of the test sections 3.4 m</td>
<td>1</td>
</tr>
<tr>
<td>ENEA/I</td>
<td>CIRCE</td>
<td>Pool</td>
<td>Thermal-hydraulics, component development, large-scale exp. and liquid metal chemistry in pool config.</td>
<td>OCS yes – no O₂ probe</td>
<td>450°C</td>
<td></td>
<td>8540 l of LBE</td>
<td>4</td>
</tr>
<tr>
<td>ENEA/I</td>
<td>CHEOPE I</td>
<td>Loop</td>
<td>Thermal-hydraulics, cooling pin</td>
<td></td>
<td>500°C</td>
<td></td>
<td>900 l of LBE</td>
<td>4</td>
</tr>
<tr>
<td>RIT/SE</td>
<td>TALL</td>
<td>Loop</td>
<td>Thermal-hydraulics and heat transfer measurements</td>
<td>No OCS – yes sensor</td>
<td>550°C</td>
<td>2.5 m³/h</td>
<td>Height of the test section: 6.8 m</td>
<td>11</td>
</tr>
<tr>
<td>JAERI/IP</td>
<td>JLBL-2</td>
<td>Loop</td>
<td>Flow studies in horizontal LBE target</td>
<td>No &lt;450°C</td>
<td></td>
<td>50 l/min</td>
<td>Proof test of target – I</td>
<td>14</td>
</tr>
<tr>
<td>JAERI/IP</td>
<td>JLBL-3</td>
<td>Loop</td>
<td>Thermal-fluid test loop</td>
<td>Yes</td>
<td>450°C</td>
<td>500 l/min</td>
<td>Collaboration with MES</td>
<td>28</td>
</tr>
<tr>
<td>CRIEPI/IP</td>
<td>Pb-Bi Thermal-hydraulics</td>
<td>Loop</td>
<td>Heat transfer characteristics of Pb-Bi, gas lift pump performance in Pb-Bi flow characteristics of Pb-Bi/gas two-phase flow</td>
<td>No</td>
<td>300°C</td>
<td>6 m³/h</td>
<td></td>
<td>15</td>
</tr>
</tbody>
</table>

* CP = contact persons for the facilities. CP are listed at the end of the chapter.
Table 12.1. Summary of the international heavy liquid metal test facilities (cont.)

<table>
<thead>
<tr>
<th>Association/country</th>
<th>Name of the facility</th>
<th>Type of facility</th>
<th>Objectives</th>
<th>OCS – O2 probe</th>
<th>Tmax</th>
<th>Flow rate</th>
<th>Other information</th>
<th>CP*</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANL/US</td>
<td>DELTA Loop</td>
<td>Loop</td>
<td>Corrosion tests in flowing LBE, corrosion/precipitation and system kinetics models, oxygen sensors and control systems, thermal-hydraulics experiments, components testing, data acquisition and control systems</td>
<td>Yes</td>
<td>550°C</td>
<td>2-5 m/s</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>UW/US</td>
<td>Wisconsin Tantalus facility</td>
<td>Loop</td>
<td>Multi-phase flow, heat transfer and flow stability/oscillations of steam/water injection into Pb/LBE</td>
<td>–</td>
<td>550°C</td>
<td>1-10 g/sec</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>KAERI/KR</td>
<td>Not named Loop</td>
<td>Loop</td>
<td>OCS, corrosion, thermal-hydraulics</td>
<td>Yes OCS – yes sensor</td>
<td>550°C</td>
<td>3.6 m³/h</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>SNU/KR</td>
<td>HELIOS Loop</td>
<td>Loop</td>
<td>OCS, materials and thermal-hydraulics (natural circulation capabilities in PEACER-300)</td>
<td>Yes OCS</td>
<td>450°C</td>
<td>200 cm/s</td>
<td>HELIOS was designed by thermo-hydraulics scaling of PEACER - 300</td>
<td>23</td>
</tr>
<tr>
<td>TIT/JP</td>
<td>LBE-H₂O Appar.</td>
<td>Appar.</td>
<td>Operation technique of steam gas lift pump type Pb-Bi-cooled fast reactor, thermal-hydraulics of Pb-Bi-water direct contact boiling flow</td>
<td></td>
<td>460°C</td>
<td>33.8 kg/h</td>
<td></td>
<td>25</td>
</tr>
</tbody>
</table>

* CP = contact persons for the facilities. CP are listed at the end of the chapter.
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