Conference Report on the 3rd International Symposium on Lithium Application for Fusion Devices

G. Mazzitelli1, Y. Hirooka2, J. S. Hu3, S. V. Mirnov4, 5, R. Nygren6, M. Shimada7, M. Ono8 and F. L. Tabares9

1 Associazione EURATOM-ENEA sulla fusione, Centro Ricerche di Frascati, C.P.65-00044, Italy
2 National Institute for Fusion Science and Graduate University for Advanced Studies, 322.6 Oroshi, Toki, Gifu 509-5292, Japan
3 Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, People’s Republic of China
4 TRINITI, Troitsk, Moscow reg. 142190, Russia
5 NRNU MEPhI, Kashirskoye sh., 31, 115409 Moscow, Russian Federation
6 Sandia National Laboratories, Albuquerque, NM 87185, USA
7 JAERI-International Fusion Research Centre, IFERC Obuchi, Aomori-ken, Japan
8 Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543, USA
9 National Institute for Fusion, As EURATOM/CIEMAT, Av. Complutense 22, 28040 Madrid, Spain

E-mail: guiseppe.mazzitelli@enea.it

Received 22 July 2014, revised 2 October 2014
Accepted for publication 30 October 2014
Published 14 January 2015

Abstract

The third International Symposium on Lithium Application for Fusion Device (ISLA-2013) was held on 9–11 October 2013 at ENEA Frascati Centre with growing participation and interest from the community working on more general aspect of liquid metal research for fusion energy development. ISLA-2013 has been confirmed to be the largest and the most important meeting dedicated to liquid metal application for the magnetic fusion research. Overall, 45 presentation plus 5 posters were given, representing 28 institutions from 11 countries. The latest experimental results from nine magnetic fusion devices were presented in 16 presentations from NSTX (PPPL, USA), FTU (ENEA, Italy), T-11M (Trinity, RF), T-10 (Kurchatov Institute, RF), TJ-II (CIEMAT, Spain), EAST (ASIPP, China), HT-7 (ASIPP, China), RFX (Padova, Italy), KTM (NNC RK, Kazakhstan).

Sessions were devoted to the following: (I) lithium in magnetic confinement experiments (facility overviews), (II) lithium in magnetic confinement experiments (topical issues), (III) special session on liquid lithium technology, (IV) lithium laboratory test stands, (V) Lithium theory/modelling/comments, (VI) innovative lithium applications and (VII) special Session on lithium-safety and lithium handling. There was a wide participation from the fusion technology communities, including IFMIF and TBM communities providing productive exchange with the physics oriented magnetic confinement liquid metal research groups. This international workshop will continue on a biennial basis (alternating with the Plasma–Surface Interactions (PSI) Conference) and the next workshop will be held at CIEMAT, Madrid, Spain, in 2015.

Keywords: conference report, lithium, liquid metal

1. Introduction

The third International Symposium on Lithium Application for Fusion Device (ISLA-2013) was held on 9–11 October 2013 at ENEA Frascati Centre. The first one was organized in Japan by NIFS in 2010 [1] and the second one was hosted in Princeton (USA) by PPPL in 2011 [2]. Since the last symposium the interest in lithium application is growing, and it concerns not only the plasma wall conditioning but also the possibility to use liquid metals as plasma-facing components (PFCs). It is well known that tungsten, the present candidate material for divertor, can...
operate in a fusion reactor only if stringent requirements on the power load are fulfilled, i.e. radiative power from core and divertor greater than 90%, electron temperature in front of the plate as low as 5 eV [3]. Alternative configurations as snowflakes or super-x divertor and liquid metals as PFC have been proposed as possibilities to mitigate the problem. For these reasons the Scientific Committee decided to open the Symposium to the other liquid metals as well, i.e. Ga and Sn. These liquid metals have melting temperatures higher than lithium and a wider operational window. In principle, heat loads of 20–25 MW m⁻² could be tolerated before evaporation becomes very strong. New suggestions, already tested in laboratory, to avoid droplet formation and about tokamaks have also been presented with significant positive results.

ISLA-2013 has confirmed to be the largest and the most important meeting dedicated to liquid metal application for the magnetic fusion research. Overall, 45 presentation plus 5 posters were given, representing 28 institutions from 11 countries. Sessions were devoted to the following: (I) lithium in magnetic confinement experiments (facility overviews), (II) lithium in magnetic confinement experiments (topical issues), (III) special session on liquid lithium technology, (IV) lithium laboratory test stands, (V) lithium theory/modelling/comments, (VI) innovative lithium applications and (VII) special session on lithium-safety and lithium handling.

The latest experimental results from nine magnetic fusion devices were presented in 16 presentations from NSTX (PPPL, USA), FTU (ENEa, Italy), T-11M (Trinity, RF), T-10 (Kurchatov Institute, RF), TJ-II (CIEMAT, Spain), EAST (ASIPP, China), HT-7 (ASIPP, China), RFx (Padova, Italy), KTM (NNC RK, Kazakhstan). The results from these devices generally indicate a growing interest on the application of lithium not only to enhance plasma performance and in generally to allow better plasma exploitation by reducing H-mode threshold and a more easy recovering from disruption, but also as possible PFC in alternative to solid materials, i.e. tungsten.

Ten presentations had as object the lithium plasma material interaction: (PMD) test stands from PPPL, University of Illinois, CNR-IFP (Italy), NIFS (Japan), Sichuan University and University of Chinese Academy of Science (China), Latvia University, JSC ‘Red Star’ (Russia Federation) and CIEMAT (Spain). Two talks were focused on other liquid metals: one from DIFFER (Netherlands) on tin and one from Latvia University on gallium. In the special liquid lithium technology session, three talks on IFMIF, three on TBM were presented. There were eight innovative lithium application presentations and three theoretical talks on magnetohydrodynamics (MHD) issue relevant to liquid metal first wall. Finally, a special session was dedicated to Lithium-Safety and Lithium Handling.

All the presentations can be downloaded from the symposium web page (www.isla2013.enea.it/). In this conference report, the symposium papers are summarized in order of presentation. It must be remarked that many of the papers which are summarized here are currently under peer review for the publication in a special issue of the Journal Fusion Engineering and Design. The international programme committee members are Drs Y. Hirooka, G. Mazzitelli, S.V. Mirnov, M. Ono (Chair), M. Shimada and F.L. Tabares. The local organizing committee members were G. Mazzitelli, M. Polidoro, M.L. Apicella, G. Bartolomei, V. Vitale and M. Vellucci.

2. Symposium summary of presentation on lithium applications for fusion devices

Session I: lithium in magnetic confinement experiments overview talks. In the session three invited talks about lithium applications for magnetic fusion devices were presented: the first one on the FTU tokamak, the second on the HT-7 and EAST tokamaks and the last one on the NSTX spherical tokamak and future reactors.

In the first talk, delivered by G. Mazzitelli (ENEa, Italy) a new version of the liquid lithium limiter (LLL), called CLL for the cooled lithium limiter, was presented. This limiter has been developed with a water-cooled tubing made of Mo for the improved performance to withstand heat loading >10 MW m⁻², a condition relevant to the divertor in ITER. Demonstrated under these high heat load conditions is a vapour shielding effect to protect the CLL structure from thermal damage. However, it has also been observed that the working temperature must be below 550 °C, because at this temperature lithium evaporation appears to start increasing exponentially. Most importantly, improvement in the energy confinement time in the FTU tokamak with the lithium-conditioned wall is reported as a result of the use of CLL. During the Q&A period, however, the safety concern was expressed about the use of liquid lithium with water as a coolant.

In the second talk, given by J.S. Hu (ASIPP, China), an overview on the lithium-effects observed in the HT-7 and EAST tokamaks was presented. On EAST the Li wall coverage has been increased up to 85% by a different displacement of the three ovens. It was emphasized that an important role in running long-pulse H-mode discharges in these tokamaks is played by lithium injected by a number of different schemes, including not only the conventional methods based on evaporation–deposition, but also a granule (i.e. pellet) injection scheme, recently developed by D. Mansfield of PPPL. Stationary H-mode up to 60 and 400 s long plasma discharges were achieved. Lithium has been known to reduce the occurrence of ELMs, which tends to accumulate impurities in the core plasma. Here, the granule injection is meant to induce periodic ELMs to discharge impurities, which has been successfully demonstrated in EAST. In general the use of lithium coating on EAST improves plasma performances and it is considered an important tool for the next operation with full metallic wall foreseen on EAST in 2014/2015. Also, reported in HT-7 was the TE-MHD experiment, originally proposed by D. Ruzic of University Illinois, in which liquid lithium did not smoothly flow by TE-MHD for technical problems such as poor surface wetting, etc. In this context, the surface temperature effects on surface wetting characteristics were presented. These practical problems on the use of flowing liquid lithium will hopefully be solved as homework by the next workshop.

The last presentation in this session was given by M. Ono (PPPL, USA). First, the data from NSTX were shown, illustrating that the divertor heat load has been reduced by
increased lithium evaporation. Then, a new divertor concept was introduced, in which the lithium that evaporated from the flowing liquid surface will act as a divertor heat radiator, while the lithium condensed on the wall will act as a hydrogen getter as well, a double-duty lithium concept. Also, presented were the results of case studies, based on the two-point model (by P. Stangeby), demonstrating the lithium effect of radiation, i.e. cooling the edge plasma, which then reduces the resultant heat load to the divertor. The concept will be PoP-examined in the NSTX-U as soon as it comes back in line. However, it was emphasized that this concept should be applicable in principle for future power reactors as well. For power reactor applications, one must pay attention to tritium inventory, which, however, may not be of a concern because generally the first wall, the plasma-facing side of the blanket structures, will be operated at elevated temperatures.

S. Mirnov (TRINITY, NRNU MEPhI RF) summarized experiments in T-11M tokamak which showed an effective lithium collection scheme with the cooled (cryogenic) target in which lithium and hydrogen isotopes were extracted from the chamber of T-11M tokamak during tokamak operation without venting the vacuum chamber. The total Li flow through boundary of steady-state tokamak reactor such as ITER should be equal to 50 ton per year. To reduce the total amount of lithium in tokamak chamber its flow must be closed in the permanent lithium loop passing into the tokamak chamber and going out for the lithium cleaning from retained hydrogen isotopes. Experiments of lithium extraction from the T-11M chamber without its venting are the first step of such loop creation. During the T-11M experiment the cooled target collected about 60 mg of lithium in 200 regular shots, which was close to the assumed total amount of lithium used in the experiment ∼0.25 mg/shot. The T-11M results suggest the concept of a dual limiter system in which one is acting as the lithium emitter and the other with lower temperature as the collector of lithium. A lithium-rod divertor for steady-state fusion neutron science facility was also discussed. Were reported the first results of cleaning the chamber wall from lithium deposit without venting. Efficacy of lithium collection by the cryogenic target during hydrogen glow discharge (HGD) was investigated as a function of the cooling temperature of the target, temperature of the chamber walls, and the electric potential between the target and the chamber walls.

D. Ruzic (University of Illinois, USA) summarized the recent developments on thermolectric-driven flow of liquid lithium in solid metal trenches: a new approach to heat removal in fusion devices termed liquid metal infused trenches (LiMITS). LiMITS uses thermo-electric currents created by temperature gradients to drive liquid lithium to flow fast enough to present a clean surface to the plasma and readily absorb incident deuterium. Using this effect may allow a low-recycling lithium PFC solution for future fusion reactors. LiMITS experiment on HT-7 in China was described, showing the liquid lithium flows along the trench with maximum velocity ∼3.7 cm s⁻¹ close to the predicted value of 4.4 cm s⁻¹. The LiMITS experiment also showed that the lithium improved the confinement time by ∼10% without causing disruptions. There is a new LiMITS test facility called TELS (thermoelectric-driven liquid-metal plasma-facing structures) where high pulse plasma heat load of >1 MJ m⁻² can be applied to the target. The planned LiMITS collaborative experiments are on Magnum-PSI (Netherlands), EAST (China), and LTX and NSTX-U (Princeton).

The heliac stellarator TJ-II, described by F.L. Tabárés (CIEMAT, Spain), has studied the effects of lithium evaporated onto its vacuum chamber walls while boronization is also applied. The use of lithium has allowed routine operation with the two neutral beam injectors. Clear transitions to the H-mode have been seen, which essentially doubled the confinement. The isotope (D&H) interchange including studies of H retention and isotope mixing on solid and liquid lithium were investigated. There were no apparent isotope (H versus D) effects on particle confinement with LLL. Exposure of the LLL to the plasma followed by TDS up to 500 °C allowed one to estimate the effect of temperature on H retention. It was found that at 400 °C, no TDS peaks were found and the total amount of H released for lower T of exposure was consistent with the expected one from the ratio of limiter to total plasma interaction area. Experiments of limiter biasing have been addressed in TJ-II under full lithium wall coverage. Two different materials, graphite and liquid lithium, were used as limiting surfaces. Positive and negative biasing with respect to the plasma and inter-limiter biasing experiments were carried out. A very different response of the plasma to the applied voltage was found depending on limiter material. While a weak effect was seen in C limiter biasing for both polarities, a strong enhancement of particle confinement was observed when the LLL was biased positively with respect to the plasmas. Furthermore, spontaneous currents at the SOL were produced when both limiters were simultaneously inserted due to different floating voltages achieved by both materials. The implications of secondary electron emission properties of the plasma-exposed surfaces were addressed.

M.A. Jaworski (PPPL, USA) gave an overview talk on high-temperature, liquid lithium PFC research for NSTX-U and next step device. The NSTX-U five-year plan for research in materials and PFCs emphasizes three main thrusts of research: surface-science for long-pulse lithium PFCs, tokamak-induced material migration and evolution and establishing the science of continuous vapour shielding. Engineering studies indicate, however, that PFC designs utilizing existing cooling technologies will result in lithium surface temperatures exceeding 700 °C under a 10 MW m⁻² surface heat-load without vapour shielding which underscores a need for additional heat flux reduction schemes such as the vapour shielding and radiative divertor. An experiment on the Magnum-PSI plasma of lithium vapour shielding revealed that the thin (∼1 µm) lithium layer is found to persist for several seconds of the discharge indicating a high re-deposition fraction and produces a bright cloud of Li emission immediately in front of the target that is approximately 2–3 mm thick. The experiment of lithium vapour-cloud PMI in Magnum-PSI already shows rich physics—somewhat unexpected observation of reduced current to target and increased power for lithium explained with reduced sound speed and higher particle reflection for high-Z surface. These observations provide the first feasibility assessments of a continuously vapour-shielded regime for use in the NSTX-U.

V.G. Skokov (St Petersburg University, RF) gave a lithium dust injection experiment using a rotary feeder technique...
which had been designed, fabricated and commissioned on T-10 tokamak. With application of duct injector, a more pronounced effect on the D recycling reduction of \(\sim 40\%\) was observed, compared with the injection of Li pellets. The 0D model for deuterium, lithium and carbon behaviour in T-10 plasma during the injection had been developed and applied. The D recycling drop can be seen from the 40\% decrease of D flux from PFC during the lithium injection. A D recycling coefficient drop from 0.9 to 0.85 was estimated. It was noted that the average lithium flux into plasma is an order of magnitude smaller than the one measured at the injector outlet. For both lithium pellet and lithium dust injection, only weak cumulative effect of lithium influence was observed in T-10 experiments due to the specific scenario of T-10 plasma shut-down with a major disruption initiation.

Session II: lithium in magnetic confinement topical experiments. After the overview session, the talks of the next session focused on specific aspects of the Li experiments in different devices.

V. Pericoli Ridolfini (NEA, Italy) showed how the SOL properties—and consequently also the properties of the bulk—are remarkably affected by the LLL on FTU. Electron density in the SOL is almost unchanged but the electron temperature is quite higher by a factor two for middle–low density range \((n_e,\text{line} < 10^{20} \text{m}^{-3})\).

The neutral density is strongly reduced. Due to the more ‘transparent’ edge, the neutrals can feed more effectively the plasma central region and higher densities are attainable with a strong density peaking and with a reduced transport of both particles and energy.

In the middle–high density range \((n_e,\text{line} \gtrsim 10^{20} \text{m}^{-3})\) the onset of a highly radiating ring (up to 60\% of the total SOL radiation) is observed. In this situation, the non-coronal equilibrium radiation from Li prevents increasing heat loads on the LLL avoiding damages to the capillary porous structure. This vapour shield is a self-protecting mechanism that needs to be investigated in depth.

P. Innocente (RFX, Italy) presented the results obtained on RFX-mod, a reverse field pinch device. The experiments were mainly focused on the control of the electron density by covering the graphite first wall by a lithium layer. Different techniques were used: Li evaporation before the discharges, single or multi-pellet injection. Despite the different amounts of Li used in the three cases (\(\sim 0.3\) g with single pellet, \(\sim 2.3\) g with multi-pellets and \(\sim 13.5\) g by evaporation) the results obtained were quite similar and generally modest. The Li toroidal distribution is completely different in the three situations. When the evaporator is used, Li forms a thick layer on the wall localized in a narrow region near the Li source, while in the case of pellet injection Li forms a quite toroidally uniform but very thin layer, due to the limited amount of injected Li. Nevertheless, an increase in the particle confinement time, due to a better neutral gas recycling control and impurity control, was observed.

A re-analysis of NSTX deuterium retention data was illustrated by F. Scotti (PPPL, USA). Tritium retention could be a possible showstopper for Li use in a reactor and an assessment is required in a relatively short time. In this context, the role played by the interaction of Li with the working gas and/or the other impurities present in the vacuum chamber is crucial. In function of the evaporated amount of Li deposited on the walls and on the divertor a higher wall pumping rate has been observed with a strong reduction up to 50\% of the ion density in plasma discharges. However, available data suggest that part of the deuterium retention could be due to the presence of oxygen unlikely after a wall boronization process in which oxygen is strongly suppressed. The Li–O–C–D chemistry has been pointed out as a possible mechanism for an enhancement of deuterium retention due to oxygen influx also after fresh lithium coatings: Li brings oxygen to surface from bulk graphite that enhances D binding.

Zhen Sun (ASIPP, China) reported more in detail about the influence of lithium coating on plasma performance on EAST. The percentage Li coverage of the vacuum vessel and divertor has increased up to 85\% in 2012 with respect to only 30\% in 2010 by an upgrade of Li evaporation system. The Li was distributed more uniformly and its thickness was between 2 mm and a few nm depending on the distance from the oven. It was found that adhesion of Li film was better on Mo tiles than on C tiles. The suppression of C and O impurities as well as a strong reduction of Mo has been observed and, compared with the 2010 campaign, a better control of C impurities was found due to the increased divertor/wall coverage. The recycling coefficient varies from 0.89 for a fresh lithumization to 0.96 as plasma operation proceeds. As a consequence the retention rate increased from 55\% to 75\%. In general plasma operation is facilitated by Li coating and 1 MA long pulse H mode plasma can be easily achieved.

On HT-7, for the first time in the same device, different solutions to expose liquid lithium to the plasma have been tested and the results were presented by G.Z. Zuo (ASIPP, China). A movable plate was exposed to the plasma both with lithium deposited on a free surface as well as confined in a capillary porous system. Lithium limiter with free surface produced a serious lithium emission since the breakdown phase and resulted in lots of disruption shots. Liquid droplets with 1–5 mm radius were observed during discharges due to the \(J \times B\) force while evaporation and sputtering processes can be neglected in that experimental conditions. The capillary porous system confines lithium much better: few and much smaller droplets were detected during discharges and no damage has been observed in the stainless steel structure. Finally, a flowing liquid Li limiter with a trench structure could work well except for bad wetting, but it still had lots of lithium emission due to wide channel. The flowing liquid Li limiter with uniform and thin lithium layer produced a little lithium emission, and most of the discharges were normal. The experience gained in these experiments will be used to improve the technical solutions that will be implemented and tested on EAST divertor.

The migration and circulation of lithium could be a serious problem for a future reactor. V. Lazarev (TRINITI, RF) presented a simple model of the shaping of Li deposition profile and lithium redistribution by deuterium based on the experimental results obtained on T-11M by the spectroscopic observation of \(H\alpha\) and \(Li\) lines. About 60\% of the injected lithium during plasma operation was found on the limiter, and this suggests the possibility to put some elements in the SOL of a tokamak to collect most of the produced lithium.
The tiles of the toroidal limiter and the dusts of FTU were analysed to determine the formation of Li compounds. The aim of the work was to demonstrate that the strong release of CO₂ in the FTU device during the operations and specially after a disruption was due to decomposition of the lithium carbonate which forms on the surface, following a machine exposure to the air. L. Laguardia (CNR, Italy) put in evidence by post-mortem XPS toroidal limiter tile analysis that Li is present like carbonate. Every single grain of dust contains up to 90% of lithium carbonate. Furthermore, the SIMS analysis confirms that most abundant element on dust particles is Li and carbon concentration is three times higher than that of molybdenum.

T. Abrams (PPPL, USA) reported about the erosion and re-deposition of Li coating on TZM molybdenum and graphite during high-flux plasma bombardment. Measurements on average Li yield carried out on MAGNUM-PSI, a linear plasma device, have shown that for TZM molybdenum significantly less erosion than what is predicted by theory assuming the Langmuir law for evaporation plus sputtering calculations from TRIM code is found. The Li re-deposition fraction on Mo is between 0.85 < R < 0.98 slightly less than predicted by modelling. The situation of Li coating on graphite is totally different: it shows a short lifetime that can be only explained if taking into account the diffusion process of Li in graphite.

On NSTX, Li evaporation is shown to reduce λₚ and peak heat flux on the divertor. The physical mechanism that could explain these experimental observations was the object of T.K. Gray’s talk (PPPL, USA). No definitive conclusion can be drawn from the data analysis, and further investigations and 2D modelling are needed. A possible explanation could be that the increased non-corporal divertor radiation or increase divertor nₑ causes more of the incident heat flux to diffuse into the private flux region, also causing a modification of the upstream nₑ and Tₑ profiles, due to Li. Or the explanation could be some combination of these mechanisms, while, according to the NSTX experimental results, an onset of divertor detachment can be excluded.

Session III: special liquid lithium session. The session was devoted to the special characteristics of lithium as measured in laboratory and tokamaks. Four presentations took place in the session.

F. Scotti (PPPL, USA), on behalf of V. Soukhanovskii, reported on recent results obtained in NSTX concerning synergistic surface effects on D recycling at the divertor. A supersonic gas injection system was used to produce high-density plasmas during short (few ms) times. Based on theoretical calculations and laboratory experiments they aimed at testing the possible correlation between oxygen plasma content and D recycling based on possible sequestration of D atoms by the Li–O bonding. Although there was evidence of oxygen plasma contamination even after strong lithium evaporation (as opposed to the boronization case), quantitative assessment of the O concentration was not achieved through spectroscopy due to the lack of the S/XB factors for the selected lines.

Y. Hirooka (NIFS, Japan) presented a paper on the observations of liquid stirring effects on the recycling properties of H and He from molten lithium at temperatures up to 350 °C. This is a piloting study to investigate how important it is to provide “forced” convection for flowing liquid lithium used as a plasma-facing material so that particle recycling can be maintained reduced below 100% even at steady state. A temperature-controlled cup of lithium is exposed to steady-state H and He plasmas in the VEHICLE-1 plasma device. Visible spectroscopy measurements have been conducted for LiI, H₂, HeI. Measurement in addition is OI from oxygen injected into the host plasma as a hypothetical impurity in a magnetic fusion device. Data indicate that liquid stirring clearly reactivates hydrogen absorption, i.e. reduced recycling, via surface de-saturation and/or uncovering oxygen-containing impurity films such as LiOH, but can also induce helium desorption, i.e. reduced recycling, via surface temperature change to affect gas solubility.

A.B. Martín-Rojo (Ciemat, Spain) described the experiments performed at the laboratory on absorption–desorption of molecular H₂ and D₂ in lithium at several temperatures, ranging up to 500 °C. Two different kinetics were observed during the trapping of gas into the liquid lithium, ascribed to the formation of a soluble phase followed by the hydride formation. These phases exhibit different activation energies in the range of a fraction of eV. By thermal desorption spectroscopy (TDS) cycles, it was found that a characteristic maximum in the pressure of H₂ appears at T ≈ 450 °C, but total particle balance indicates that the desorbed amount at these temperatures accounts only for a few % of the total absorbed gas. Isotopic exchange experiments on the samples evidenced a very weak (if any) isotope effect. Preliminary experiments on plasma exposure (dc glow) and LiH thermal decomposition, showing TDS peaks at T well below the nominal melting temperature (690 °C), were also shown.

To properly implement flowing liquid lithium divertor concepts, it will be important to understand the wetting properties of lithium on the constituent materials of the divertor concept, and of particular interest to TEMHD-driven concepts, the thermopower of lithium on those self-same materials is also of importance. P. Fiflis (University of Illinois, USA) described the experiments performed on the wetting characteristics of liquid lithium droplets with various surfaces, as well as methods to decrease the contact angle of lithium with a given surface. The contact angle, as well as its dependence on temperature was measured. For example, at 200 °C, tungsten registers a contact angle of 130 °C, whereas above its wetting temperature of 350 °C, the contact angle is less than 80 °C. Glow discharge cleaning of the target surface and evaporation of a thin layer of liquid lithium onto the surface prior to performing wetting measurements were both found to decrease the wetting temperature, the effect being more drastic in the case of lithium vapour pre-exposure. Moreover, thermo-powers were measured relative to stainless steel for different liquid metals and substrates. For lithium, a distinct increase in the Seebeck coefficient around the melting temperature was found. TZM and Mo were found the best possible materials in terms of wetting and thermo-power if liquid lithium is to be used as a reactor material.

Session IV: special liquid lithium technology session. In this session most of the contributions were focused on the IFMIF/EVEDA project (International Fusion Material Irradiation Facility/Engineering Validation and Engineering
Design Activity) and on some technology aspects related to the use of the Li or Li alloy. The International Fusion Materials Irradiation Facility (IFMIF) is the most promising machine designed for testing structural materials to be used for the design, construction, licensing and safer operation of the future fusion nuclear power reactor.

The first talk was given by E. Wakai (JAERI, Japan) about the present status and recent evaluation of Li target facility development in the IFMIF/EVEDA project. He also presented an overview of the status of the entire project IFMIF. The Li target is one of the most important element of IFMIF and an EVEDA Li Test Loop (ELTL) has been constructed to test the characteristic of a circuit in which Li flows at 3000 l min$^{-1}$ under pressure/vacuum conditions. Studies and experimental results have been presented for erosion/corrosion and Li purification system. Special attention has been paid to the issues related to remote handling and to Li safety. In particular, after many tests, Natrex-L was selected as optimal fire extinguishing material for the ELTL and, in the future, for IFMIF.

The European target assembly was designed to simplify the maintenance operation and to reduce the material for disposal. It is based on the bayonet concept design whose peculiarities are to be provided with a removable backplate, to be connected with the Li loop and the duct beam by means of fast disconnecting system. P. Favuzza (ENEA, Italy) reported about the results obtained on the qualification tests of the sealing system of the IFMIF European target assembly concept. The gasket to be used has to ensure the vacuum gradient between the target chamber and the test cell and to seal the edge of the pipe to pipe connections in contact with Li. The selected metallic gasket has been positively tested up to 5500 h at an operating temperature of 350°C and it was exposed about 7000 h to Li.

Wangyu Hu (University of Hunan, China) presented a work on the thermodynamic properties of Li, Pb and Li–Pb alloys that have been proposed as materials for the test blanket module. Due to the high reactivity of Li–Pb alloys with the container materials, air and water, very few studies have been performed on the thermodynamic properties such as enthalpy, isobaric capacity, surface tension and latent heat of fusion. The conclusion is that the thermodynamic properties as investigated in this work are in reasonable agreement with the published data. Moreover, the diffusion coefficient of Li atoms in Li17Pb83 is much smaller than the ones in pure Li.

Lithium is the tritium breeder for a future reactor and its compatibility with the structural materials is under investigation. Xuegui Sun (University of Hunan, China) illustrated the chemical properties of the Fe–Li solid–liquid interface system. A theoretical model has been developed with a strong emphasis on the characterization of the interface region whose width increases with the temperature of the Li liquid.

The applications of liquid lithium require knowledge about the properties of solid–liquid interfaces between liquid lithium and substrates. Xuegui Sun (University of Hunan, China), in his talk, examined the equilibrium interface between solid Cu and liquid Li at a temperature just above the melting point of lithium (470 K) using a modified analytic embedded atom model (MAEAM) and molecular dynamics simulations. There is a considerable anisotropy in the structural properties of three different Cu–Li interfaces and a ‘prefreezing’ layer of crystalline Li is observed to form at the (1 1 1) Cu interface.

A. Shishko (Latvia University, Latvia) described the experiments performed to address the difficulties of creating a thin lithium film on the stainless steel substrate. An experimental setup was realized in which the liquid lithium flows over an inclined heated test plate and it is collected at the bottom in a box. Then the lithium is pumped to the nozzles placed at the top of the plate so that a circulating lithium loop is realized. If the stainless steel surface is clean and the vacuum in the chamber is better than 5×10$^{-5}$ Pa, good enough wettability is achieved at a minimum surface temperature around 350°C. Theoretical evaluations have been presented for a divertor module made by a cooled copper plate coated with a stainless steel layer in which flows a thin layer of lithium that it can withstand heat load equal or greater than 10 MW m$^{-2}$.

Session V: liquid metal laboratory tests. In the session, five reports on liquid metal laboratory tests are given and the results were presented for different liquid metals. Up to now most of the experiments are focused on Li but other liquid metals could be used. Ga or Sn could in principle withstand greater heat loads and higher surface temperature before evaporation becomes very big. Furthermore, hydrogen retention should be quite low but quantitative experimental data are missing.

I.E. Lyublinski (JSC ‘Red Star’, RF) gave a comparative assessment about low melting metal application with capillary–pore systems in a tokamak. An estimation of opportunity of liquid Li, Ga and Sn application is carried out on the basis of its physics, chemical and technological properties, and with respect to prospective design of the tokamak in-vessel components. The basic criterion is on the reliable wetting of CPS materials, the value of capillary pressure determining stability of liquid metal film, corrosion activity, vapour pressure of liquid metal, interaction with plasma, possible accumulation and technology of extraction. He draws out that the Li is the most preferable liquid metal for use in PFC with CPS. And despite of advantage in boiling temperature, Ga and Sn appear unacceptable due to its high corrosion activity. He also points out that the developed technologies of liquid metal removal from the tokamak and the good compatibility of Li with tokamak plasma improved the attractiveness of Li as plasma-facing material.

T.W. Morgan (FOM, Netherlands) introduced the initial experimental results of power handling of a Sn-based surface in high flux linear plasma in Pilot-PSI linear device while a Sn-filled mesh was exposed to high Ar or H$_2$ plasma. While a vapour cloud is predicted for shielding of plasma-facing surface, he wants to resolve the vapour shield could be also efficient in improving divertor performance and understanding the dynamics of the region of plasma close to the liquid surface and the interaction between the two. Sn-based surface temperature could increase to 2000°C both with and without bias. He demonstrated the erosion yields has temperature-dependent sputtering effect for both Ar and H$_2$ plasmas and the vapour shielding does indeed take place in high-flux conditions despite Sn’s low vapour pressure and small high temperature region. Planned experiment in Magnum-PSI device using
Sn and Li to study the plasma-liquid metal interaction were illustrated.

O. Lielausis (Latvia University, Latvia) gave a talk about MHD experiments on LM jets passing over curved substrates. Promising results on ISTTOK have been obtained to eliminate the intensity of MHD interaction to fast moving jet or droplet screens. In a superconducting solenoid, liquid GaSn jet was tested on various substrates, wetted or non-wetted substrates, at a velocity of 0.36–0.8 m s\(^{-1}\) without/with magnetic field. The experiments showed that in up to 4 T field, the jets remained stable and well organized over full length (~200 mm) of their path on a non-wetted wall (non-prepared SS wall). However, on a wetted wall (4 mm Cu covered on SS substrate), the jets were tending to merge and to form a film flow. Those possibly give reference for the design a stable LLL/divertor to avoid strong MHD behaviour.

D.N. Ruzic (University of Illinois, USA) described the development of a high energy pulsed plasma simulator for lithium PFCs. A pulsed plasma source utilizing a theta pinch in conjunction with a coaxial plasma accelerator has been developed. Using the thermoelectric-driven liquid metal plasma-facing structure (TELS) device, the divertor erosion and vapour shielding experiment has undergone with application of the accelerator as a pre-ionization source, which has a peak energy flux of 0.04 MJ m\(^{-2}\) and a plasma velocity of approximately 20 km s\(^{-1}\). He also informs that a new test bench for TELS is also planned to test lithium trench test in pulsed plasma with energy flux larger than 0.2 MJ m\(^{-2}\).

Session VI: lithium theory/modelling/comments. This session was dedicated to theory that plays an important role to understand the observed phenomenology as well as the modelling for extrapolation to DEMO.

A. Sternlieb (Ariel University, Israel) gave a talk that outlined the advantages of lithium wall fusion research, underlining the opportunities of engineering and scientific breakthroughs that may result from it. The main idea is to reduce energy losses to walls, instead of increasing the input power, which is much more expensive and also more damaging for the plasma stability. The clear result is that fusion becomes both feasible from a scientific point of view and affordable from an economic point of view, because of the resulting compactness of the device when lithium walls are used. He expressed the opinion that ITER should reconsider its priorities and ARIES study should be carried out considering Li wall.

L. Benos (University of Thessaloniki, Greece) presented a theoretical model to explain the results obtained from experiments for a liquid Ga loop mounted on ISTTOK tokamak and for a free surface jet at Latvia University. In the presence of plasma, the Ga jet is destabilized forming drops and it is deflected: this behaviour has been explained taking into account the effect of external electric potential gradients and magnetic field. The deviation was found to be of the same order of magnitude for both drop and jet. This observed deflection increases as the magnetic field intensity increases. When plasma is absent, no deviation is predicted by the model, as experimentally observed.

MHD modelling for liquid metal film flow was the argument of the talk by Ming-Ju Ni (University of Chinese Academy of Sciences, China). An algorithm for multi-fluid MHD flow has been designed, which can accurately calculate the Lorentz force, surface tension with Marangoni effect. MHD solver has been developed for simulation of multi-fluid MHD flows. Multi-fluid MHD application, to simulate droplet splash on a film flow, has been illustrated. Finally, an analytical solution with the Seebeck effect has been illustrated as a demonstration of its effectiveness on driving liquid lithium flows.

The slow flowing liquid lithium (SFLiLi) systems presented in the talk by L. Zakharov (PPPL, USA) represent the technology tool for implementation of the guiding idea of magnetic fusion. It utilizes the unique properties of flowing LiLi to pump plasma particles and, thus, to insulate plasma from the walls. The necessary flow rate, ~1 g s\(^{-1}\), is very small, making thus the use of lithium practical and consistent with safety requirements. The talk has described how the chemical activity of LiLi is addressed by SFLiLi systems at the level of already performed (HT-7) or ongoing implementations for a prototype of SFLiLi for tokamak divertors and THEMID-plane limiter for EAST tokamak, which is intended to be tested next year.

O. Lielausis (Latvia University, Latvia) illustrated a new, already realized and tested, MHD lithium semi-levitation system, called as ‘in-and-out honeycomb’, which is designed for high radiation heat flux removal in the first wall and diverter area of a fusion reactor. The system is based on a two new principles: (1) the progressive increasing of retention Lorentz forces at free surface, and (2) the decreasing of the flow dimension (distance between the flow inlet-outlet), as much as technically possible, in order to diminish the linear scale of free surface instability. The magnetic field of fusion reactor is used to generate the retention magnetic field. The free surface, which absorbs the radiation flux from plasma, is stable upon different orientations. Experiments using different liquid metals are in progress.

Session VII: innovative lithium applications. In this session innovative methods to inject lithium into plasma or to use liquid lithium as PFCs were presented.

The first talk of this session was given by I. Ljublinski (JSC ‘Red Star’, RF) about the tests performed on the capillary porous system module prepared for the Kazakhstan tokamak KTM. This module will replace a graphite tile of divertor module and will be connected with module’s external components through the pipelines. The module will be actively cooled with an eutectic liquid. The tests with Na–K coolant confirmed the efficiency of all the elements and subsystems of the thermo-stabilization system. The system operation was reliable during the whole test cycle over the temperature range 20–200 °C. Currently, an uncooled module that will be used only during the KTM starting phase with ohmic plasma has been installed and checked on the machine.

D. Mansfield (PPPL, USA) presented an apparatus that accomplishes the repetitive injection of small (0.1–1 mm diameter) commercially available spherical Li granules into fusion research devises. Injection speeds approaching 100 m s\(^{-1}\) and repetition rates approaching 1000 granule s\(^{-1}\)—for granule sizes less than 0.8 mm—have been achieved in laboratory tests. The injector employs three sections: (1) a dropper section—previously described in literature—which
uses a resonating piezoelectric disc with a central aperture to drop granules in a controllable manner; (2) a 44 cm long tube with 4 mm inside diameter to guide the falling granules and (3) a two-blade horizontally spinning plastic impeller. The guide tube is used to deliver the falling granules to within 2 mm of the top of the impeller blades. As granules fall into the impact column directly below the guide tube they are struck by the next arriving impeller blade and mechanically redirected horizontally at higher speed. The apparatus has been used on RFX to attempt Li conditioning and on EAST to trigger ELMs. The experimental results were described in other presentations at this symposium.

A.L. Roquemore (PPPL, USA) illustrated a liquid lithium device developed to produce spherical pellets of lithium that could aid in the controlled excitation or pacing of edge-localized plasma modes (ELMs) and replenishing lithium coatings of PFCs during a plasma discharge.

It uses a 'dripper' design, where the liquid lithium is forced through a small orifice. Sub-millimetre pellets of liquid lithium could be dropped so that vaporization at the plasma edge will redistribute and deposit the lithium to recoat the PFCs during the discharge. Tests were performed at University of Illinois using high-pressure argon to force the liquid lithium through the nozzle to form lithium pellets with the dripper. Frequencies up to 1.2 kHz for lithium and pellet diameter $d_{\text{drop}}$ between 0.6 and 2 mm have been measured.

Starting from the lithium/metal infused trench (LiMIT) concept developed at the University of Illinois, D. Curreli (University of Illinois, USA) presented an improved flowing lithium system with active control of the temperature gradient inside the lithium trenches and back flow channels. With this improved design a better control of liquid lithium flow was achieved. A detailed characterization of the TEMHD driven open trench flow in weak magnetic fields (0.01–0.19 T) has been performed using a fast camera. A similar design with different trench sizes will be tested in Magnum-PSI to demonstrate its feasibility for implementation in fusion reactors serving as the divertor target plate.

A.L. Roquemore (PPPL, USA) gave a talk on a new upward, facing lithium evaporator (U-LITER) system, developed for NSTX-U with the goal of coating the upper divertor with a fresh coating of Li between plasma discharges. The new evaporator is based on a commercial e-beam gun and should be capable of applying $\sim 200$ mg of Li to the region of the upper divertor in a few seconds as compared with the 10 min evaporation period required for the present LITER. A Helmholtz coil is required to bend the beam into a crucible holding the Li inventory.

VIII. Special session: lithium-safety and lithium handling. This session, requested and organized by Richard Nygren (Sanda National Laboratories, USA), included two groups of panel discussions with the objectives of (a) promoting awareness of issues related to lithium (Li) safety, (b) sharing information on Li safety and handling and (c) identifying a continuing process through which researchers could exchange, archive and access useful information. The session began with a brief overview and then presentations by Nygren and by Dr Eichi Wakai, Leader of the IFMIF Irradiation and Test Facilities Development Group at the Japan Atomic Energy Agency (JAEA).

In his overview Nygren noted that the rules and practices at the various institutions with researchers who handle Li differ and that this group can collectively assist itself by exchanging information and discuss processes, for example to achieve a compilation of ‘best practices.’ Also, since experimental facilities where Li is handled do have the potential for fires, the community of users need to understand and clarify to others which safety hazards are specific to Li and which are more general, e.g. for dust, thin films, aerosols, etc.

The overview also briefly summarized several US activities that involve handling of Li handling. R&D with Li free surfaces (open to vacuum) at the Princeton Plasma Physics Laboratory (PPPL) include the following activities and the asterisks (*) denote papers presented at ISLA2013: a modular system for EAST/HT-7 (*Zakharov); injection of liquid Li into CDX-U: stirring of Li in LTX with an electron beam (*Majeski); evaluation of NSTX-U options for a Li surface replenished from a reservoir; and a circulating Li loop in a lab using a clever electromagnetic pump (*Jaworski). Activities at the University of Illinois include a modular system for EAST/HT-7 (*Ruzic and Curreli); an experiment, LIMITs, that combines electromagnetic and thermoelectric drive of Li flow (*Ruzic and Curreli); and experiments on wetting and plasma shielding by Li vapour. The experimental work above is directed at plasma-facing surfaces. The fusion activity at the University of California, Los Angeles, has experiments on fusion blanket technology that include a Pb–Li loop.

Two presentations focused on the use of Li in lab settings. Nygren summarized experience based on a Li fire that occurred at Sandia in 2011 and lessons learned. Wakai presented an overview of the large facility that has been constructed for the development of the flowing Li target for IFMIF/EVEDA.

Nygren summarized the Li fire at Sandia and emphasized several aspects of Li safety. The previously operated Li loop (LIMITs) at Sandia had a maximum capacity of $70$ or $\sim 33$ kg of Li. In particular he noted that the specific combination of failures that led to the fire was unexpected and improbable; however, the result had high impact and the possibility for serious injury. The deflagration ruptured a perimeter weld on the large port for one of the electron beam lines and the fireball was in an area where the staff had been present just before the event. As equipment was being prepared for operation of the Li loop, failure in a ferritic steel cartridge that was to be used to preheat the lithium stream occurred within seconds after Li flowed into the cartridge. Li streamed roughly a metre from fine cracks in the cartridge into the beam line and attacked a water–propylene–glycol-cooled insulator that failed. The safety analysis for this system considered a breach of the vacuum vessel due to general overpressure (mitigated by a burst disc and ducting), but not the type of rapid shock that evidently broke the weld on the large port flange. Nygren made the point that safety is a design requirement but very often treated as an ‘add on.’ He further commented on approaches researchers might use in evaluating their labs. Nygren also noted the issue of liquid metal embrittlement of ferritic steels, related to the rapid failure of the 1018 lithium cartridge, and the difficulty researchers may have in interpreting the literature since ferritic steel is recommended and used in many applications for the containment of molten lithium.
Wakai presented an overview of the ELTL, which has three Li loops, the main loop that directs flow to the nozzle for IFMIF plus loops for purification and impurity monitoring. The Japanese installation, the EVEDA lithium test loop or ELTL at JAEA’s O-arai site, has an inventory of 2500 kg and is by far the largest lithium facility in use in the fusion programme. In designing the facility, the Japanese drew upon experience from their development of liquid metal fast breeder reactors that use sodium as a coolant. The extensive research and evaluation for safety at the ELTL included development of contact-type electrical sensors along the piping to detect leaks and evaluations of appropriate fire extinguishers. They concluded that extinguishers with sodium chloride performed best rather than the dry systems with sand and perlite. Also, the concrete floor of the lab is covered with a steel liner to prevent Li-concrete fires as well as to provide a reservoir to control the spread of any leaked lithium and any combustion.

‘Li handling in labs’ was the first of the two-panel discussion. The invited panel members were Eichi Wakai (JAEA-IJMIF-EVEDA), Leonid Zakharov (PPPL), Ming-Ju Ni (CAS U. Beijing), Igor Lyublinski (Red Star—Éfremov). Also invited but not able to attend was Thomas Lin (Applied Research Lab, Pennsylvania State University). Prompting some discussion was the thought problem of how one would construct a lab in which a hot lithium loop could continue to operate for several days, e.g. could this be left unmanned and what would be necessary to achieve safe shutdown for conditions such as a power failure. Among the items discussed were cleaning techniques for lithium-contaminated vessels and tools. PPPL uses vinegar for some cleaning and the waste is a neutral solution whereas Sandia cleans much of its equipment in a cordoned-off area with a large water drum. Vapours go into the atmosphere but the resulting waste is highly basic (pH 14) and requires special handling for disposal.

‘Li in fusion experiments’ was the second panel discussion. The invited panel members were Giuseppe Mazzitelli (ENEA Frascati), Masa Ono (PPPL), Jianzheng Hu and J.G. Li (IPP-CAS Hefei), Francisco Tabares (CIEMAT) and Alexander Vertkov (Red Star). Tazhibayeva (NTSC Kazakhstan) was also invited but did attend ISLA2013. The amounts of Li in confinement devices with Li experiments vary. The capillary systems such as the lithium limiter deployed in the Frascati Tokamak use a relatively small amount of lithium in a contained volume. NSTX uses an evaporative system (LITER) to coat the lower portion of the device. CDXU and LTX, both also at PPPL, introduce Li in heated trays. The US systems being supplied for use in HT7 and EAST are modular with Li reservoirs. A critical issue for the use of Li in vacuum vessels is avoiding the explosive limit. This has been one of the criteria limiting the amount of Li permitted in NSTX, CDXU and LTX. Zakharov explained this limit in a brief presentation.

The concluding discussion focused on future actions. The group present affirmed that a working group to formulate a process for exchanging information on Li handling and promoting awareness and good practices in regard to Li safety would be beneficial. Nygren accepted the responsibility to form such a group and to steward the activity in the near term. Conference Chair Mazzitelli requested that a report on progress be included at the 4th ISLA in Madrid in 2015.

3. Conclusions

In the last session, each chairman summarized the principal findings of his session and gave some general remarks or hints on future liquid metal activities.

1. How much erosion there is and where does it migrate to?
2. How much eroded material reaches the core plasma and how much of it could be tolerated?
3. What is the optimal operating temperature range of the liquid metal, and is it compatible with DEMO wall temperature?
4. How do liquid metals behave under ELMs, transients and disruptions?

Up to now no integrated core-edge simulations have been performed and the vapour shield phenomenon needs to be investigated more in detail, both experimentally as well as theoretically.

Furthermore, reactor applications of solid/liquid lithium PFCs need to be discussed more seriously. Reactor studies with liquid metals as plasma facing components are necessary for consistency check:

a. coolant-related safety, if water is used;
b. initial installation of large amounts of liquid lithium,
c. maintenance opening and re-use of ‘frozen lithium’
d. continuous flow prevents clogging and oxidation but will require purification

Finally, the success of this workshop, in terms of both presented papers and attendance, confirms the growing interest in the fusion community on liquid metal as possible solution for power exhaust. Therefore, this international workshop will continue on a biennial basis (alternating with the Plasma-Surface Interactions (PSI) Conference) with the following past and future schedule:

1. 1st workshop was held at NIFS, Toki, Japan, in 2010;
2. 2nd workshop was held at PPPL, Princeton, USA, in 2011;
3. 3rd workshop was held at ENEA, Frascati, Italy, in 2013;
4. 4th workshop to be held at NIF, Madrid, Spain, in 2015;
5. 5th workshop to be held at TRINITI, Moscow, Russia, in 2017.

References

[1] Hirooka Y. et al 2010 Nucl. Fusion 50 077001
[2] Ono M. et al 2012 Nucl. Fusion 53 037001
[3] Zohm H. et al 2013 Nucl. Fusion 53 073019