Techno
Fusión

National Centre for Fusion Technologies

Scientific-Technical Report

September 2009

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This document has been elaborated with the enthusiastic contribution of a large group of researchers from seven Universities and Research Centres. We are enormously grateful to them for their help and support during these past two years.

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Summary

The development of nuclear fusion is rapidly becoming a vital necessity in view of the continuing rise of the world's energy demand. Nuclear fusion offers a virtually endless source of energy that is both environmentally friendly and capable of meeting any foreseeable energy demand.

The progress of fusion constitutes one of the greatest technological challenges for humanity. Indeed, this field is one of the main areas of research of the European Union (EU), as was evident in June 2005, when the final agreement to construct ITER[1] (the *International Thermonuclear Experimental Reactor*) was signed, together with the USA, Russia, China, South Korea, Japan and India. ITER is an experimental reactor intended to demonstrate the scientific viability of fusion.

As the design of ITER is already defined, over the next 20 to 30 years the main focus will be on the development of technological components for future commercial reactors, rather than on basic plasma physics. The most important challenges for fusion research are the selection, development and testing of materials and the various elements for reactors, together with the design of energy extraction systems and tritium production methods.

At present, Spain has a unique opportunity to be at the forefront of this new technological field in Europe. However, there is a need for new facilities to simulate the extreme conditions to which materials and components will be exposed inside a fusion reactor.

The project outlined in this report describes the construction of a singular scientific and technological facility (the National Centre for Fusion Technologies -*TechnoFusión*) in the Madrid region, to create the infrastructure required to develop the technologies needed in future commercial fusion reactors, and to assure the participation of Spanish research groups and companies.

The Spanish scientific community has achieved an international recognition in the science and technology areas needed for the success of this ambitious project, as is evident from the results obtained by Spanish researchers in the fusion field over the past few decades. *TechnoFusión* intends to take advantage of the existing expertise of university research groups, public research institutions (*Organismo Público de Investigación, OPI*) and private companies. The performance of materials and components under the extreme conditions of a fusion reactor is largely unknown, and this is precisely what *TechoFusión* intends to explore. For this purpose, facilities are required for the manufacture, testing and analysis of critical materials. Additional resources are planned to develop and exploit numerical codes for the simulation of

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[1] ITER (originally the International Thermonuclear Experimental Reactor) is an international tokamak (magnetic confinement fusion) research/engineering project being built in Cadarache, France.

materials in special environments, to develop remote handling technologies and other areas related to the management of liquid metals.

In summary, *TechnoFusión* focus is the creation of infrastructures for the following research areas: 1) material production and processing, 2) material irradiation, 3) plasma-wall interaction (thermal loads and the mechanism of atomic damage), 4) liquid metal technologies, 5) material characterization techniques, 6) remote handling technologies and 7) computer simulation.

Therefore, *TechnoFusión* Scientific-Technical Facility will thus consist of a complex of seven large research areas, many of which are unique in the world, with the following main technical objectives:

1) *Material production and processing*. There are still some uncertainties about the materials that will be used to construct future fusion reactors, partly because it has not yet been possible to reproduce the extreme conditions to which such materials will be subjected. Therefore, it is of utmost importance to dispose of installations capable of manufacturing new materials on a semi-industrial scale and fabricating prototypes. Top priority materials include metals such as reinforced low activation ODS type steels (*Oxide Dispersion Strengthened steels*) and tungsten alloys. To manufacture such materials, equipment is required that currently is scarce or inexistent in Spain, such as a *Vacuum Induction Melting Furnace* (VIM), a *Hot Isostatic Pressing Furnace* (HIP), a Furnace for Sintering assisted by a Pulsed Plasma Current (*Spark Plasma Sintering*, SPS), or a *Vacuum Plasma Spraying* (VPS).

2) *Material Irradiation*. Even though the exact reactor conditions are only reproduced inside a reactor, it is possible to simulate the effects of neutrons and gamma radiation on materials by irradiating by ion and electron accelerators.

The effect of neutronic radiation will be characterized by combining three ion accelerators: one light ion accelerator of the tandem type for irradiating with He, with an energy of 6 MV, one light ion accelerator of the tandem type for irradiating with H (or D), with an energy of 5-6 MV, and a heavy ion accelerator of the cyclotron type, with k = 110, to implant heavy ions (Fe, W, Si, C) or high energy protons.

Additionally, a high magnetic field, between 5 and 10 T, must be incorporated into this facility in order to study the simultaneous effect of radiation and magnetic fields on materials.

The effects of ionizing *gamma* radiation will be studied using a *Rhodotron®* electron accelerator with a fixed energy of 10 MeV that will be shared with other *TechnoFusión* facilities.

3) *Plasma-wall interaction*. Inside a fusion reactor, some materials will not be subjected only to radiation, but also to enormous heat loads in the case of plasma disruptions. In view of this, both: i) stationary conditions due to the intrinsic reactor properties: high density, low temperature and high power and ii) violent transient events (called ELMs in plasma physics literature) must be reproduced. Therefore, it is essential to dispose of a device (which it will be called “plasma gun”) to study plasma-material interactions simultaneously in steady state and transient regimes, thereby allowing an analysis of the modification of the materials and their properties in fusion reactors.

The mentioned plasma gun would consist of two main elements: i) a linear plasma device capable of generating hydrogen plasmas with steady state particle fluxes of up to 10^{24} $m^{-2}s^{-1}$ (i.e., of the order of the expected ITER fluxes) and impact energies in the range of 1-10 eV, and ii) a device of the quasi-stationary plasma accelerators (*QSPA*) type, providing pulses lasting 0.1-1.0 ms and energy fluxes in the 0.1-20 MJm^{-2} range, in a longitudinal magnetic field of the order of 1 T or greater.

These devices are connected by a common vacuum chamber, allowing the exchange of samples, and their simultaneous or consecutive exposure to the steady state and transient plasma flows under controlled conditions. Both devices will operate with hydrogen, deuterium, helium, and argon.

4) *<u>Liquid metal technologies</u>*. A number of, ITER, DEMO (*DEMOstration Fusion Power Reactor*)[2], and IFMIF (*International Fusion Materials Irradiation Facility*)[3] components will use liquid metals as refrigerants, tritium generators, neutron reproducers, moderators, etc., all of them under extreme conditions. Therefore, these applications need further research to be finally implemented in such installations.

The basic working scheme for this Facility in *TechnoFusión* is an arrangement of two liquid lithium loops, one of them coupled to the *Rhodotron®* electron accelerator to investigate the effects of gamma radiation on different conditions of the liquid lithium.

The main goals of this Facility are the studies of i) the free surface of liquid metals under conditions of internal energy deposition, and ii) the compatibility of structural materials and liquid metals in the presence of radiation. In addition, it will be possible to study the influence of magnetic fields on the cited phenomena as well as the development of methods for i) purification of liquid metals, ii) enrichment of lithium, iii) extraction of tritium, and iv) development of safety protocols for liquid metal handling.

5) *<u>Characterization techniques</u>*. Ambitious and well-understood research requires an accurate knowledge of the materials under study. Therefore, a range of techniques to characterize them under different situations is a key element in the global scheme of *TechnoFusión*. These techniques include mechanical testing (creep, nanoindentation, fatigue, etc.), compositional analysis (Secondary Ion Mass Spectrometry and Atomic Probe Tomography), and structural characterization (Energy Filtered Transmission Electron Microscopy, X-Ray Diffraction), as well as a number of material processing techniques (Focused Ion Beam Systems coupled to a Scanning Electron Microscope). Additional systems will be used to characterize physical properties (electrical, dielectric, optical, etc.).

Some of the above-mentioned techniques will be implemented to test the materials either in-beam –while being irradiating— or *in-situ*, inside the lithium loop. Needless to say, these techniques can also be performed before and after irradiation or before and after experiencing any other physical or chemical processes.

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[2] DEMO (DEMOnstration Power Plant) is a proposed nuclear fusion power plant that is intended to build upon the expected success of the ITER experimental nuclear fusion reactor.

[3] IFMIF is a planned high-intensity neutron reactor whose spectrum should be equivalent to that of a fusion reactor. The final design comprises two deuteron accelerators impinging on a liquid lithium target to generate nuclear stripping reactions to provide the desired neutron spectrum

6) *Remote handling technologies*. The conditions inside a fusion reactor are incompatible with a manual repair or replacement of parts. Therefore remote handling is indispensable. New robotic techniques, compatible with such hostile conditions, need to be developed; while existing techniques need certification in order to be applied at installations such as ITER or IFMIF.

TechnoFusión Facility will contribute to this knowledge with: i) a large installation for the prototypes manipulation such as: *Diagnostic Port Plug* of ITER, *Test Blanket Modules* of ITER and Modules of irradiation of IFMIF, and ii) an Irradiated Room coupled to the electron accelerator –*Rhodotron*®— in order to carry out validation, certification and characterization of remote handling tools and machines in an uniform ionizing field equivalent to ITER-DEMO trying to simulate the fusion reactor environment.

7) *Computer simulation*. To study conditions that cannot be reproduced experimentally and to accelerate the development of novel systems for a future commercial fusion power plant, *TechnoFusión* will stimulate an ambitious programme of computer simulations, combining existing experience in the fusion field with resources from the National Supercomputation Network[4]. The goals include the implementation of the global simulation of a commercial fusion reactor, the interpretation of results, the validation of numerical tools, and the development of new tools. Another indispensable goal is the creation of a data acquisition system and the visualisation of results.

Based on the existing experience of research groups at Universities, Public Research Organisations and company research departments, *TechnoFusión* proposes the development of a large scientific infrastructure in order to make a significant contribution to the development of new technologies needed for the construction of commercial fusion reactors. The project described here will permit the generation of highly relevant technological knowledge for all types of fusion reactors, irrespective of the underlying concept (magnetic or inertial confinement).

The goal of TechnoFusión is to bring together sufficient human and material resources to contribute significantly to the development of a safe, clean, and inexhaustible source of energy for future generations.

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[4] http://www.bsc.es/index.php. September 2009.

7. Liquid Metal Technologies

7.1. Introduction

In the energy sector, liquid metals have mainly been applied in the manufacturing process of industrial batteries, in nuclear fission reactors (as coolants), and in thermal solar power plants. For such applications, molten metals such as sodium, lead and eutectic lead-bismuth are chosen for their beneficial properties as coolants or their resistance to high temperatures. New technological applications are being developed for liquid metals such as tin, mercury, lithium or eutectic lead-lithium.

In particular, liquid metals have some thermal and physical properties that make them very appropriate for future fusion-related applications. Their thermo-hydraulic properties make them very suitable for use as coolants, allowing the extraction of a large amount of energy, such as that produced by fusion reactions. Due to their reliability at high temperatures, they are candidates for the base material of the first wall facing the plasma, and for divertors and limiters in fusion containment vessels that need to withstand high radiation fluxes.

Aside from its thermo-hydraulic properties, the neutronic features of lithium (Li, tritium production by neutron capture) convert this material in an ideal candidate for the design of *Test Blanket Modules* (TBM), which are a key element for the sustainability of future fusion devices as DEMO. In some conceptual designs of TBMs, lead (in the form of eutectic lead-lithium) is used as an effective neutron multiplier in the range of neutron energies produced by a fusion reactor, increasing the tritium breading capacity of the system and its overall fuel sustainability.

Liquid metals are used as target materials for high intensity neutron sources. Materials with high atomic numbers, such as lead (Pb) or mercury (Hg), and with a high nuclear neutron/proton ratio, are efficient spallation sources. Light nuclei, such as lithium, are also being used as neutron sources, but function by means of stripping reactions. Lithium is also used in particle accelerators, such as the RIA (*Rare Isotope Accelerator*); and it has been proposed to use a thin lithium layer to enhance the static charge and to improve the accelerator efficiency.

Each of these applications of liquid metals, and many others that have not been mentioned, require specific operational conditions, since the behaviour of the metal is affected by various physical phenomena. These phenomena depend on the liquid metal, but they share some common features, so that many technological developments are based on the same physical principles and hypotheses, mainly referring to their use as coolants.

The development of innovative applications for liquid metals (like the one for fusion) requires improving the mastery of many technological aspects. New scientific and technological infrastructures are needed to advance with respect to the following issues:

- The generation of technological data regarding.
- Material compatibility.

- Thermo-hydrodynamic behaviour.
- Liquid metal magneto-hydro-dynamics.
- Validation of design software.
- The analysis of the configuration of proposed components based on liquid metals, either individually or integrated.
- The development of components and equipment for instrumentation and for the characterization of liquid metal loops.
- The development of auxiliary systems for liquid metal loops, such as purification systems, liquid metal charges and instrumentation.
- The adequate transfer of technology from research centres and universities to regional and national engineering and industrial companies, stimulating the formation of scientists and engineers needed for the start-up of technological projects based on liquid metal applications. This is one of the main objectives of the *TechnoFusión* proposal.

Taking into account the above, and focusing on the research needs regarding fusion technology, a flexible **Liquid Metal Technologies Facility (LMT)** is proposed at *TechnoFusión*`s Centre, mainly devoted to lithium, with sufficient flexibility to allow a large variety of experiments.

7.2. Objectives

The main goal of the LMT Facility is to become a scientific and technical infrastructure of reference, insofar the development of liquid metal technology related to international fusion programmes is concerned. This facility, integrated in *TechnoFusión*, will serve as a knowledge hub to promote the technology transfer to the regional and national industrial sector.

A review of the state of the art of liquid metal research activities in fusion has been performed (mainly related to lithium and eutectic lead-lithium). The goal of this review was to establish design requirements and make an inventory of potential experiments that could be performed at the facility. The results of this review, summarised in the next section, show that eutectic lead-bismuth is generally considered to be one of the top materials for future fusion reactors by the scientific community, at least in the medium term. Most of the current experiments in international facilities are devoted to the study of this eutectic material. Therefore, focusing on this material is unlikely to convert this facility into a facility of reference and to allow it to compete on an equal footing with other well-established facilities.

On the other hand, there is an increasing interest in the study of lithium as a material for fusion-related applications, either in neutron sources for material irradiation experiments, or in fusion reactor components such as blankets, divertors or first-wall layers.

In the framework of *TechnoFusión*`s goals, the main interest lies in the construction of a **lithium facility** in our liquid metal laboratory, for the reasons outlined below:

- In the medium term, it constitutes a strategic commitment in support of the Spanish candidature for the IFMIF laboratory site for material research, which will be based on a lithium neutron source and, therefore, a fully operational lithium loop. The existing know-how and the mastery of lithium technology will be a fundamental factor in the success of any candidature.

- Only very few lithium facilities exist worldwide, which allows reducing the redundancy of any proposed experiments and stimulating competition, so that the LMT Facility can become a reference installation in the short term.

The proposed liquid metal facility will have the following specific objectives:

- The production of critical technical information related to the use of liquid lithium, such as:
    - Free surface phenomena under conditions relevant for fusion applications.
    - Studies of corrosion/erosion and the compatibility of structural materials.
    - Magneto-hydrodynamic effects.
    - Thermo-hydraulic phenomena and modelling.
    - Chemical properties and the effect of impurities.
    - The development and testing of a purification system.
    - Safety.

- The validation of design tools for liquid lithium, such as thermo-hydraulic modelling and the corresponding codes.

In addition, this experimental facility will have the added value of coupling an electron accelerator to a liquid metal loop. Thus, heat will be deposited in the liquid metal flow, mimicking the power deposition produced by deuterons at the IFMIF facility, and producing phenomena similar to those expected with the latter’s neutron source. It is foreseen that the electron accelerator will also be used for other purposes, e.g., to study the behaviour of materials in contact with liquid lithium under irradiation. These multi-effect experiments will allow improving our understanding of physical phenomena due to combined irradiation and liquid-metal interaction, in particular regarding such aspects as: corrosion, gas diffusion, chemical properties, and others, fundamental for the development of fusion technology. It is worth pointing out that at present, no laboratory in the world is able to perform this type of experiments.

7.3. *International status of the proposed technologies*

7.3.1. State of the art of liquid lithium technology

The excellent properties of liquid metals and their associated technologies make them an important key of in the following fusion areas.

a) The liquid lithium target at IFMIF [76]

IFMIF consists of a few deuteron accelerators that irradiate a pure liquid lithium stream (Figure 7.1). Stripping reactions between deuteron and lithium then produce a neutron beam with approximately the same energy as fusion reactions. One of the most challenging issues confronting IFMIF is to keep the free surface of the lithium flow stable, so that neutron generation is stable likewise and the deuteron energy is deposited in the required areas. There are huge uncertainties regarding the behaviour of lithium under the impact produced by the deuteron beam: the energy deposited in the metal flow could cause unknown phenomena that might affect surface stability; and lithium evaporation or liquid metal vapour might deteriorate the vacuum of the accelerator line. Furthermore, the study of the phenomena of erosion and corrosion occurring in the structural components that are in contact with the liquid lithium and exposed to neutron irradiation still is a pending issue, as these might increase instability due to an enhancement of impurities in the flow.

Research into and development of the cited issues is of fundamental importance for fusion technology, and the availability of experimental facilities allowing their study and mutual interaction is quite relevant.

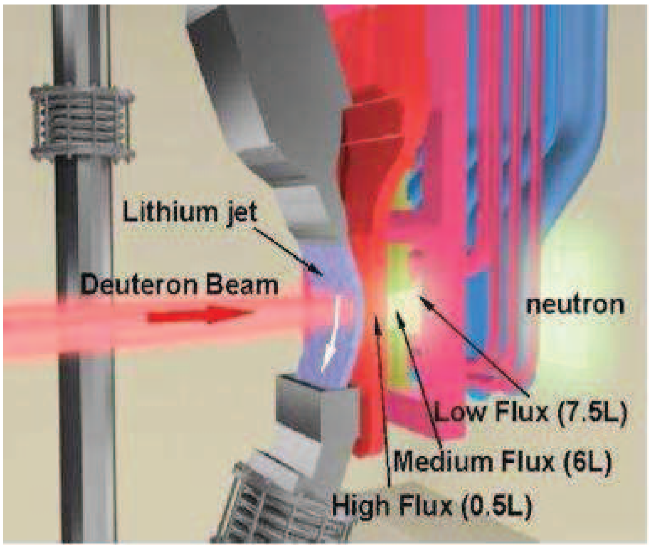

Figure 7.1. IFMIF neutron source.

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[76] IFMIF Comprehensive Design Report, January 2004.

b) Plasma first wall, divertors and limiters for novel fusion reactor concepts

Lithium is an attractive material for the first wall facing the plasma, divertors, and limiters for fusion devices (Figure 7.2). Experimental studies have shown the reliability of liquid lithium as a material for the first wall in fusion chambers, either due to its good behaviour in the presence of plasma (low-Z and low plasma recycling), or due to its thermal properties, allowing the distribution of radiated power from the plasma and the handling of very large thermal loads (~10 MW/m^2). Moreover, since this material is liquid, its surface is less affected by the thermal stress produced by transients, due to the protective mechanism based on lithium evaporation (shielding). Solid materials are unable to withstand such high-energy depositions and suffer more radiation damage.

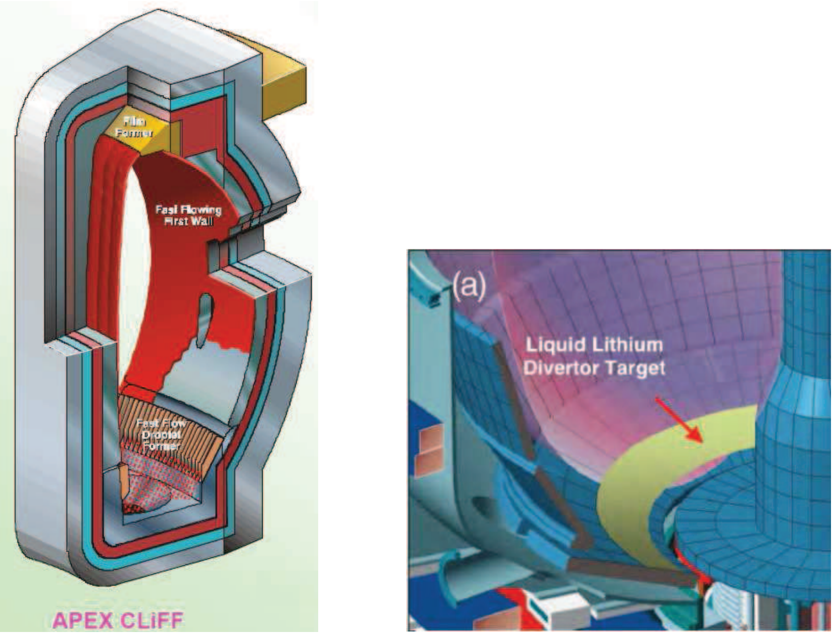

Figure 7.2. Applications of liquid metal technology for the first wall (left) and the divertor structure (right) of a fusion reactor.

Nevertheless, some problems remain, related to free surface instabilities of the liquid metal, due to such unwanted effects as waves, i.e., MHD perturbations produced by mechanical and electromagnetic forces[77]. Moreover, the chemical purity of liquid lithium may be modified by extreme environmental conditions (such as having a free surface in the accelerator vacuum), and possibly the free flow at the surface is different from the mass flow in the bulk, thus affecting the stability of the liquid metal stream.

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[77] B.I. Khripunov, "Liquid Lithium surface research and development", Journal of Nuclear Materials ,Volumes 313-316, March 2003

One of the proposed concept designs for Tokamak first wall structures meant to handle free surface instabilities is based on a *Capillary Porous Structure* (CPS), filled with liquid lithium, in which the liquid metal layer is kept stable in high magnetic fields due to its high surface tension in a porous grid.

c) Tritium blanket modules based on liquid metals

Lithium is an important material for fusion technology, whether pure or as an alloy such as the eutectic lithium-lead, or as part of the tritium blanket modules of fusion devices. Some conceptual designs for tritium production plants based on these materials have been proposed for ITER and DEMO (Figure 7.3).

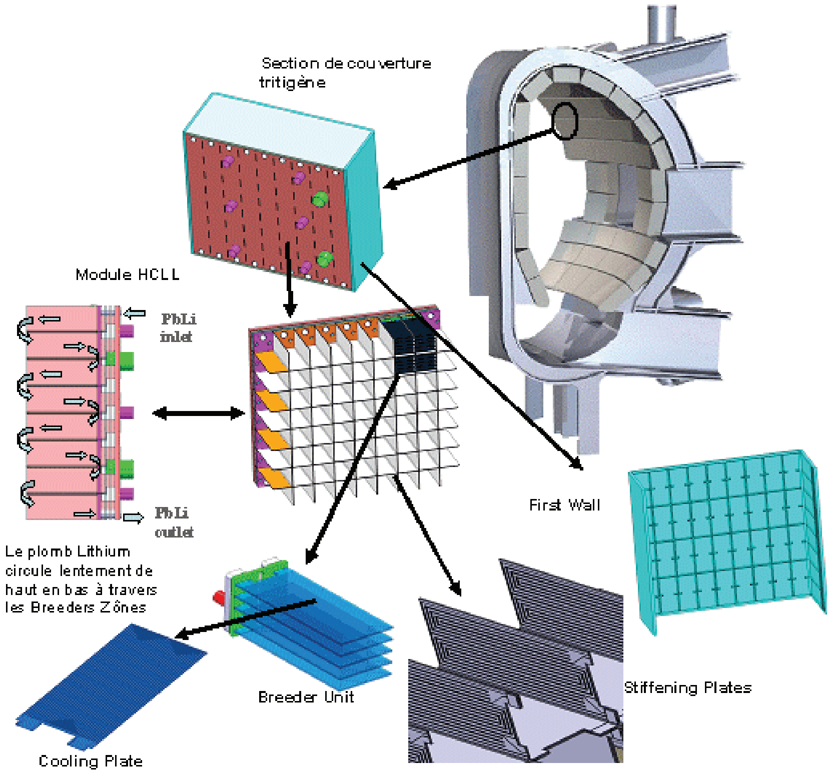

Figure 7.3. Tritium blanket module of the type HCLL (*Helium Cooled Lithium Lead*) for ITER (source: CEA)

The main technological problems associated with these applications are:

- Magneto-hydro-dynamic effects for a wide range of flow velocities of the liquid metal (from mm/s to m/s, depending on the design proposal), leading to pressure loss, discontinuities in the flow of the liquid metal in different cooling channels, the reduction of heat transfer, etc.

- The corrosion of structural materials that are in contact with the liquid metal.
- Tritium management issues: lithium enrichment techniques, tritium permeation and tritium extraction from the liquid metal flow, etc.
- The safety of liquid metal applications, in particular regarding lithium.

Every one of these technical challenges has spawned a great effort in research and development, in order to validate specific materials designed to reduce permeation, corrosion, or electrostatic problems.

The phenomena described above must also be studied under heavy particle bombardment, which may enhance and increase uncertainties. Moreover, radiation fields can modify important phenomena, such as gas diffusion or the generation of impurities.

Thus, further research and development is needed on lithium applications, and particularly on lithium itself. Many question marks remain regarding the use of liquid lithium, such as the corrosion of structural materials in lithium flows, the compatibility of materials, and purification techniques.

7.3.2. International facilities for liquid metal experiments for the development of fusion technology

Worldwide, only a small number of facilities exist whose activities include the study of liquid metal technology for fusion. Table 7.1 shows a list of existing facilities in the world working on Li and eutectic Pb-Li, the main liquid metals for fusion. The lack of lithium technology facilities is evident from this table, particularly in Europe, which is the main area of influence of the facility proposed in this document.

By contrast, Europe has a large amount of experimental installations for Pb-Li. Several loops related to the compatibility of liquid metals with structural materials are available in Italy (LIFUS), Germany (PICOLO) and Latvia (IPUL loop). The former permits the analysis of liquid metal corrosion in combination with magnetic fields. In Europe, the field of MHD is studied mainly at the MEKKA loop in Germany, using eutectic NaK. Other technological issues, such as gas diffusion in Pb-Li, the study of permeation barriers, or tritium extraction, are studied in installations such as TRIEX, VIVALDI or LEDI in Italy, and MELODIE in France. In the latter country one can find another loop, such as PABLITO, built to test different components, such as pumps. The Czech Republic has a Pb-Li loop designed for purification studies.

Table 7.1. List of Li and euctectic Pb-Li facilities in the world.

Lithium	**Pb17Li**
USA	**ITALY (ENEA)**
University of Illinois ORNL Sandia NL Argonne NL University of California	LIFUS-2 LIFUS-5 TRIEX RELA III LEDI LTF-M SOLE
ITALY (ENEA)	
LIFUS-3	
JAPAN	**FRANCE (CEA)**
NIFS University of Osaka	MELODIE PABLITO DIADEMO
RUSSIA	**GERMANY (FZK)**
IPPE	PICOLO
	RUSSIA
	IPPE
	CZECH REPUBLIC
	IPP
	LATVIA
	IPUL

Research on Pb-Li safety, focusing mainly on its interaction with water, is carried out in Italy at the facilities LIFUS-5 and RELA III. There are at least three dedicated loops for prototype testing of components for fusion blanket modules, such as EBBTF in Italy, DIADEMO in France, which also offers a coupled Helium section.

Regarding pure lithium facilities en Europe, Italy has the LIFUS-3 (Figure 7.4), devoted to research on material compatibility. This loop has a total lithium inventory of 46 litres, providing a flow of 0.5 l/s, with a lithium velocity at the test section of around 12-18 m/s, at a pressure of 2.5 bar and a temperature of 350 ºC.

In the United States, the main choice for fusion coolants and blanket has always been lithium. Therefore, their facilities have been designed for lithium research, mainly focusing on its magneto-hydrodynamic behaviour. Such studies are performed at the LIMITS facility located at the Sandia National Laboratory (Figure 7.5). This facility has three main test components: a vacuum chamber to study the behaviour of liquid metals, a pumping section, and a transfer tank. In the vacuum chamber, tube sections with different shapes can be tested in a magnetic field. The liquid metal pumps have been custom-made for this loop, due to the lack of commercial providers.

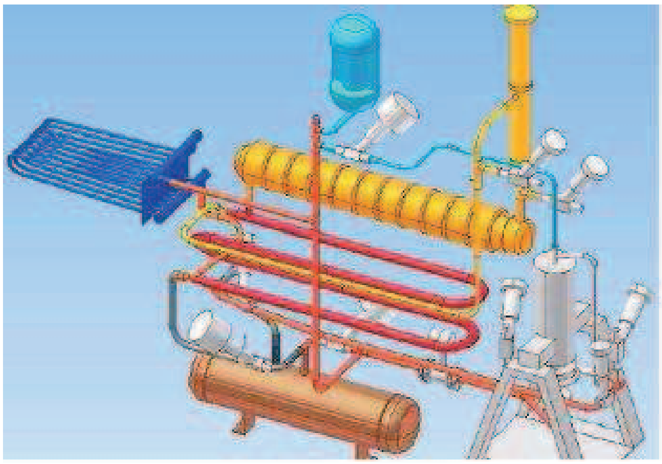

Figure 7.4. LIFUS3 facility (ENEA).

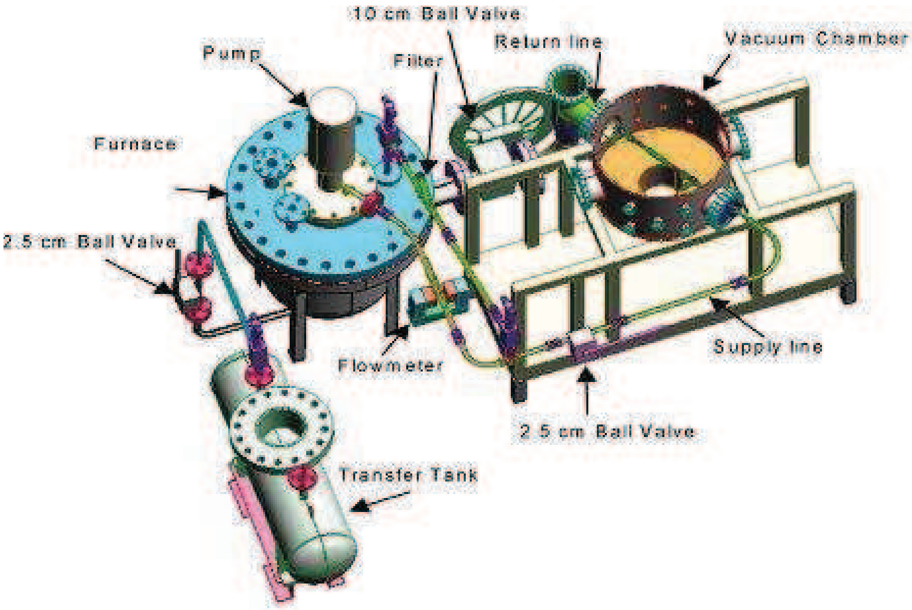

Figure 7.5. LIMITS facility at the Sandia National Laboratory (USA).

In the United States, another loop is installed at the University of Illinois (Figure 7.6), designed for the experimental analysis of deuterium retention in liquid lithium. These phenomena are especially relevant for the application of this liquid metal in the first wall of the plasma chamber of future fusion devices based on magnetic confinement.

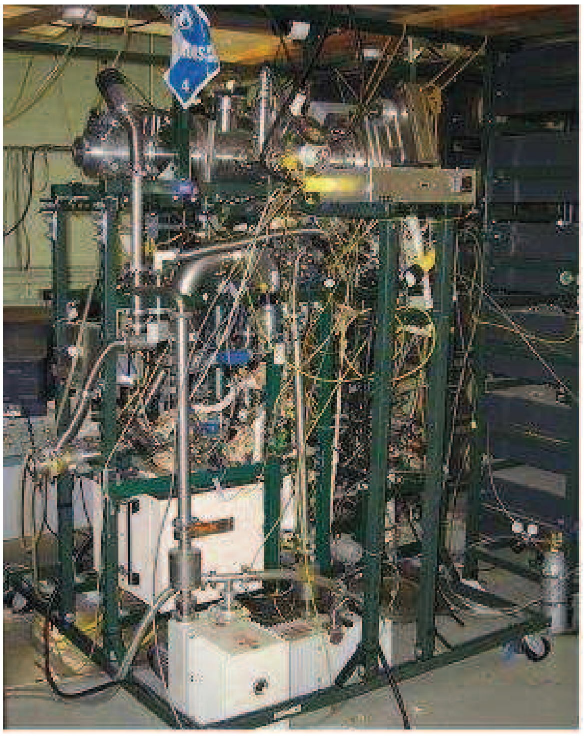

Figure 7.6. Experimental loop at the University of Illinois (USA).

In Japan, the University of Osaka is very active in the field of fusion technology, studying physical phenomena such as the free surface behaviour of lithium at the IFMIF[78] target, and this activity may provide technical support for the Japanese candidature to host the site of this material irradiation facility. The university has a lithium loop (Figure 7.7) with a free surface test section. The loop has a length of 40 m, and consists of 304 stainless steel ducts with a diameter of 53.7 mm. The pressure of the inner loop is of the order of 400 kPa, and it supports lithium flow of 500 l/min at 300 ºC, with a reasonable safety margin to avoid lithium solidification below 180 ºC.

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[78] H. Kondo et al. 'Experimental study of Lithium free-surface flow for IFMIF target design'. Fusion Engineering and Design 81 (2006) 687-693.

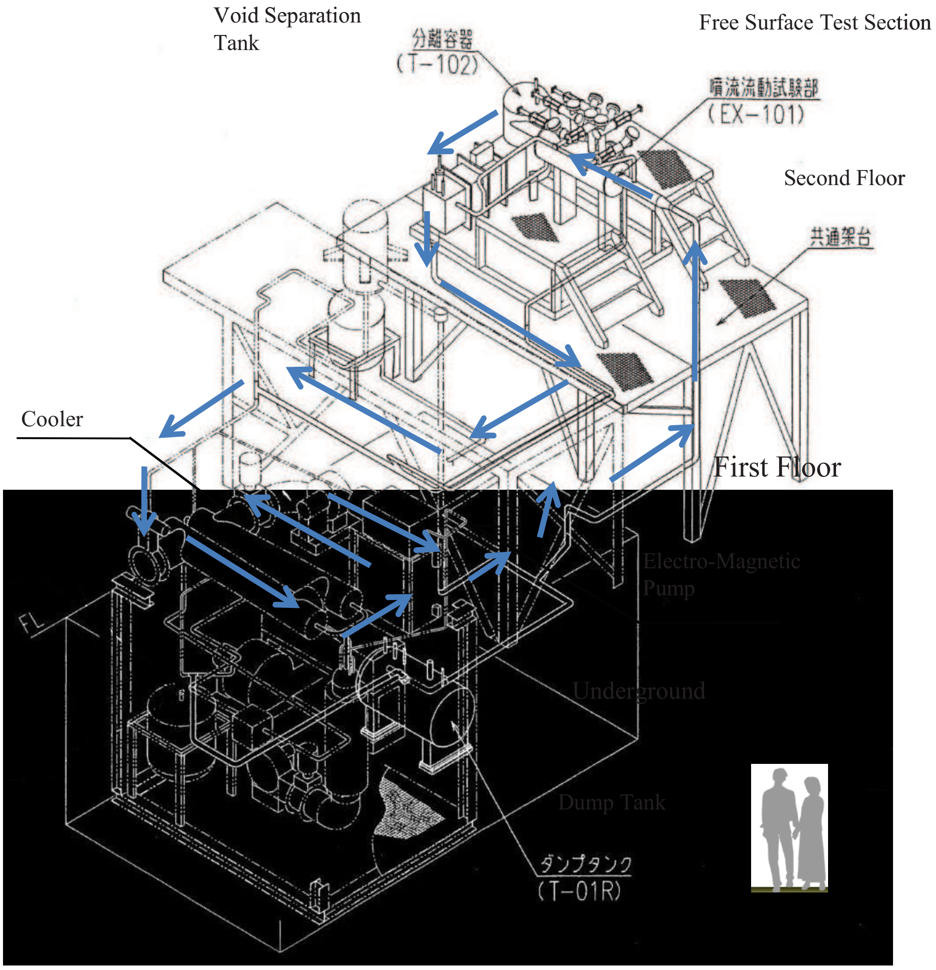

Figure 7.7. Diagram of the lithium loop for IFMIF research at the University of Osaka (Japan).

The free surface test section is shown in Figure 7.8. This is a model at a scale of 1/2.5 of the JAERI design for IFMIF. In contrast with the actual IFMIF design, the model has certain curves to let the centrifugal force help avoid the liquid metal from boiling. The test section at the Osaka loop is plain and horizontal, as with other experiments oriented towards IFMIF. The effect of bends at the target position has been discussed by Itoh[79], and apparently it is negligible in simulations of the behaviour of the free surface.

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[79] K. Itoh, H. Nakamura, Y. Kukita, “Free-surface shear layer instabilities on a high-speed liquid jet”, Fusion Technol. 37 (2000) 74–88

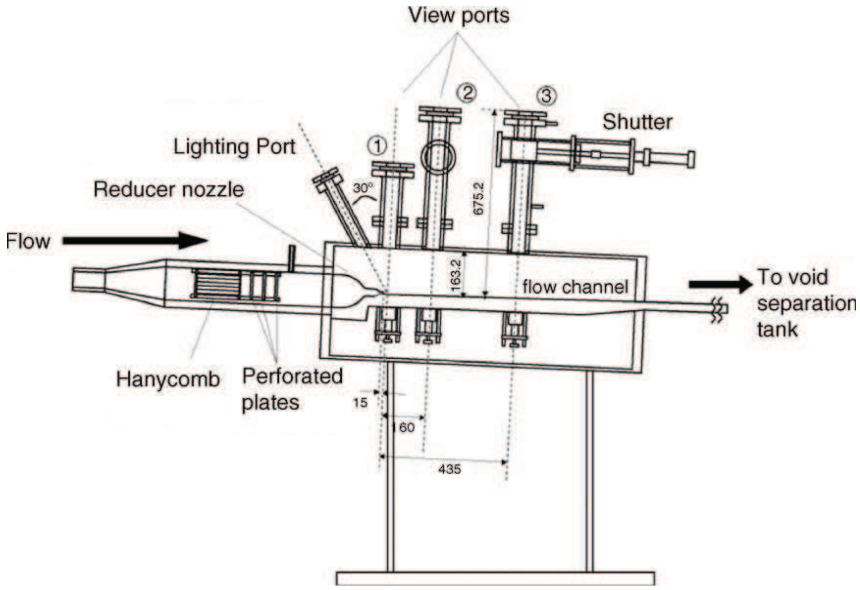


Figure 7.8. Lithium free surface test section at Osaka (Japan).

A limited number of additional facilities are devoted to lithium technology. Among these, it has been highlighted the LTF-M loop (Figure 7.9), developed in Obnisnk (IPPE, Russia) in the framework of an ISTC project. The main goal of this loop is to the study the thermo-hydraulics of water and lithium at the free surface, and it includes auxiliary systems such as lithium impurity monitoring and purification, and control.

Figure 7.9. IPPE loop in Obsnisk (Russia).

In contrast with the American laboratories, mainly devoted to liquid lithium studies for a future fusion reactor, the facilities in Italy, Russia and Japan have made a large effort oriented towards IFMIF. Figure 7.10 presents a comparison between the cross sections of the free surface flow in these international laboratories focused on IFMIF. The geometry of the test liquid flow (thickness, width, bend, straight channel, etc) varies, as well as the fluid, which is either lithium, in the case of Osaka and IPPE, or water, in the case of Italy, where lithium has been used only for material studies.

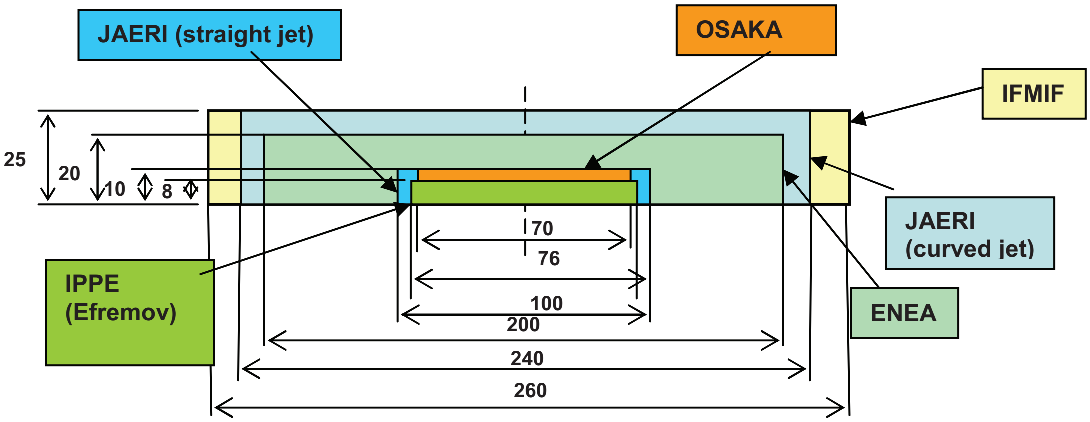


Figure 7.10. Cross section of the lithium flow in some experiments in the world related to IFMIF.

As mentioned above, none of these International laboratories perform experiments that contemplate energy deposition in the lithium flow. Furthermore, the maximum velocity that can be attained in some loops is not always similar to the planned flow velocity at IFMIF, and in some cases the working fluid is not even lithium.

This brief analysis of the experimental facilities available worldwide shows that the amount of installations dedicated to lithium technology is very small, highlighting the need for the construction of new loops, either for carrying out redundant experiments to asses the reproducibility of results, or for increasing the experimental capacity for performing tests needed in view of the cited technological challenges, as is the case of the behaviour of the free surface when heat is deposited into the liquid metal flow, this being of paramount importance for IFMIF. At the present time, no facility in the world is able to test this type of phenomena. Furthermore, most of the tests related to the contact of materials with liquid lithium are performed at low temperatures. This may be appropriate for IFMIF, but is not very useful for the development of a future fusion reactor, where temperatures are expected to reach 1000ºC. There is also a lack of experimental capacity to study coupled effects due to liquid-metal compatibility, electromagnetic fields, and irradiation, which are important for fusion applications.

The goal of the LMT Facility, part of the *TechnoFusión* initiative, will be to raise the temperature data range of studies of materials subject to corrosion by lithium. Moreover, an interface between an electron accelerator and the lithium loop will be made to allow studying the behaviour of the free surface of liquid lithium subject to heat deposition into the internal flow, as well as testing materials under irradiation. With the projected infrastructure, it will be possible to perform relevant tests, either for IFMIF or for any other liquid metal application in the nuclear fusion field, with an approach that combines multiple physics effects.

7.4. Projected facility

The design of any experimental facility is motivated by a technological objective or is a response to a demand by the national and international scientific community. The technological facilities offered by such a "will then attempt to meet any experimental deficits that have been detected. As mentioned, there is an important shortage of experimental facilities dedicated to the development of lithium technology for fusion applications. Consequently, it is justified the construction of an experimental facility incorporating various liquid metal loops, and in particular a lithium loop, relevant in the framework of fusion. Liquid Pb-Li studies are considered a secondary experimental objective.

The existing international installations of reference were studied to clarify the technical definition of the liquid metal loops proposed here. Also, an initial study was made of the experimental tests that will be carried out (described in detail in the section "Experimental capacity"). The description of these potential experiments has made it clear that the operational requirements of some experiments will be mutually incompatible, in terms of temperature, mass-flow, or time, thus justifying the incorporation of various loops in the proposal, each one for specific experimental objectives.

For instance, a loop devoted to free surface experiments in preparation for IFMIF should be able to handle a certain lithium mass-flow, as the liquid metal velocity is one of the critical factors for the stability of the free surface. Moreover, if an electron accelerator will be used to deposit a certain amount of power in the flow, the beam line should be kept in vacuum, and consequently so should the free surface interface, which then imposes a minimum size requirement on the loop to avoid cavitations. Another factor that affects the design of the loop is the operational temperature. In the mentioned case, temperatures of the order of 250 ºC are required. Another operational constraint that must be taken into account is the time schedule of the experimental campaign. Relate to this, note that a free surface experiment might last a few weeks, depending on other installations.

On the other hand, tests of the compatibility of materials with liquid metals may require much slower liquid metal flows, and more compact loops with less liquid metal. Nevertheless, operational temperatures should be much higher, requiring a powerful heat evacuation system, which in turn may lead to a complex design. Regarding the experimental campaigns, tests are expected to last a few thousands of hours in a continuous, stable mode of operation.

In principle, MHD tests do not require a large amount of flowing liquid metal, but it would be interesting to be able to change operation speeds and temperatures. It would also be interesting to study the influence of magnetic fields in other experiments, such as corrosion tests or hydrodynamic experiments. One may consider installing some magnets on the track where the hydrodynamic experiments are carried out, as well as on the track for studying material compatibility, provided these facilities are designed with sufficient flexibility.

In the same way, tests can be proposed concerning the diffusion of gases in the liquid metal, or concerning the materials in contact with it, with relevance for the management of tritium in fusion reactors. These tests can be performed on a track that was designed for other trials, provided it has been built with flexibility in mind.

Security tests must probably be carried out at an independent track with a small amount of liquid metal.

Purification tests will be done at several purification systems installed on the various tracks, so these would not require a dedicated track, in principle.

Although it has been mentioned that the study of the Li-Pb eutectic is not the main goal of this experimental Facility, one should not reject this possibility offhand, due to its significance for fusion technology. It has to taken into account the possibility whether a given track, originally designed and dimensioned for working with lithium, can be changed to Li-Pb; or whether experimentation with Li-Pb needs a dedicated track. In any case, as lithium-lead experiments usually require low working speeds (from a few millimetres per second to a few metres per second), it could be also considered installing a basic circuit based on natural convection.

The analysis of the various experiments that could be carried out lead to propose the following basic requirement for the LMT of *TechnoFusión*, namely: two liquid lithium tracks, one mainly dedicated to hydrodynamic studies, and the other dedicated to mechanical tests of materials, corrosion and compatibility. It has not been still rejected the possibility that these two circuits share some components or systems, such as: filling systems, the tank for storage of the inventory, or purification systems.

Both circuits will be designed with enough flexibility to carry out various kinds of tests. The layout of the required floor space in the LMT Facility should allow adding further minor tracks in the future, or enhancing the existing ones. This approach also fits in nicely with the option of a staggered start of the facility.

The Figure 7.11 shows a summary of the objectives that must be met by the Liquid Metal Technologies Facility, including the specific experimental conditions required for each type of test, which have been used for the initial design of the tracks. In the section 7.5 “Experimental capacity”, further detail about the tests is provided.

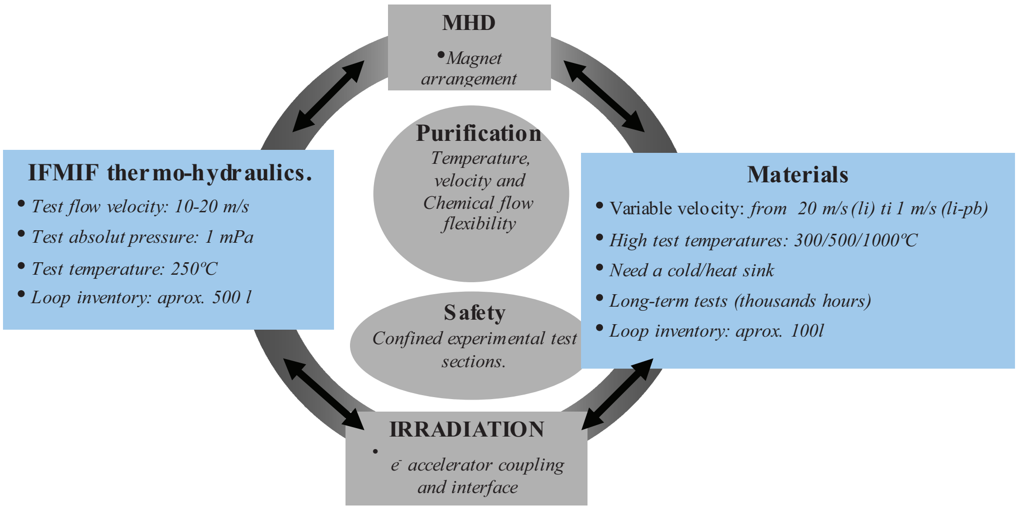


Figure 7.11. Main objetives of the Liquid Metal Technologies Facility of *TechnoFusión*

7.4.1. Technical definition of the experimental loops

(I) Free surface experimental loop

As mentioned in preceding sections, free surface tests are required for licensing and commissioning the IFMIF target. This experimental loop will be dedicated to experimental work on the free surface. The lithium inventory in this test installation has been estimated at 500 litres. The installation will contain:

1) Basic components:

- Ducts: designed for a liquid lithium velocity in the range 5-20 m/s.
- Pump: able to drive a liquid lithium flow of at most 50 m^3/h, without risk of cavitations.
- Common storage tank: with a capacity of approx. 1000 litres, for storage of all the lithium of the whole facility, including this test section and any other in the LMT Facility.
- Control and diagnostic instrumentation: flow meters, thermometers, pressure gauges, level meters, and so on.

2) Testing zone, that will consist of:

- A free surface zone, basically consisting of an element that forces the flow to become laminar (a “straightener”), an exit tube for the liquid lithium, and a tray where it will circulate with a free surface. The size of these components must be calculated on the basis of their relevance for IFMIF.

- Enough access ports at the test zone to allow installation of the required instrumentation (cameras, speedometers, etc.), to allow entry of the electron accelerator beam, and to provide space for the installation of future diagnostics.

- An intermidium tank (“Quench tank”) that will reduce the speed of the liquid metal when it leaves the testing zone, and will absorb the thermal expansion and damp the fluctuations of the fluid before it reaches the pump. It will also be used to separate any gases (mainly argon) that could remain in the liquid metal. This tank should have a capacity of about 200 l.

Other decisive factors for the design of the circuit are:

a) The coupling of the testing zone with the electron accelerator will impose some specific requirements: the vacuum of the testing zone (argon atmosphere 10^{-3} Pa), the viability of the physical connexion between both systems (accelerator-lithium track), shielding, etc.

b) The free surface testing zone will be extractable, in order to install components with different shapes and/or sizes and/or materials.

c) Suitable mechanisms must be implemented in order to change the speed of the liquid metal in the testing zone (up to 20 m/s), for instance by installing flow regulation valves.

d) It should be possible to perform other types of experiments in some stretches of the track. Such experiments are:

    - MHD: There should be enough space to install magnets.
    - Gas diffusion: leaving open this possibility requires the installation of spare access ports on the track, to be linked to additional gas feed lines.
    - Etc.

e) One of the fundamental activities of this facility is the validation of computer tools for the design of components and systems working with liquid metals. Therefore, the loops should be fully diagnosed for a proper computer code validation.

(II) Material testing loop

Structural materials for fusion applications that are in contact with liquid lithium must be able to withstand temperatures above 300 ºC and relatively high velocities, as in the case of

IFMIF (highly turbulent flow), or up to 1000 ºC, as with some TBM designs, although at low velocities (laminar flow). Therefore, the materials testing loop should be designed with sufficient flexibility to be able to perform experiments under these extreme conditions. This materials testing loop will have a lithium inventory of about 200 l, and will consist of the following components:

1) Main components

- As with the free-surface experiments: ducts, valves, pumps, instrumentation, control equipment, diagnostics, etc.
- Some components may be common to all loops in the facility and be shared with the rest of experiments, such as the lithium storage system and the purification system.
- Since high temperature tests will be conducted at this loop, a heat extraction system may be installed, based, e.g., on an intermediate oil loop with an oil-lithium heat exchanger, and a final water heat sink consisting of an oil-water heat exchanger and a cooling system.

2) Testing zone

- The section for corrosion and material compatibility tests should be installed at a duct port where the different material test probes are inserted.
- The design of the mechanical test section should contemplate the coupling to a testing device that produces the mechanical stress.
- The material chosen to construct the loop and the other equipment must withstand high temperatures.

Other issues to be taken into account when designing the loop are:

a) An interface with an electron accelerator should allow performing experiments with gamma irradiation in the loop. This radiation is produced when an electron beam impinges on an appropriate target layer in the vicinity of the material test probe. This interface will impose specific design requirements on the test loop regarding its lay-out, shielding, etc. Radiation detectors should also be contemplated.

b) High temperature tests imply strict requirements for the choice of the structural materials for the loop.

c) Test sections should be designed for easy replacement, and with sufficient flexibility to run experiments with different geometries, sizes and materials.

d) Mechanisms for regulating the flow speed of the liquid metal (from a few mm/s to 20 m/s) in the test sections should be implemented, by means of, e.g., flow regulation valves.

e) The design of the loop should allow different types of experiments, such as:

- MHD: allocating space for the installation of magnets.
- Gas diffusion: installing ports for connecting additional gas lines.

(III) Auxiliary systems

1) All the equipment and components will be heated by means of electric resistors, and will be thermally isolated. Control of the loop temperature will require a suitable amount of thermocouples.

2) One or several vacuum systems, including steam traps, connected to the various tanks and to the free surface testing zone.

3) An Argon supply system, also connected to the various tanks and to the free surface testing zone.

4) A high-pressure air supply system for pneumatic valves and other active components.

5) An electric power supply system to provide power for the pump, the electric heaters, the vacuum systems, and the rest of the active components: a load of about 300kW is expected.

6) A control system (based, for instance, on programmable automatons) to collect and process the instrumentation readings, and to operate the active components of the installation via a user interface.

7) A filling system: lithium is supplied in the form of ingots that will be heated and melted in a dedicated and isolated tank. The liquid lithium will then be transferred to the track via a connecting valve, while injecting argon (cf. the Osaka University loop). In other cases (Obninsk loop) an intermediate step is implemented in the form of another storage tank where impurities are removed. The LMT Facility should have sufficient space to accommodate the mentioned filling tanks.

8) Systems for the purification process and for monitoring the impurities: a further study must be carried out regarding the possibility of installing a common purification system for the free surface tracks and the materials tests; possibly, each track should have its own system. Due to the great importance of these systems, which may be a subject of study on their own, they will be treated separately at the end of this section.

(IV) Comments on the structural material for the proposed facility

Liquid metals cause a relatively intense corrosion process, leading to the progressive wear of the system pipes. Logically, the latter must be designed for safe operation for the lifetime of the installation. The estimated useful lifetime is 20 years.

The speed of corrosion is directly related to the operating temperature of the system. As mentioned before, the free surface studies will be carried out at 250 ºC, while the materials studies will be performed at various temperatures, some of which are quite high. Since the low temperature track could also be used for experiments other than the free surface experiments, and which may require higher temperatures, the pipes will be designed to withstand corrosion rates similar to those of the high temperature loop. A temperature of 500 ºC will be used as reference value. Higher temperatures could be considered, but that would require the use of special materials or steels for the whole loop. Tests that require higher temperatures should be designed so that the track itself is not subjected to temperatures exceeding 500 ºC, by incorporating appropriate systems for local heating/cooling.

Using the information shown in Figure 7.12, and assuming an operating temperature of 500 ºC during 8.760 h/year, the corrosion values listed in Table 7.2 are obtained.

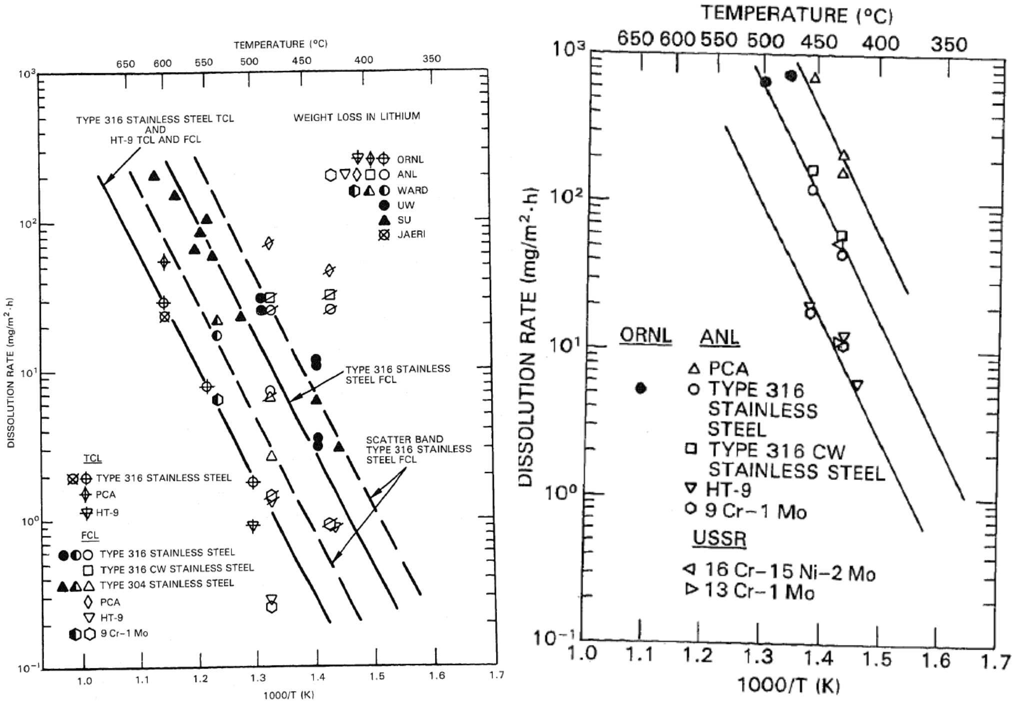


Figure 7.12. (left) Corrosion values for austenitic 304 and 316 stainless steels and ferritic alloys PCA, HT-9, Fe-9Cr-1Mo. Exposure to a lithium flow, speed 1.4 m/s. (right) Corrosion rate for austenitic stainless steels type 316 and ferritic alloys HT-9 and Fe-9Cr-1Mo. Exposure to a lead-lithium flow, speed 1.5 m/s.

Table 7.2. Estimated corrosion rates.

	HT-9 Steel	316 SS Steel
Li (mg /m²-h)	1.43	12.9
PB-Li (mg /m²-h)	66.4	540
Li Density (Kg/m³)	254.75	-
Pb-Li Density (Kg/m³)	10436.99	-
Li Corrosion (μm/year)	49.17	443.58
Pb-Li Corrosion (μm/añoyear	55.73	453.23
20 years Li Corrosion (μm)	983.44	8871.59
20 years Pb Corrosion (μm)	1114.62	9064.68

Corrosion values are very similar in Li and Pb-Li, so the system of pipes of the *TechnoFusión* loop is probably compatible with both materials, thus permitting the future change of research focus in this sense. Among steels, one can immediately reject austenitic stainless steels, since the corrosion rates multiplied by the lifetime of the facility exceed the pipe thickness by far. To avoid replacing the pipes, HT-9 ferritic base steels or 9Cr-1Mo are considered.

Assuming ferritic base steels are used, the corrosion acting during the 20 years of operation of the installation would imply a reduction of the pipe thickness by 1 mm.

(V) Impurity treatment

One of the most important issues related to the practical operation of the liquid metal, while exposed to the radiation produced by the electron accelerator, is the level of purity of the fluid. The connection of the loop to the accelerator must include an empty tube in order to minimize impurity transport from the last sections to the accelerator. The deposition of energy in the liquid metal, and the high temperatures at which some experiments will be performed, will lead to a release of impurities in gaseous form, which may enter the fluid or affect particle transport.

With experiments not involving the free surface these phenomena are less important, but still they can affect the operation of the liquid metal pumping system. Impurities could act as nucleation kernels for lithium steam, which could have important effects locally.

On the other hand, the motion of lithium along the loop also contributes to the total amount of impurities, as a consequence of corrosion and erosion.

Summarizing, impurities in the Li loop may have different origins, such as:

- Impurities of the lithium provided by the supplier.

- Impurities caused by diffusion in structural materials, originating from the surfaces along which the liquid metal flows.

- Impurities originating from the inert gas that is used in the protection system against lithium corrosion/oxidation.

- Impurities from the corrosion of structural materials.

- Impurities that seep into the loop due to maintenance and from auxiliary systems.

- Impurities from nuclear reactions.

Some elements entering the system by some of the mentioned mechanisms require special attention in the lithium track:

- *Oxygen*: this gas combines with lithium to form the stable lithium oxide, so one may consider that it produces no deleterious effects, or rather that it acts as a protector against corrosion for many materials, such as steels, heat-resistant metals, and some alloys. However, the presence of some impurities, such as beryllium or calcium, may cause its reduction and cause the formation of solid oxides inside the liquid metal flow, in turn causing the erosion of the structural materials. The concentration of oxygen in the lithium flow must not exceed the saturation value (i.e., 30 ppm at 250 ºC).

- *Nitrogen*: this is one of the impurities that dissolve best in lithium. It can form lithium nitrates and complex nitrates when combining with the structural components of steel, even at low temperatures. One may consider that this is the most active impurity from the point of view of corrosion, and in some studies 5 its concentration is therefore limited to 100 ppm at 500 ºC. One of the main impurity systems is the nitrogen purification trap.

In view of the preceding, the liquid metal tracks in the LMT Facility must be fitted with one (or several) purification systems, which have some implications for the experiments, especially regarding purification efficiencies and the kind of impurity to be extracted. The proposed built-in purification system would consist of three sections, namely:

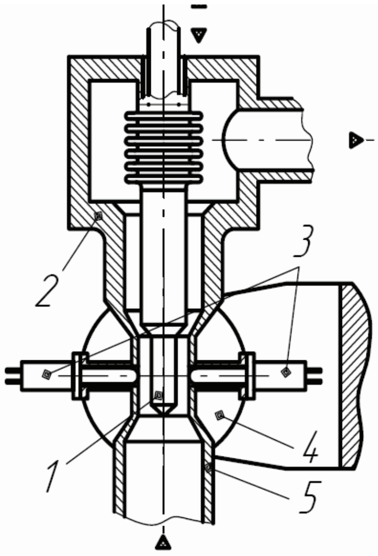
- *An oxygen and hydrogen extraction system*. This extraction is performed using cold traps and diffusion disks up to temperatures of 190 ºC. In the case of oxygen, the saturation concentration at this temperature is about 5.5 ppm. The concentration of hydrogen in lithium does not exceed 50ppm.

- *A nitrogen extraction system*. The nitrogen extraction system consists of an aluminium filter. This process can be operated at moderate temperatures. Using this method, the final concentration will range from 1.6 to 6 ppm. The purification system produces aluminium nitrates that settle down, purifying the flow in the tank at (200 – 250) ºC, and avoiding their entrance in the main loop by using filters.

- *A system for the separation of solid particles*.

(VI) Impurity monitoring systems

In order to maintain the degree of purity of the liquid metal that is required for satisfactory operation, purification mechanisms such as those described above must be implemented, along with monitoring devices to evaluate the concentration of the main impurities. For this purpose, the design of the experimental installation must include appropriate instrumentation (e.g. Figure 7.13). An analysis system for impurities that can be adapted easily when changing the working fluid is recommended, and additionally this system may perhaps even provide for automatic adjustment of the purification system. In any case, the priority of this facility is lithium operation.



1 – rod, 2 – case, 3 – thermocouples, 4 – flow rate, 5 – pipeline

Figure 7.13. Impurity measurement device based on the analysis of the saturation temperature

Many analysis methods are available, depending on the type of impurity:

1) *Impurity detection system by means of the determination of the saturation temperature,* for non-metallic impurities (nitrogen, hydrogen, oxygen and carbon). This detection process works by continuously cooling the flow through a narrow channel in a controlled way, by means of flowing cold water. The cooling of the liquid metal makes it reach the impurity saturation temperature, causing its decantation

and the reduction of the liquid metal flow due to its blocking action. This approach allows monitoring the impurity level in real time. The temperature at which the flow reduction is detected is the saturation temperature, and equations 7.1 show how the latter relates to the impurity concentrations:

$$\log[H] = 6{,}68 - \frac{2308}{T}$$
$$\log[O] = 6{,}99 - \frac{2896}{T} \qquad \text{eq. 7.1}$$
$$\log[N] = 7{,}57 - \frac{2080}{T}$$

2) *Detection system based on the distillation of liquid metal samples*. Useful for oxygen, and it has been applied in some reactors, such as the BN-600.

3) *Taking samples* to complete the analysis in the Characterization Techniques Facility. This process would involve installing a *by-pass* in the track through which the liquid metal flows until the flow is stabilized. Once stabilized, shut-off valves are closed and the samples are cooled, extracted from the loop, and transported to the laboratory.

7.5. Experimental capacity

Several specific lines of investigation can be followed in an installation of this kind. They can be subdivided into horizontal technological developments, common to any liquid metal installation; and vertical developments, referring to specific issues for specialised purposes, such as the IFMIF neutron source:

(a) Horizontal technological developments:

- Material corrosion and its compatibility with liquid metals (of interest both for fusion reactors and for IFMIF).
- Heat transfer.
- The development of auxiliary systems.
- The development of diagnostics.
- The purification of liquid metals.
- Safety.

(b) Vertical development:

- Studies of the behaviour of liquid metals in a magnetic field, and the development of insulating coatings.
- The diffusion of gases, particularly hydrogen.
- Studies of free surface flow, with and without energy deposition.
- Specific studies of material behaviour at extreme temperatures, and in contact with liquid metal.
- Specific studies of materials bathed in liquid metal, subjected to stress and energy deposition.

Suggested main experiments to be carried out in the LMT Facility are detailed below:

7.5.1. Studies of free surface flow

The studies of free surface flow while coupled to the electron accelerator are, as mentioned above, oriented mainly towards IFMIF and will fill an experimental void, key to the design of the latter's neutron source.

Figures 7.14 and 7.15 show different configurations of the testing zones of some international installations. It has been indicated the possible appearance of the free surface testing zone of *TechnoFusión*`s Installation. The lithium stream will have a medium size cross-section (of about 70mm x 10mm), with a rather high lithium speed (of about 15 or 20 m/s), requiring about 40 m^3/h of fluid flow.

Experiments will include the measurement of the surface ripples (transversal and longitudinal), any change in the flow thickness, the speed and pressure fields, etc. The flexibility of this experimental zone is a basic requirement to study various types of geometry, which is important because the geometry of the pipe and the tray has a direct effect on the generation of surface instabilities in the lithium flow. The dependence of these parameters on the speed of the liquid metal flow will also be studied. Erosion processes in the exit pipe (bursts, material deposits, etc.), distortions, and misalignments of the assembly of the various components, will have an effect on the appearance and development of instabilities, and this will also be studied. These experiments will be carried out at a relatively low temperature of about 250 ºC.

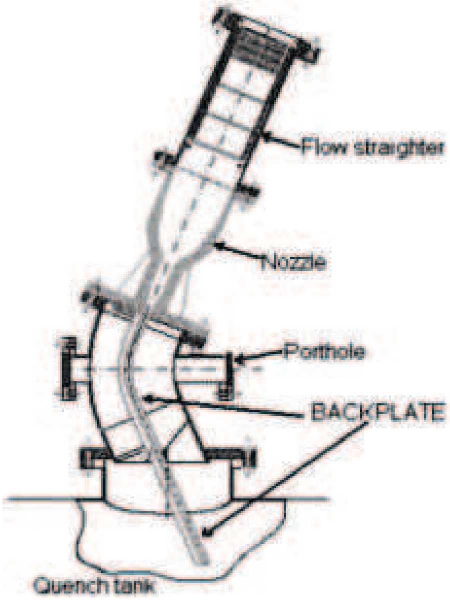


Figure 7.14. Experimental configuration for studies regarding the lithium free surface.

Figure 7.15. Free surface test gate of the ISTC 2036 project for water experiments [80].

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[80] Final Report on R&D activities on #2036 project."The thermal-hydraulic and technological investigations for validation of the project of lithium circulation loop and neutron lithium target for IFMIF", Obninsk 2006.

Furthermore, problems associated with heat deposition in the liquid metal will be studied. In the IFMIF liquid lithium target, the deuteron beam that impinges onto the free lithium flow, generating neutrons, leads to a heat deposition with a distribution as indicated in Figure 7.16. At *TechnoFusión*, this heat deposition will be obtained from the accelerator electron beam. Many preliminary calculations have been carried out, using MCNP and hydrodynamic codes like FLUENT and CFX, to show that an electron accelerator with energy of 1MeV, an intensity of 70 mA, and a properly focused beam, can produce local temperature and power density profiles that are similar to those expected at IFMIF. Figure 7.17 shows the heat deposition due to electron beams with different energies.

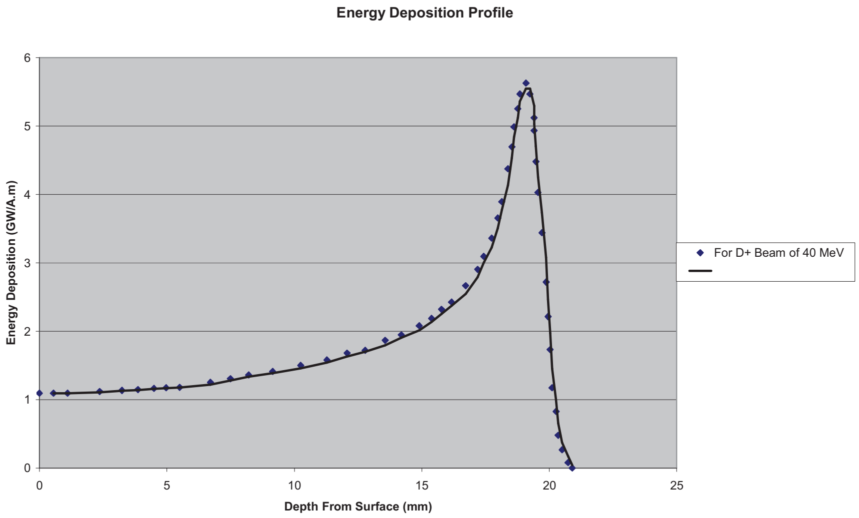

Figure 7.16. Heat deposition in the IFMIF[81] target

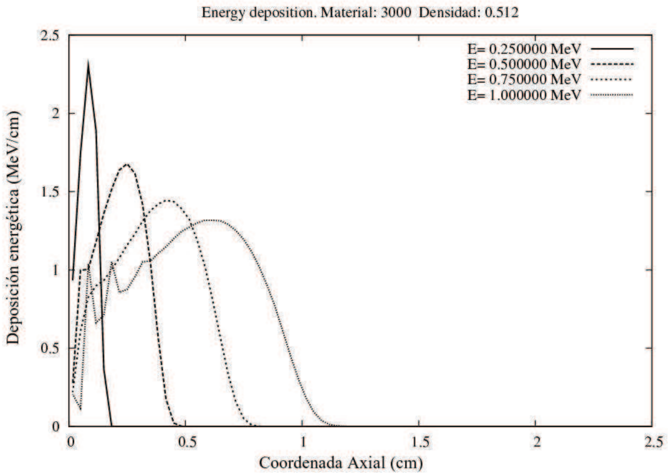

Figure 7.17. Heat deposition produced by electrons in lithium.

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[81] M. Ida, Hideo Nakamura, Hiroshi Nakamura, Hiroo Nakamura, K. Ezato, H. Takeuchi, "Thermal-hydraulic characteristics of IFMIF liquid lithium target" Fusion Engineering and Design 63-64, p.333-342, 2002

Other interesting issues are related to the operation under vacuum conditions, which is needed in case of coupling with the accelerator. The experimental operation of a track at the nominal conditions of the IFMIF lithium loop has led to significant technological problems at the international installations that have tried to do so, such as the appearance of cavitations at various points of the loop. The experimental test section by itself constitutes a technological challenge that should be studied in the framework of the thermo-hydraulics of IFMIF and the design of the loop.

The hydrodynamic test loop will also be useful for the study of liquid walls for fusion reactors. For that purpose, the experiments dedicated to IFMIF can be replaced by divertor prototypes (Figure 7.18), first wall, etc. Such work will also involve studies concerning the composition of the free surface, its stability, heat deposition, etc.

Since the components of fusion reactors will be subjected to electromagnetic fields, the test zone will be designed to allow installing a high field magnet. In this framework, new liquid metal concepts can be explored, such as a porous structure filled with liquid lithium (CPS, Figure 7.19), minimizing the problem of liquid metal stability in the presence of the magnetic field by sequestering Li in a porous mesh, making use of its high surface tension.

Each specific experiment will require its own instrumentation, and the latter will also be subject to study and development. This instrumentation includes surface ripple detectors, lasers for obtaining speed profiles, cavitations and vaporization gauges, high speed chambers, etc.

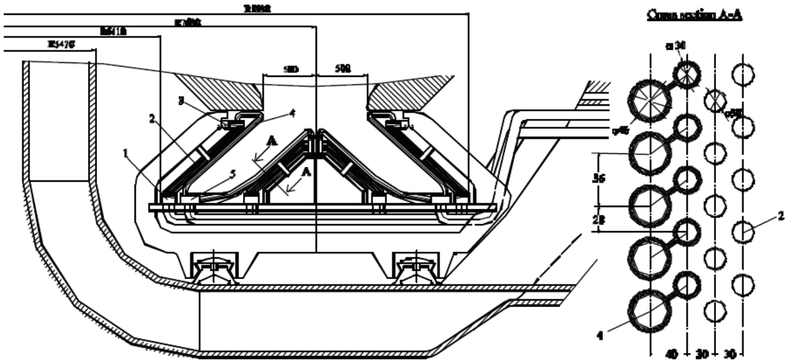

FIG.1. Lithium divertor section design option:
1-input collector, 2-channels of condensation zone, 3-intermediate collector, 4-channels of evaporation zone, 5-output collector.

Figure 7.18. Liquid lithium divertor scheme [82].

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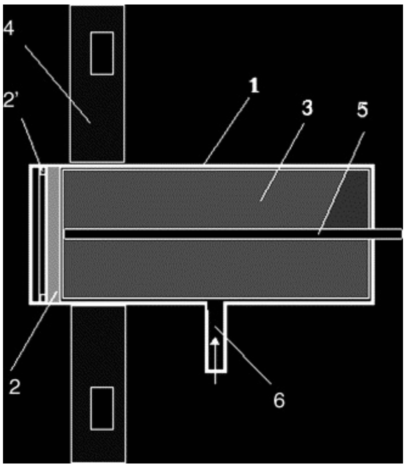
[82] H. Kondo et al. 'Experimental study of lithium free-surface flow for IFMIF target design'. Fusion Engineering and Design 81 (2006) 687-693



1 – Frame
2 – CPS (d = 40 mm)
2' – Brace
3 – Transport structure
4 – Cooling water flap
5 – Termocouple
6 – Lithium supply

Figure 7.19. Lithium target with CPS technology.

7.5.2. Material tests

In the material testing zone of the LMT Facility, many experiments will be performed, including: material compatibility, corrosion, the diffusion of gas through various materials, the mechanical properties of materials while subjected to fatigue cycles, flowing lithium in contact with the various materials of interest for fusion (ferritic-martensitic steels, EUROFER, ceramic materials, graphite, etc), and all this under extreme environmental conditions, appropriate for fusion applications.

The experimental conditions will depend on the goal of each study. For instance, tests of materials for IFMIF will be carried out at high speeds (up to 20 m/s) and low temperatures (below 300 ºC). Tests related to materials for fusion will require very high temperatures of about 1000 ºC and low speeds (≈ 1 m/s). For the gas diffusion experiments (Figure 7.20), the track will be fitted with the required gas feeds (hydrogen, deuterium, etc.) appropriate for each experiment. For the fatigue tests, machines will be installed to apply loads.

As most aspects of the interaction of lithium with other materials are influenced by a radiation field, the experiments will be carried out with and without radiation. To do so, electrons will impinge on a sheet of a certain material in order to generate the radiation field that will be used to irradiate the testing subject. In Figure 7.21, a sketch of an experiment with radiation is shown. This is the LiSoR experiment (Paul Scherrer Institute of Switzerland), in which the behaviour of materials in contact with the lead bismuth alloy is studied.

Occasionally, the duration of these tests will be quite long (some thousands of hours). Furthermore, key parameters such as the speed, temperature and chemistry of lithium are to be varied.

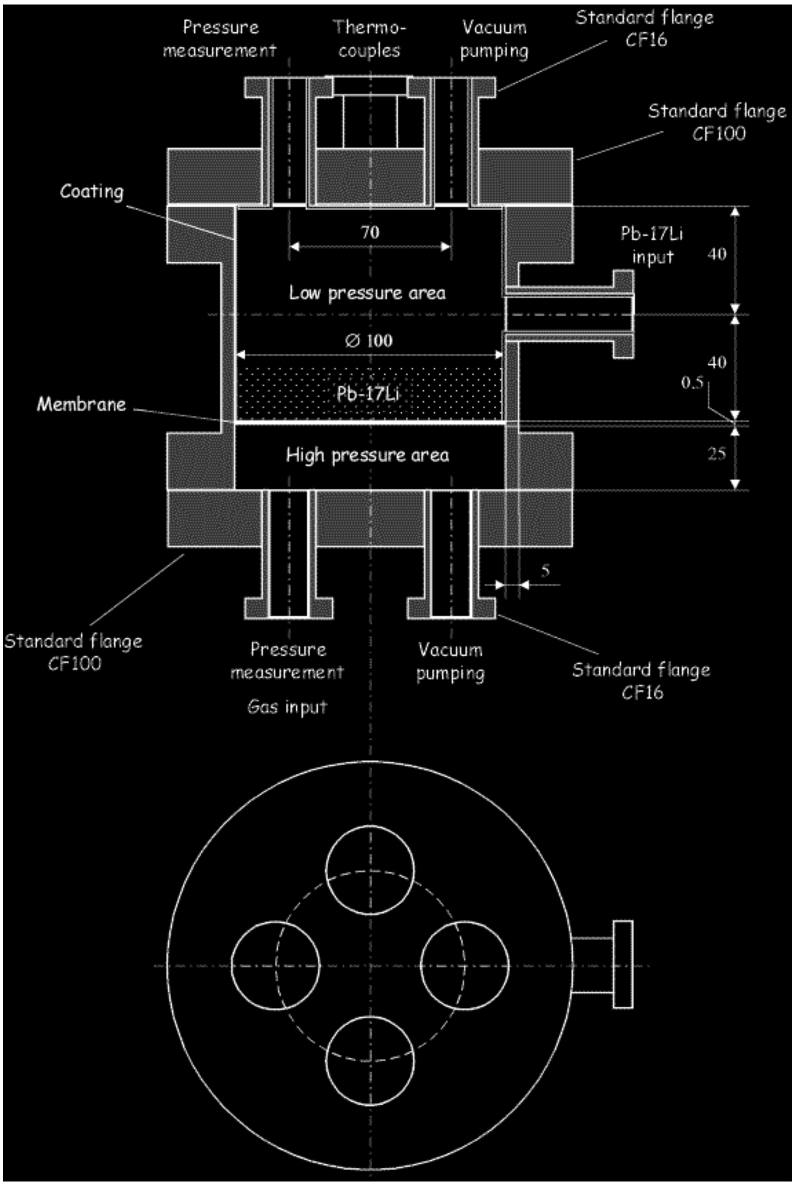


Figure 7.20. Experimental section of the LEDI facility for the study of gas diffusion across membranes in contact with LiPb.

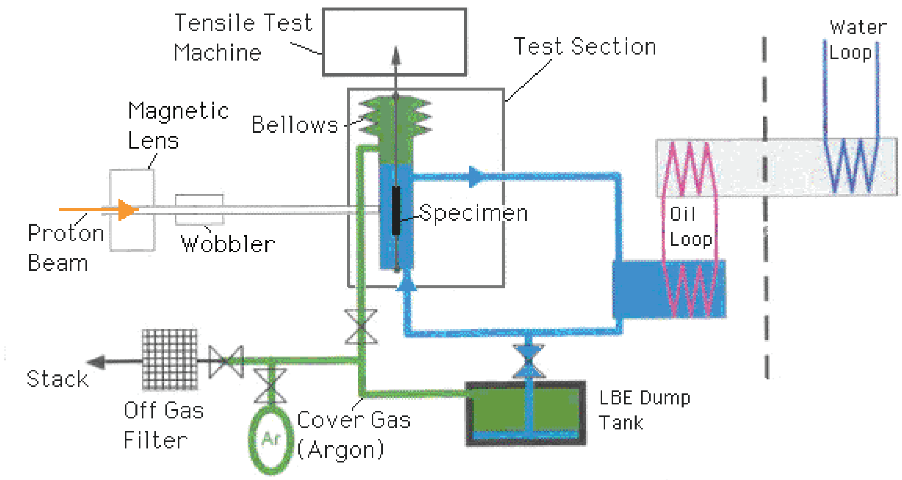


Figure 7.21. LISoR experimental facility of *Paul Scherrer Institut* (Switzerland).

7.5.3. Magneto-hydrodynamic tests

Since environment of a fusion reactor includes electromagnetic fields, the study of corrosion, heat transfer, of the hydrodynamic behaviour of the liquid metal in prototypes should also be carried out in such a field. Thus, the installation of large field magnets is planned at both experimentation zones of *TechnoFusión*.

As mentioned earlier, a magnet can be installed at the free surface experimentation zone in order to study its stability under the influence of an electromagnetic field. At the materials track, studies can also be carried out regarding the influence of an electromagnetic field on, e.g., pressure drops, speed profiles, heat transfer, gas diffusion, impurities, or corrosion. To carry out such experiments, a magnet must be coupled to the materials test loop described above. This track should also be capable of varying the speed and temperature of the lithium to match the range of future liquid lithium blankets.

In the case of, e.g., corrosion tests, samples will be introduced and brought into contact with the liquid metal, while the magnet distorts the flow field. Experimentation times will frequently be of the order of several thousands of hours. For other types of experiment, the required times will be much lower.

Figure 7.22 shows a diagram of the MHD testing facility. To perform heat transfer tests in an electromagnetic field, heating and cooling systems will be required, as well as instrumentation to control the temperature of the track. To measure the pressure drop caused by the electromagnetic fields, the track must be provided with pressure gauges.

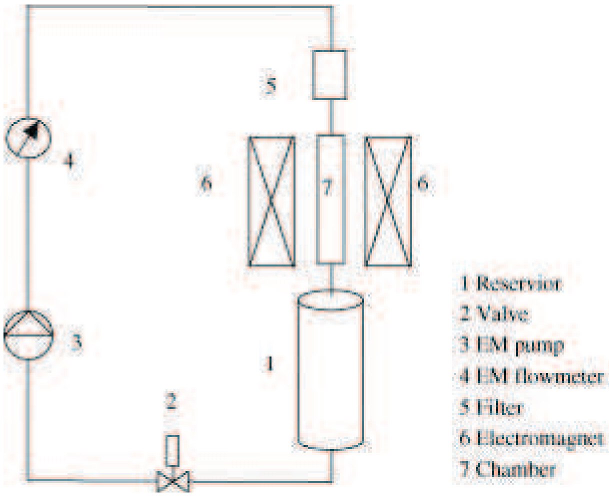


Figure 7.22. Diagram of the MHD[83] experimentation zone.

Summarizing, for this kind of tests, the requirements of the experimentation zone will depend on the type of test. The following points should be taken into account:

1) There must be enough space to install a magnet for generating a high magnetic field, and its auxiliary systems and diagnostics.

2) Since the geometry of the canal is very important for the MHD tests, the materials test loop should have a certain degree of flexibility, permitting the incorporation of different types of track sections, e.g., a circular canal, a square canal, a narrow canal, parallel canals, etc.

7.5.4. Purification and gas treatment tests

When the lithium has passed through the mentioned testing zones, it will be contaminated with corrosion products, solid or gas impurities, etc. In addition, some experiments can require the deliberate addition of impurities to the track. Thus, the lithium loop must be equipped with in installation for purification, so that the lithium enters the track with an optimal degree of purity. Such an installation may be the subject of further development efforts in order to obtain better or innovative components.

In principle, the purification system will consist of a first section to remove any gases dissolved in the lithium (resulting from chemical reactions or purposely added in an experiment), and a second section to remove any corrosion products. An ideal purification system will include gas trap injectors, cold traps, etc., and lithium purity probes to ensure the

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[83] M. Ida, Hideo Nakamura, Hiroshi Nakamura, Hiroo Nakamura, K. Ezato, H. Takeuchi, “Thermal-hydraulic characteristics of IFMIF liquid Lithium target” Fusion Engineering and Design 63-64, p.333-342, 2002

cleanliness of the material. In addition, the latter will serve to quantify the effectiveness of the various purification approaches.

The study of the retention, permeability, solubility and diffusivity of tritium, being a particular case of the diffusion of gases in liquid metals, and the associated extraction systems, constitute one of the most interesting issues in the fusion field, with a view to the development of permeation barriers or tritium extraction systems. Although a large amount of information on the subject of LiPb is available, much of it is contradictory, and a similar situation is bound to occur with pure lithium (which has been much less studied). Therefore, this line of investigation will certainly require much international cooperation. The mentioned processes can be investigated in this experimentation zone, for instance by injecting hydrogen or deuterium into a lithium flow. In Figure 7.23, an example is shown of tritium control by means of an Yttrium trap.

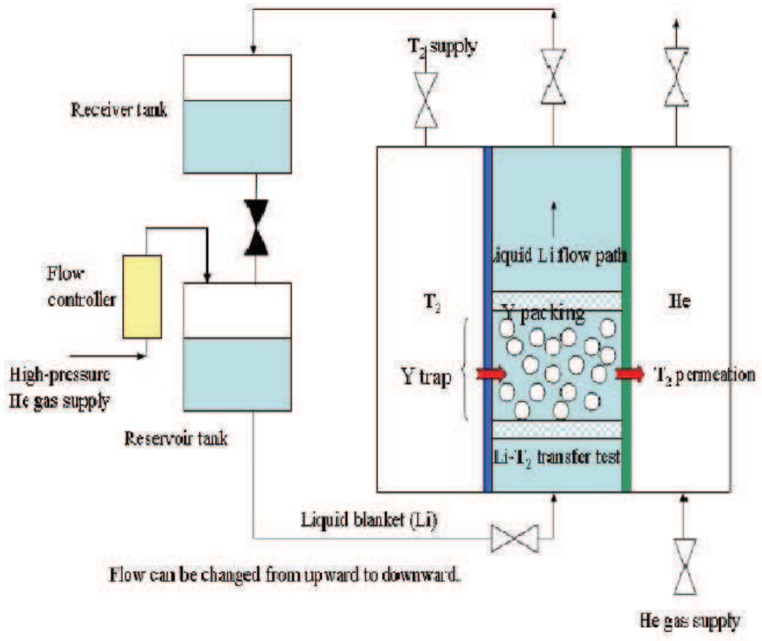

Figure 7.23. Tritium control using an yttrium trap, Kyushu University (Japan)

7.5.5. Safety tests

The handling of pure lithium requires specific safety precautions. Thus, safety will be one of the subjects of study at *TechnoFusión*, and the interaction of Li with water, air, and residues will be analysed, accident analyses will be made, etc.

The main difficulty of using lithium as a working fluid is its reaction with air and water. In order to elaborate an appropriate handling safety protocol, experiments must be performed and calculations must be made. Accordingly, such safety issues have been identified as one of the subjects of study at *TechnoFusión*. These include: the pouring of lithium in the atmosphere and/or in water, the injection of air and/or water, simulations of accidents with a loss of cooling (LOCA) oriented towards future facilities such as IFMIF, fires, etc.

7.5.6. Auxiliary systems and diagnostics

The liquid lithium tracks will be fitted with many diagnostics, such as chambers (Figure 7.24), laser accelerometers, various types of sensors (Figure 7.25), thermocouples, and radiation meters.

The main elements of the loop and the diagnostics will need to be designed specifically due to the lack of commercial technology related to this kind of facilities.

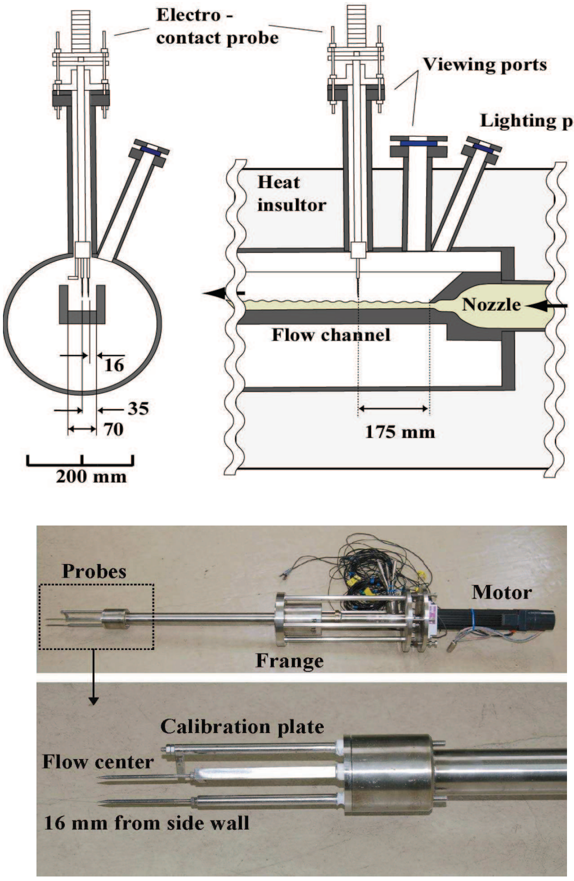

Figure 7.24. Picture and sketch of an electric contact sensor for measuring surface waves.

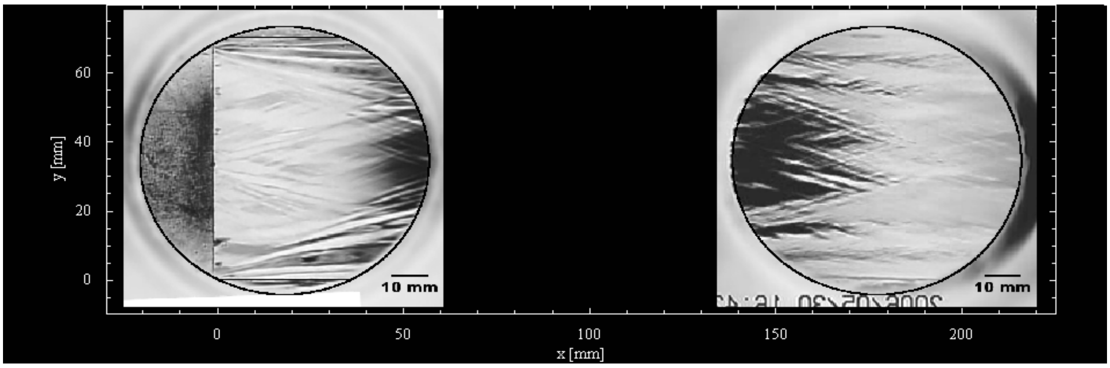

Figure 7.25. Picture taken by the Sensicam QE (PCO AG) camera at the University of Osaka

7.5.7. Tests with Pb-Li

Due to the great importance of the eutectic lithium-lead in the fusion field, and in spite of the fact that Europe already has a number of facilities dedicated to this material, it is considered appropriate that the possibility of performing experiments with this material at *TechnoFusión* is left open.

Therefore, the tracks should be compatible for operation with LiPb. Since lithium-lead experiments usually require low working speeds, it would be sufficient to have a basic dedicated track based on natural convection. In this way, advantage could be taken of the diagnostics and the experimental zones designed for the lithium track. A sketch of such a loop is shown in Figure 7.26.

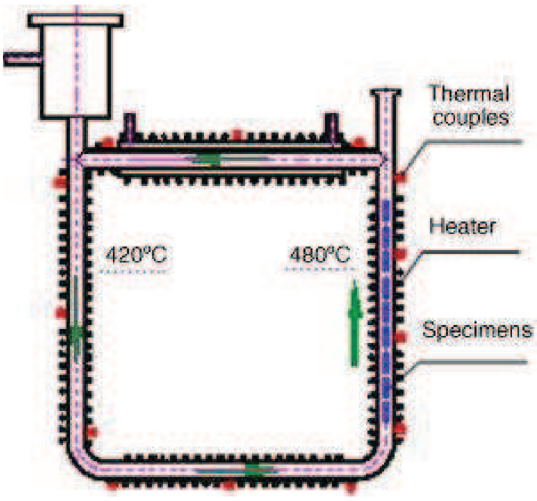

Figure 7.26. Conceptual sketch of a lead-Litium loop for free convection studies.

In addition, this zone might also be subjected to electromagnetic fields and used to test various configurations for future ITER and DEMO blankets.

7.5.8. Validation of computer codes

Computer codes for fusion system engineering and design must be able to manage and simulate the main phenomena related to the behaviour of the materials that will be used. Liquid metals will very likely be one of the main constituents of future fusion devices because of their cooling and neutronic properties.

Therefore, it is important to validate the design tools used to simulate the flow of the liquid metal through the tracks [10]. The design of the cooling channels for ITER and DEMO, as well as the design of the neutron source at IFMIF, is being executed using CFD codes. It has been noted that the full validation of these multipurpose codes is required when liquid metals are used, because of the following:

- The turbulence models that are used in commercial CFD codes are not verified in the full parameter range, i.e., their validity limits in terms of the turbulent Prandtl (Pr) number are not known.

- Models based on commercial CDF codes do not seem suitable for the analysis of liquid metal flow, since they usually assume that the Reynolds analogy holds, in which the thermal and velocity boundary layers are coincident, which is not true in fluids with a low Pr number. The latter is the case of the lithium.

- In CFD codes, the forcing effects due to gravity, and the corresponding multistage models must be improved for fluids with low Pr and Peclet numbers, as is the case of liquid metals.

7.6. Layout, supplies and safety requirements

(I) Layout and equipment

The building for the LMT Facility of *TechnoFusión* will have to comply with a set of requirements, e.g., to provide sufficient space for the physical volume of the planned equipment. It will also need to provide safe experimental conditions in relation to, e.g., the handling of liquid metal, the presence of magnetic fields, high temperatures, etc., and, critically, the utilization of an electron accelerator at the liquid metal loop, considering the relative location of both systems and radiation protection requirements (shielding, access control, etc.)

Regarding the needed space, note that the free surface experiment, including its coupling to the accelerator, should measure about 15 metres. This number arises due to the necessity of having a lithium column large enough to avoid cavitations at the entry of the driving pump. To achieve this height, part of the track could be built underground, placing the tanks and pumps in a basement, or, preferably, in a ditch (as with the existing installation at the University of Osaka), that could be flooded with argon in case of a lithium leak.

The International installations that have been studied as reference models for the *TechnoFusión* design usually have the experimentation tracks placed in a well-lit building, with cranes to manipulate the equipment. The Obninsk installation is special, as its lithium track is locked inside a metallic box that traverses the various floors of the facility. This design is probably motivated by the reuse of existing installations initially dedicated to other uses. Both solutions are possible, but the first one allows more flexibility when installing the different tracks, and better access to all the parts.

Further research into the track implantation, and the required space for auxiliary systems, will require more specific information about the available space. As a first estimate, the LMT Facility would need an area of approximately 300 m^2.

(II) Safety

The routine handling of alkaline metals in experiments, such as Li, requires establishing specific procedures.

Safety is a key issue in a facility of this kind, as a consequence of the chemical reactions that may occur when the metal comes into contact with components of the air, such as oxygen, nitrogen and water. Lithium reacts violently with water, and can suffer spontaneous combustion when in contact with air at a high temperature.

Lithium reacts with oxygen producing lithium oxide (eqs. 7.2.).

$$2Li + \frac{1}{2}O_2 \longrightarrow Li_2O \quad \left(\Delta H_{25^\circ C} = -142.65 Kcal/mol\right)$$

eq. 7.2

$$2Li + O_2 \longrightarrow Li_2O_2 \quad \left(\Delta H_{25^\circ C} = -151.9 Kcal/mol\right)$$

Li_2O is very reactive with water, carbon dioxide and heat-resistant compounds. Its reaction with water produces hydroxide, which causes burns on the skin, eyes and other tissues (eq. 7.3).

$$LiO_2 + H_2O \longrightarrow 2LiOH$$ eq. 7.3

In the presence of nitrogen, lithium reacts according to the reaction (equation 7.4.):

$$3Li + \frac{1}{2}N_2 \longrightarrow Li_3N \quad \left(\Delta H_{25^\circ C} = -47.5 Kcal/mol\right)$$ eq. 7.4

The generated lithium nitride is highly reactive. In the presence of water, ammonia can be formed. No metal or pottery can resist molten nitride.

Lithium will react with oxygen and any other gas, except the noble gases. The ignition temperature of lithium in air ranges from 180 ºC to 640 ºC. This means that lithium handling must be done in an environment with inert gases.

In the presence of water, lithium reacts violently, forming lithium hydroxide and hydrogen gas. Usually, this reaction is accompanied by an explosion, caused by the secondary reaction of hydrogen with oxygen.

$$\begin{aligned} &2Li + 2H_2O \longrightarrow 2LiOH + H_2 + Q \\ &2H_2 + O_2 \longrightarrow 2H_2O \end{aligned} \qquad \text{eq 7.5}$$

The heat generated in the first reaction is enough to drive the second reaction.

The following safety measures must be taken when operating a lithium loop:

- All staff that comes into contact with the installation or that operates it must be qualified.
- There should be emergency plans to stop operation safely.
- Protective emergency gear should be available, such as protective suits, facial masks, and fire extinguishers appropriate for the expected type of fire.
- Protective gear for the operation staff in case of a leak or fissure in the loop.
- Auxiliary lithium tanks for die-casting the track and collecting leakage flows.
- A ventilation system and a filtering system in case lithium oxide or hydroxide fumes are formed.
- Detection systems for lithium leaks and fires, and fire extinction systems.
- Safeguards to prevent the entry of water and other incompatible materials into the lithium loop.
- Protection systems for the equipment in case of anomalous circumstances.
- Appropriate signalling of any rooms containing a certain amount of lithium.

(a) Safety analysis of loop operation

One of the main goals of the LMT Facility of *TechnoFusión* is to serve as an installation of reference for the development of the IFMIF project. In this sense, many of the security issues are identical to the issues that will arise there.

The lithium target of the experimental installation of IFMIF[84, 85, 86] has been subjected to many security tests, and the most important risk factors have been evaluated. The cited studies follow the procedure known as FMEA (*Failure Mode and Effect Analysis).* Failure tree techniques have also been applied to evaluate all possible failures of any component needed for safe loop operation. Testing the safety of a liquid metal loop requires using a thermo-hydraulic simulation code that allows estimating the effects of a given event.

In case of the *TechnoFusión* loop, a particular list of possible events has been identified, based on the studies for the IFMIF installation:

- A loss of lithium flow in the loop.
- A flow loss in the *Cold trap* cooling loop.
- A loss of heat drainage.
- A cooling (LOCA) loss accident in the lithium loop.
- A loss of lithium purification.
- The escape of lithium inside the building.
- A burst in the lithium pipe.
- A loss of vacuum in the free surface zone.
- A loss of argon.

Other events that must be studied further during the design of the track:

- A failure of auxiliary systems (pumps, valves, etc.).
- A failure of the control system.
- A loss of the electric power supply.

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[84] L. Burgazzi, "Safety assessment of a lithium target", Nuclear Engineering and Design, 2006

[85] L. Burgazzi, " Probabilistic safety analysis of an accelerator-Lithium target based experimental facility", Nuclear Engineering and Design, 2006

[86] L. Burgazzi, "Hazard evaluation of The International Fusion Materials Irradiation Facility", Fusion Engineering and Design, 2005

- A loss of high-pressure air.
- The entrance of water in the track.
- The entrance of air in the track.
- The entrance of oil in the track.

(b) Safety when filling up or training the system

One of the most hazardous tasks when operating the liquid metal track is filling or draining it. This issue is particularly important when the tracks are used with several liquid metals.

Liquid lithium is a material that requires taking important safety measures, mainly to avoid contact with the atmosphere and water. Most likely, the material will be supplied in a tank fitted with electric heaters, underneath a protective layer consisting of a mixture of oil and paraffin.

(c) Waste Management safety

Spanish legislation regulates the storage of raw materials in any installation where chemical products are handled. The Ministry of Industry issued Royal Decree 379/2001, dated 6th April, concerning the 'Regulations for the storage of chemical products and complementary technical instructions', aiming to establish the safety requirements for the storage, loading, unloading, and transfer of dangerous chemical products. It includes a detailed description of the procedure for requesting the registration of an installation, subject to the approval of a system of periodic controls, as well as administrative controls and sanctions for infringements of the regulation. This regulation also includes Complementary Technical Instructions (ITC) for each product.

In article 2, the scope of the rules is established. Lithium, which is the main constituent of the experimental area of the liquid metal installation, is placed in the group of corrosive solids, provided its inventory is less than 200 kg. Currently, there is no specific regulation for products such as lithium, so there is no requirement to obtain a project license for this kind of installations, although it is foreseen that the installations are subject to the regulations concerning the use and storage of flammable goods.

This means that the LMT Facility only needs to comply with the applicable regulations and principles of the *International Chemical Safety Card* (ICSC), and with the rules described in the Guide for the Response to Emergencies (GRE 2004).

These documents do not have a legal status, but they clearly summarise the essential requirements regarding hygiene and safety for the mentioned chemical substances. The record number for lithium is ICSC 0710, and some of the main instructions are:

- Avoid flames and sparks, and do not smoke.

- Do not expose the product to water.

- In case of fire, do not use water but special quenching agents such as dry sand.

- Keep storage tanks and related installations refrigerated.

- In case of spillage or leakage, remove the spilled substance and collect it in a sealable metallic container, carefully gathering the residue using dry sand or another inert absorbent. Never pour it to the sewer.

- Staff must wear a total protection suit, including respiratory equipment.