REACTOR DIVERTOR DESIGNS BASED ON LIQUID METAL CONCEPTS

FL Tabares, E. Oyarzabal, A.B. Martin-Rojo, D. Tafalla, A de Castro and A. Soleto

This is an author-created un-copyedited version of an article accepted for publication/published in Nuclear Fusion.
IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at `http://iopscience.iop.org/article/10.1088/0029-5515/57/1/016029/meta`

Reactor Plasma Facing Component designs based on Liquid Metal Concepts Supported In Porous Systems

F. L. Tabarés[1*], E. Oyarzabal, A.B. Martin-Rojo, D. Tafalla, A de Castro and A. Soleto
[1] National Institute for Fusion, As EURATOM/CIEMAT, Av. Complutense 22, 28040 Madrid, Spain
*email: tabares@ciemat.es

Abstract

The use of liquid metals (LMs) as plasma facing components in fusion devices was proposed as early as 1970 for a field reversed concept and inertial fusion reactors. The idea was extensively developed during the APEX Project, at the turn of the century, and it is the subject at present of the biennial International Symposium on Lithium Applications (ISLA), whose fourth meeting took place in Granada, Spain at the end of September2015. While liquid metal flowing concepts were specially addressed in USA research projects, the idea of embedding the metal in a Capillary Porous System (CPS) was put forwards by Russian teams in the 90's, thus opening the possibility of static concepts. Since then, many ideas and accompanying experimental tests in fusion devices and laboratories have been produced, involving a large fraction of countries within the International Fusion Community. Within the EUROFusion Road map, these activities are encompassed into the Working Programs of the Plasma Facing Components (PFC) and Divertor Tokamak Test (DTT) packages.

In this paper, a review of the state of the art in concepts based on the CPS set-up for a fusion reactor divertor target, aimed at preventing the ejection of the liquid metal by electro-magnetic (EM) forces generated under plasma operation, is described and required R+D activities on the topic, including ongoing work at CIEMAT specifically oriented to filling the remaining gaps, are stressed.

Key words: Fusion Reactor, Liquid Metals, Divertors, CPS.

1. Introduction.

Developing a reactor-compatible divertor is a particularly challenging physics and technology problem for magnetic confinement fusion [1]. While tungsten has been identified as the most attractive solid divertor material, many challenges including surface cracking and deleterious modification of the surfaces by the plasma must be overcome to develop robust plasma-facing components (PFCs) [2,3]. In recent DEMO divertor design studies [4–6], the steady-state heat handling capability of a tungsten based divertor design is only about 5–10 MWm^{-2}. This value can only be realized if massive radiation (larger than a 95% of the power reaching the target plates) is induced by impurity seeding, with unknown impact on global plasma performance, and it is nearly an order of magnitude lower than the anticipated heat flux ~40–60 MWm^{-2} foreseen in the absence of detachment [7]. In addition, there are serious concerns over potential deterioration and damage to the plasma-facing surfaces by very high heat fluxes accompanying edge localized mode (ELMs) and other transient events. Clearly it is highly desirable to formulate a DEMO-relevant divertor concept, which can handle the high steady-state divertor heat flux and also survive transient events.

Liquid metals (LM) offer unique properties as plasma facing materials for a fusion reactor. They are practically free from permanent damage by neutron and plasma irradiation and can be re-circulated and regenerated during their lifetime, so that could resolve particle and heat exhaust issues. These properties have motivated intense research activity, with a variety of concepts, elements and proposals for practical implementation in a future fusion reactor [8-10]. However, many aspects still remain unresolved and integration of these proposals into a realistic scenario may be challenging.

Although lithium is by far the best-known liquid metal applied to fusion device and has produced outstanding improvements in confinement, concerns about tritium retention and elevated vapor pressure still exist. Tin has emerged as a feasible alternative due to the lack of these issues, but its high Z poses concerns about plasma contamination. The confinement of liquid metals in a porous mesh has been put forward to prevent splashing of the liquid under electro-magnetic forces [11], but wetting of the mesh by metal is not a trivial issue and efforts to develop the best combination taking into account corrosion aspects are still ongoing. The choice of first wall material in a liquid metal PFC scenario has to be made considering recovery of evaporated metal as well as interaction between ionized LM species and the wall material in terms of sputtering and fuel retention, among other issues.

In this contribution, a review of ongoing activities worldwide on the CPS-LM concept is undertaken. Different options in terms of liquid metal choice (Li, Sn. Ga, LiSn alloys, etc…); power handling capabilities, retention of H isotopes, erosion, plasma contamination and system integration issues are addressed. Although these topics are rather common for all concepts based on liquid metals, specific issues of free flowing

proposals are not discussed here and excellent reviews on the state of the art of this approach can be found elsewhere [12]. A particular emphasis is given to activities performed at Ciemat facilities, including exposure of liquid metals and alloys to TJ-II stellarator plasmas through CPS Liquid Lithium Limiters [13] and liquid metal probes and experiments at the laboratory devoted to the recovery and integration aspects, including present tests on the effect that the structure of the chosen porous matrix has on evaporation and hydrogen retention.

The structure of the paper is as follows: In chapter 2 a review of different concepts based on the use of liquid metals in fusion devices worldwide is presented. Then in chapter 3, a description of the basic physical and chemical processes governing some critical issues as fuel retention and material erosion and transport is given. Finally, in chapter 4, some aspects of component integration and remaining issues for the design of a LM-based alternative reactor divertor are analyzed.

2. Review of LM based proposals for Fusion Applications.

Under the term "Liquid Metals for Fusion Applications", one will find many different concepts in the literature. This topic is periodically reviewed since 2010 in the devoted biennial Symposia, whose last meeting corresponded to the ISLA-4 held in Granada, Spain, Sept 2015. A summary of worldwide activities and their evolution in the last five years can be found in refs 8-10, corresponding to the conference reports of the three first symposia. A more detailed description of the works presented to the ISLA meetings can be found in the associated issues of Fus. Eng. Design. In addition to this, the reader is also referred to devoted reviews presented in other, less specific conferences [14,15]. There are two main approaches, leading to a variety of different proposals, for the implementation of LM-based solutions to the existing fusion reactor operation issues. The first one, moving the plasma facing liquid within the reactor vessel, takes full advantage of the LM concept. If lithium is used, its large trapping efficiency for H isotopes makes it a perfect element for particle exhaust at the divertor. Furthermore, the large heat capacity and latent heat of vaporization of this low Z element, represents a clear advantage when dealing with fast removal of the power impinging on the divertor while keeping a low level of plasma contamination. A recirculating loop provides the required control of tritium content and impurities in the liquid metal [12]. Still within the flowing LM concept, Ruzic and coworkers at the University of Illinois at Urbana-Champaign, Illinois, developed the so-called LiMIT (Liquid Metal Infused Trenches) concept [16]. The proposal takes advantage of the thermoelectric currents developed between the flowing lithium and the container (stainless steel) by the presence of a strong temperature gradient. The presence of an external magnetic field and the associated JxB forces drive the flow of the liquid metal along an arrangement of narrow trenches thus providing the required continuous replenishment of the PF surface. Other proposals involving the use of circulating

lithium in guide type structures can be found in [8-10].

Lithium is not the only LM proposed for free flowing divertor concepts in Fusion. A free falling liquid gallium curtain was tested on the T-3M [17] and ISTTOK [18] tokamaks. Even when fluid discontinuity in liquid curtain should preclude any kind of JxB force in the presence of an external magnetic field with a given orientation, it was found in ISTTOK that the strong gradients in plasma parameters at the edge can induce charge asymmetries on the individual drops and hence, act on their trajectory across the plasma [18].

An alternative option to the liquid flowing concept, the capillary porous system (CPS) [11], was proposed by Russian teams in the 90's. It is based on the strong capillary forces arising when a LM is embedded in a microstructure due to the high surface tension characterizing these materials, providing good wetting to the metallic structure. Pore sizes in the range of tens of microns can develop capillary pressures of the order of one atmosphere, which is sufficient to prevent liquid splashing in the presence of magnetohydro- dynamic (MHD) induced forces under operation of fusion devices even during transient events like disruptions. Technical issues like wetting conditions and possible chemical interactions (corrosion) must be considered when selecting the LM-porous mesh combination. Having high surface tension, wetting of liquid metals to solids may be challenging sometimes. It has been observed that preheating of the LM-mesh system is often required to drive the liquid metal through the mesh structure. The chemical state of the surface is crucial in achieving full wetting condition, since oxides and other compounds may drastically change the adhesion forces. Temperatures above 300ºC are typically required for good wetting [19], while oxide-free surfaces are mandatory for tin [20]. To date, a reasonable knowledge of these items exists at least for the main candidates: lithium, tin and gallium as LMs and W, Mo and SS as supports. Table I shows some relevant parameters of LMs for the CPS design.

The strong resistance that micro-porous systems offer to the movement of liquid metal within them makes CPS-based flowing concepts for heat and particle exhaust impossible. Therefore, the CPS structure is coupled to a more conventional, actively cooled target or heat is removed by the latent heat of vaporization of LM or by the associated radiation in the divertor plasma, very much the same as for impurity seeded radiative cooling in present solid state target designs. Among the LM options, lithium is the element with the highest vapor pressure and hence the most suitable for evaporative cooling heat exhaust concepts. Figure 1 shows the vapor pressure – temperature diagram for the three LM candidates addressed here. However, if evaporation takes place from the LM target facing a dense plasma, as it is the case for most proposals, one has to keep in mind that prompt redeposition of the evaporated lithium by fast ionization in the SOL and backflow to the target makes vaporization mostly inefficient as a heat removal option. Several years ago, Nagayama [21] proposed a system inspired in the heat pipe concept [22] combining porous structures and in situ evaporation of

lithium, but in separate volumes decoupled from the main plasma. Even with the high latent heat of vaporization of 147 kJ/mole, evaporation rates of the order of tens of liters per second are foreseen under conservative fusion reactor heat exhaust requirements [21].

Compared to evaporation, lithium radiation can become an excellent candidate for energy dissipation when introduced in a plasma. However, due to its very low atomic number, very low radiation in a plasma is to be expected compared with high Z alternatives. The fact that Li does not reach the condition of coronal equilibrium due to its low residence time in the plasma makes non-coronal radiation highly effective for areas near the target (low Te). Compared to a vaporization-cooling rate of 147 kJ/mole, values from 20 to 100 MJ/mole could be achieved by plasma radiation under lithium contamination [23].

This fact has motivated many proposals involving the presence of static lithium trapped in a CPS structure. Thus, for example, Mirnov and coworkers put forward the concept of double CPS limiter based on their experience in the T-10 and T11-M tokamaks. The idea is to capture the lithium escaping from a first, main CPS limiter into a second one, recessed with respect to the first, and then revert the role of limiters in an emitter-receiver scheme. It relies on the high efficiency of capturing lithium flowing along the flux tube by nearby structures observed in their devices [24]. Furthermore, Ono et al proposed the Radiative Liquid Lithium Divertor (RLLD) [23] and its active version (ARLLD) [25] on which the strike point is taken to the bottom of a devoted lithium-filled chamber, so that strong non-coronal lithium radiation drastically mitigates the thermal load to the target. The inner wall of the special chamber is also coated with slowly flowing lithium to provide particle exhaust capabilities and protection against the localized strong radiation. In its active version [25], a second injector close to the entrance to the divertor chamber works as an active feedback controlled lithium source, for enhancing the spreading of the localized radiation and guaranteeing that lithium undergoes a large number of ionization events in the devoted chamber. Compared to the huge amount of lithium to be mobilized in evaporation cooling-based schemes, few moles of liquid lithium per second are needed in the RLLD concepts.

Common to all these concepts, however, is the fact that the low electronic temperatures characteristic of detached plasmas would significantly decrease the radiating capabilities of lithium thus requiring the injection of much higher fluxes. The required amount of lithium could become unacceptable from the plasma dilution point of view. This fact has triggered the recent proposal by Goldston et al. [26] of using a set of differentially pumped (by wall condensation) chambers of decreasing temperature towards the end facing the plasma side, which could provide the required volume losses of power and momentum with very moderate lithium influxes to the divertor plasma.

In more conservative grounds, the combination of CPS structures with conventional cooling schemes is also a matter of active research. The power handling capabilities of

CPS structures have been proven very high, especially under transients. As an example, figure 2 shows a micrograph of 50 micron pore Mo mesh exposed to type I ELMs heat loads in the QSPA device [11 and ref therein]. While melting of the unfilled mesh is readily seen at the first shot, as expected, no apparent effect on its structure is observed in the lithium filled case after 22 plasma shots. A 10-15 mm protecting layer of lithium vapor seems to be developed under ELM and disruption-type transient loads, leading to a >10x reduction of the power reaching the plate, as reported in T11 experiments [11]. Although these are certainly very encouraging results, the power handling characteristics of CPS structures under lower but quasi-continuous heat loads still needs benchmarking. This is the case for the FTU activity on actively cooled CPS structures [27]. A feed back temperature controlled water circuit is used to extract the heat from a W mesh-based CPS system with liquid lithium aimed at impinging powers up to 10 MWm^{-2}, while a new design using tin as LM will use vaporized water as cooling fluid [28]. A Na-K eutectic alloy will be used in the KTM tokamak for cooling purposes, thus combining different liquid metals for the PFC and the back cooling system of the target in this PWI-devoted divertor tokamak being built at Kazakhstan [29].

3. Basic physiochemical processes in liquid metals exposed to a plasma.

Compared to solid materials as PFCs, LMs are physical systems far less investigated in the fusion community. Among the different elements with potential use in a divertor target, lithium is doubtless the best characterized one. Incidentally, it is this element the one showing a more complex chemistry.

a) Fuel retention.

The well-known affinity of lithium with hydrogen isotopes to form stable hydrides has traditionally represented a matter of concern and a potential showstopper for the application of lithium-based concepts to the design of a fusion reactor. Paradoxically, it is this affinity that allows for low recycling operation of high performance plasmas in lithium-coated devices [30] and opens up a possible reactor design with continuous particle pumping and tritium recovery as put forward by several authors [8-10]. Under this conception, however, formation of low-soluble hydride may lead to clogging of the required liquid manifold. For systems based on capillary forces, as the CPS, precipitation of hydrides can prevent free flow of lithium to the surface, thus leading to surface overheating and eventual melting of the metallic mesh.

Formation of lithium hydrides is certainly a common observation under high pressure exposure of liquid lithium to molecular hydrogen [31] and its production in a fusion plasma would lead to an unacceptable level of in-vessel tritium retention of difficult solution, requiring temperatures near 700 ºC for its decomposition under vacuum. A very large body of literature exists on the characteristics of the Li-LiH-H system and its temperature and pressure stability limits. In the absence of hydride formation, the absorption of hydrogen by a liquid metal, M, follows the well-known Sieverts' law:

1) $P^{1/2} = k_s.c$

where P stands for the external pressure, k_s is the Sieverts' constant and c the relative atomic ratio H/M in the liquid. This law is followed up to a c value corresponding to the saturated solubility limit, c_s, depending only on temperature for a pure metal, for which a value of $P=P_{eq}$ is established by H recombination. Beyond that value, no further absorption is observed any longer as far as P is not increased. Sieverts' curves for the D/Li system are shown in figure 3 at several temperatures [32].

Conversely, if a molecular species (hydride) is formed by the interaction of H and M in the liquid phase, then absorption will continue until the stoichiometric composition of the hydride is reached. All these processes correspond to an equilibrium situation and hence, they are reversible. One critical parameter in the presence of hydride formation is the decomposition pressure, P_{dec}. For P values below that figure, the hydride will decompose until the solubility limit, c_s, is recovered. For Li/H, D and T systems the relevant parameters c_s and P_{eq} are available in the literature [31,32]. Figure 4 displays the equilibrium pressures and concentrations for D and H in Li at temperatures between 400 and 650 ºC, while a summary of these values at temperatures of interest for fusion applications of liquid Li is shown in Table II together with the corresponding Li fluxes deduced from the saturation vapor pressure of the metal. As can be seen, typical divertor pressures of ~100 Pa call for Li target temperatures ~550ºC, although experimental data from CIEMAT indicate that this temperature could be reduced by 50ºC, i.e. in the range of equivalent vapor Li fluxes of the order of 1% of those of the divertor plasma. Whether this shift is caused by different degrees of contamination of the Li samples or by other effects (see below) is still unknown. Moreover, it is also clear from the figure that much lower temperatures are required to avoid LiH formation at the FW, with ambient pressures well below 1Pa. Thus, for example, a FW temperature of 600K will be required for pressures near the FW up to 10^{-5} Torr.

Compared to gas-liquid metal systems, information on plasma or high-energy particle experiments is rather scarce. In a seminal work, Baldwin et al [33] showed that formation of a Li-LiD system took place when liquid lithium samples were exposed to deuterium plasmas at temperatures up to 400ºC and total fluences of 10^{22} D/cm^2 in PISCES-B. Both neutral and ionic species were considered to contribute to the retention. Interestingly, no retention was observed at 573 K on liquid samples exposed to molecular D_2 at 100 mPa. Furuyama et al [34] exposed solid lithium films to a 1keV deuteron beam: TDS spectra of the released D show a single peak at 560ºC, more than 100ºC lower than that obtained from LiH decomposition. Furthermore, they showed that co-deposition of carbon on the Li film raises the peak temperature of the thermal desorption spectroscopy (TDS) by 150ºC. Pisarev et al [35] used a 50 eV D beam for the irradiation of Li at 350 ºC, followed by TDS, although no quantitative analysis was shown and only information from the location of the TDS peaks was analyzed. Their results pointed to the formation of a LiD precipitate with decomposition temperatures

above 600 ºC. At this point, it is important to note that although the presence of LiH precipitates has been postulated for the explanation of the characteristics of the TDS spectra, no direct observation of such precipitates has ever been reported.

Work at Ciemat on this topic was initiated under the auspices of Euratom's Power Plant Physics and Technology (PPPT) power exhaust (PEX) program and more recently under the EUROFusion DTT and PFC working programs. Exposure of lithium at several temperatures, pressures, hydrogen isotopes and supporting structures was carried out, typically followed by TDS analysis and quartz microbalance (QMB) recordings of evaporation rates. High pressure experiments yielded results in good agreement with expectations, i.e., H is absorbed in two different phases with different activation energies, leading to the formation of LiH solved in Li when the H concentration exceeds the solubility limit [36]. Experiments with pure LiH ad LiH/Li mixtures showed lower TDS peak values for the latter. Moreover, when the mixture is cooled down under vacuum, so that the corresponding solubility limit is lower, the excess H is not converted in LiH but just outgasses from the sample. Furthermore, no evidence of isolated LiH in the form of precipitate was ever found [37]. The required temperatures for a full recovery of all the trapped H were in the range of 500-550ºC, well below the decomposition point of pure LiH at 690ºC. Experiments at pressures of about 1 Torr, corresponding to the equivalent particle flux in a reactor divertor with $\Gamma = 10^{24}$ $m^{-2}s^{-1}$, basically agree with the data presented in Table I, although values of equilibrium pressure systematically higher (hence implying lower solubility at a given pressure value) were recorded, as shown in figure 4. Since the recombination rate of H on the surface decreases with the degree of contamination [33] a cleaner surface in these experiments could be behind this observation.

An important question of how far the results from gas phase exposure can be used for predicting retention characteristics under real plasma conditions deserves some comments. The main differences in terms of particle balance between these two scenarios are: H atoms (and protons) are directly produced by the plasma so that no dissociation within the liquid metal is required and, a higher energy per particle characterizes plasma irradiation. In common, atomic recombination sets the equilibrium solubility value. While the first will affect the rate of particle uptake by the liquid metal as no activation energy is to be overcome, the second will affect the deposition profile, more internal for plasma generated species. Although these peculiarities are behind the conspicuous formation of D rich co-deposits in present fusion devices, care has to be taken when it deals with extrapolating them to liquid metal scenarios. As described above [36], there are two different energy barriers for the formation of LiH from the H_2-Li system. The first one was associated to the dissociation of H_2 into H(s)-Li solution, where H_s stands for H atoms dissolved into the liquid matrix, and the second one to the formation of a chemical bond H-Li, i.e., hydride formation. Although a clear transition between these two processes was identified at T<400ºC, one single time derivative

value was seen in the plot of H uptake vs. t at T=400ºC, corresponding to direct formation of the hydride [36]. Therefore, it can be postulated that at the high temperatures involved in a liquid lithium reactor target no significant slow down of the absorption process due to molecular dissociation is expected.

A second important difference for the behavior of H atoms in solid and liquid materials is its diffusivity. For the H/Li system, values up to 10^{-3} cm^2 s^{-1} have been recently reported [38], i.e., a factor at least 10^4 higher than for the H/Be and H/W solid systems. Such high values obviously promote fast distribution of H within the liquid phase, and hence, they preclude any kind of strong concentration gradient within it. At the end, however, two main differences between gas and plasma exposure behavior remain, sputtering of surface atoms and heating of the target in plasma-exposed liquid lithium samples. Systematic comparisons between these two scenarios are still missing and devoted work is deemed necessary to verify the assumption made here.

Possible influence of the capillary structure of the supporting element in the CPS design on the evaporation and outgassing characteristics of liquid lithium was also experimentally addressed [39]. Sintered stainless steel samples with varying porous size (5 and 20 μm) and porosity (50-80%) together with a SS mesh with porous size of 50 μm were soaked in lithium and heated under vacuum. Two main new results were obtained, First, although no significant change in H absorption and desorption characteristics was seen, full recovery of trapped H was achieved by heating the porous sample at ~500ºC without full evaporation of the lithium present in the sample. Second, evaporation of lithium showed a hysteresis behavior, most likely due to the delayed transport motivated by the porous viscosity. These results bode well for the in situ recovery of trapped plasma fuel in CPS-based designs, but more work on the parametric dependence is still needed.

Finally, full evaporation of the lithium content in a porous system was used for the assessment of the thickness of the film created at the top of the CPS structure [38]. A plateau in the evaporating flux is maintained as far as lithium is flowing through the pores in order to maintain the film integrity. Once the pore dries out, a continuous decay on the vapor flux is observed, associated with the shrinking of the film on top. In this way, film thickness of 19 and 35 mm were deduced for the sintered samples of 5 and 28 mm pore diameter, respectively.

A few reports exist on the behavior of liquid lithium surfaces at high temperature in fusion plasma devices. For CPS limiter devices, full recycling conditions at T> 400ºC and D recovery temperatures in the range of 500-550 ºC were reported by the TM-11 team [24] while no measurable retention at 400ºC and recovery temperature of 380ªC after exposure at 250 ºC has been found in TJ-II [40]. Care has to be taken, however, when these results are extrapolated to a divertor regime, as the external pressure facing the liquid Li element is to be orders of magnitude higher in divertor plasmas and a higher equilibrium concentration of H isotopes will be reached accordingly. For a

plasma pressure of 100Pa, temperatures above 550 ºC may be required for avoiding hydride formation, according to the data shown in Table II. In addition, due to the relatively high amounts of lithium used with CPS concepts and the short plasma duration followed by pumping down intervals, simple calculations indicate that the solubility limit is not usually achieved at present limiter devices.

Obviously, the surface of any material exposed to a high-density plasma is far from any kind of equilibrium state and continuous evolution of the surface structure and chemical composition has been commonly observed in dedicated experiments. In the particular case of lithium-based elements, a strong degree of erosion (evaporation and sputtering) and redeposition (95-100%) has been calculated [41] and observed [42]. No simple model has yet been developed for the assessment of the H retention under this dynamic situation. Indeed, strong redeposition will drastically decrease the amount of Li entering the plasma, thus allowing for a higher temperature operation of the PFC components.

Moreover, in a fusion reactor simultaneous bombardment of the target surfaces by D, T and He ions will take place. No results from experiments of simultaneous exposure of Li to D and He ions have been reported so far. Since helium is a more effective projectile for momentum and energy transfer than H and D on Li, leading to particle induced desorption and sputtering yields higher when compared to D and, in the absence of a plasma, D recombination is the only mechanism able to decrease the D content of Li, some contribution from particle induced desorption (or enhanced recombination) might lead to a different equilibrium state with less D content. This remains to be proven, however.

It is also worth noting that contradictory explanations for the effect that oxides on the lithium surface have on the enhanced H retention have been put forward. While a strong reduction of the recombination rate (by a factor of 100) was needed to fit the experimental results in PISCES-B [33], the NSTX team postulated a bounding effect of the Li-O leading to a strong H uptake with desorption peaks at temperatures well below that of the LiH decomposition [43]. The obvious implications that this effect has on the required baking temperature for T release under Li PFCs call for more devoted experiments.

Based on the solubility of H in tin and the absence of stable hydride formation (SnH_4 with decomposition temperature of 100ºC), very low tritium retention in this material is foreseen [44]. Devoted experiments at ISTTOK indeed have confirmed retention rates of <0.1% for liquid tin exposed to a hot D plasma followed by nuclear reaction analysis (NRA) measurements [45]. Very similar values were also recently obtained for LiSn alloys (30/70 at %) under identical conditions, in spite of their lithium content [46,47].

b) Erosion

The lifetime of a material exposed to high particle fluxes is limited by its net erosion rate, i.e., the existing balance between gross erosion, commonly given by the sputtering

rate, and local redepostion by plasma transport. For elements with low ionization potential, generation of ions with low charge state and short residence time in the plasma (precluding full thermalization) may take place at the SOL, where the powerful electric field associated with the sheath potential prevents them from entering the confined region of the plasma. Lithium sputtering by H, D and He has been extensively investigated in the past, including its dependence on D content, surface impurities and enhancement of the yield by synergistic thermal effects [48-50]. However, for the temperatures foreseen in a fusion reactor evaporation fluxes dominate erosion. This is partially due to the very specific properties of the ejected sputtering flux, composed of 2/3 of low energy ions [48]. On the other hand, in a high recycling divertor, elastic collisions with the gaseous species (atoms and molecules) have to be considered in addition to ionization effects. A relatively high cross section for elastic collisions with D atoms, molecules and ions has been deduced from quantum mechanical calculations [51]. The overall situation cannot be predicted by simple considerations and devoted modeling is required in this respect. However, according to previous simulation, a high fraction of ejected Li from the surface will be redeposited at the target within millimeters away from the strike point yielding a net erosion rate below 1% [41].

Sn sputtering has been characterized for solid and liquid samples by several authors [52]. Temperature enhanced erosion has been reported for liquid tin [18], a fact not quantitatively explained by any of the present liquid metal sputtering theories [53]. Even so, low values of Sn sputtering yield y by D and He ions were found, and the only existing concern in terms of its potential behavior in a divertor plasma is reaching the impact energies required for strong self-sputtering (y=1 for E>300eV). In spite of this, the net erosion of tin at divertor relevant fluxes is expected to be very low due to strong redeposition of the sputtered atoms [18,41].

The sputtering behavior of lithium tin alloys was extensively characterized during the APEX project [54]. An interesting picture was drawn from laboratory observation. A pure “tin-like” performance was seen in the solid state, while strong segregation of the lithium component to the surface upon melting of the alloy leads to “pure lithium” characteristics [55]. Li/Sn atomic ratios between 20/80 and 30/70 were tested in these experiments. It should be noted here that the redeposition of the sputtered species by the plasma could induce changes on the surface composition of the alloy along plasma operation. For a selective deposition of lithium for example, the threat of reaching the stoichiometry of some of the stable eutectics, leading to the formation of crystallites of high melting point, exists. Conversely, depleting the surface of lithium will eventually lead to a pure tin scenario, of higher plasma contamination potential than lithium. These issues should be experimentally addressed before validating LiSn alloys for divertor target application.

c) Radiation/ conduction

As stated above, the main goal of the present paper is to evaluate the power exhaust capabilities of divertor concepts based on the use of liquid metals for a reactor design. Removing the power delivered to the solid components of a fusion device has been traditionally made through conduction from the PFCs to a suitable cooling system, a method adopted also for ITER. Impurity seeding, on the other hand, is a useful way to effectively decrease the power reaching the divertor targets to the level imposed for the thermo-mechanical properties of the selected material. Compared to this scheme, liquid metals offer the possibility to use the target material itself as the cooling element by circulating it across the area of strong plasma-wall interaction. However, circulating a conducting fluid in the presence of the strong magnetic field required for a fusion reactor is a challenging task involving the investment of very high powers. This fact, together with splashing issues, motivate the more conventional approach of static liquid metals trapped into porous systems as alternative PFCs. Three possible mechanisms for power removal in a CPS based scenario exist: liquid metal evaporation, plasma radiation induced by the liquid metal element(s) entering the plasma and conventional heat transport to a devoted cooling circuit.

With latent heats of vaporization of 147 and 296 KJ/mol respectively, lithium and tin evaporations are highly endothermic processes. Even so, unacceptable levels of liquid metal evaporation would be required to dissipate the heat fluxes expected in a reactor divertor. Furthermore, the strong redepostion of evaporated materials foreseen under continuous plasma operation makes this potential cooling mechanism irrelevant. However, the fact that condensation of the evaporated material at the surface releases the corresponding energy on the plasma facing side of the liquid metal must be accounted for when modeling of the thermal flux through the CPS structure is needed. This is also true for the particle-refilling rate at the surface, otherwise limited by transport across the porous array. This effect could become critical in the presence of fast transients like ELMs, since the risk of surface drying leading to the destruction of the metallic mesh could be high for ELMy plasmas.

As described above, several concepts of LM-based divertors based on the radiation cooling effect of lithium and tin injected into the plasma exist. The underlying assumption is the short residence time expected for these species into the plasma boundary, which makes coronal radiation models invalid and leads to radiation power per particle values several orders of magnitude higher than for full-recycling species like noble gases. Although these concepts predict that a high fraction of the power entering the SOL will be readily distributed by radiation into an area much larger than that given by the λ_q value and the impact angle, of the order of $2m^2$ for present DEMO designs [4- 6], uncertainties about these model-based estimates still exist. Thus, an average radiation energy of 1.2 keV per Li atom was deduced by Rognlien and Rensik [56] with higher values corresponding to Sn [57]. Therefore, an influx of Li of 2.10^{23} m^{-2} s^{-1}, corresponding to a target temperature of ~600ºC, would be required to radiate 40

MW/m^2, thus reducing the power load to ~30 MW/m^2 for a DEMO-type reactor operating at maximum power leading to a power of 150 MW across the separatrix and a plasma wet are of $2m^2$ [4]. However, for detached plasmas, much lower electron temperatures should be considered in this calculation, as the contribution from Li ionization will be negligible [26]. Thus, for lithium elements with electron densities of the order of 10^{19} m^{-3} near the target and residence times for Li into the plasma of 0.1 ms, a cooling rate of 10^{-33} Wm^3 for Te<10eV leads to an average radiated power of 12 eV per atom, thus calling for much higher injection fluxes [25].

The existing limitations on the allowed amount of liquid metal into the plasma may preclude evaporation rates above a certain value, even if redeposition is strong enough to avoid the continuous refilling of the CPS structure. These limitations are related to excessive fuel dilution of the DT plasma at the center, for the case of Li, and to excessive central plasma radiation for the case of Sn. Preliminary calculations [58] indicate that for a minimum Q factor of 20, a 15% of Li in the divertor flux will still be allowed. Although simulation for the case of using Sn as liquid metal does not exist at the same level, much higher radiation power and much lower vapor pressure of this metal may provide a better solution for the power exhaust issue, as indicated by previous studies [54], even when a maximum concentration allowed at the core would be <0.1%. However, detailed studies of Sn transport to the plasma core and associated maximum allowed fluxes are still missing.

Although it is not clear at this stage if the present choice of LMs can provide the same radiation levels as those achieved by injection of extrinsic impurities, as Ar or Ne, development of a radiation layer protecting the exposed side of liquid metal embedded into a CPS arrangement has been experimentally verified in several plasma devices at high fluxes. Examples of that are T-11 [24], FTU [59] and Magnum PSI [20]. More recently, the effect has also been documented for tin in Pilot-PSI [60] and clamping of the surface temperature under power loads of >20 MW/m^2 due to evaporation and local plasma formation was observed in high power plasmas lasting 20s. A reduction of 1/3 of the incident power loads by vapor shielding effects was inferred from these data [60].

Finally, heat transfer by thermal conduction from the target surface to a devoted cooling system must be provided as the basic mechanism of heat exhaust in a reactor. Compared to the solid target case, the presence of a porous structure filled with liquid metal represents a hindrance from the thermo-mechanical point of view. Not only liquid metals have lower thermal conductivities than refractory metals as W and Mo, but also mesh structures are not ideally suited for this function. For a sandwich-like arrangement, simple calculations predict maximum power load handling values of 8.2 and 28.7 MW/m^2 for Li and Sn, respectively, under the assumption of a maximum contribution of 1% from the metal vapor to the total divertor flux [15]. Maximum T_{surf} values of 775 and 1528 K for Li and Sn, respectively, result from this constraint. Even when these estimates neglect the important issue of redeposition, enlarging the

temperature range allowed for LM surface operation, optimization of the CPS concept is still possible [61], and more work in this line could significantly change the power handling capabilities of CPS structures, ultimately limited by the cooling circuit design.

d) Other properties

Among the proposed liquid metal options here addressed, lithium is by far the most reactive element. Its contamination by O, N and C leads to important changes of its erosion and fuel retention properties as well as its corrosion activity against structural metals [62,63]. This last feature has deep implications on the long-term stability of the CPS-LM structure, even in the absence of a plasma. Since corrosion issues show a strong dependence on temperature, keeping the CPS system at the lowest possible working temperature seems highly advisable. Making this requirement compatible with hydrogen retention, however, could be challenging and more research should be devoted to this topic.

The lithium surfaces exposed to a plasma also show unexpected electrical properties. In recent experiments at Ciemat [64], it was found that the secondary electron emission (SEE) by electron impact could reach values up to 2.5 for electron energies <100eV. Although the expected behavior and associated thermal loads of surfaces with secondary electron emission above unity is still unclear [65], a voltage drop between surfaces with different SEE coefficients connected through the plasma boundary will develop, thus driving a poloidal current with potential impact on plasma confinement, as observed in TJ-II [66]. The observed anomalous SEE could be related to the high fraction of ions produced in the sputtering of lithium surfaces, and then a similar effect would be expected for LiSn surfaces in the liquid state. This effect is being presently investigated.

4. System Integration and open issues.

Bringing together solid and LM-based elements into a reactor design poses specific integration issues. The fact that the first wall together with the rest of the vacuum vessel must remain at relatively high temperatures in a reactor, for example, has a direct impact on the lifetime of the divertor liquid metal component. Being the coldest part of the inner side of the vacuum vessel, as a consequence of the required evaporation-limited temperature of the target together with a high T at the FW, the divertor may become a preferred area for condensing the evaporated metal, thus providing a recycling mechanism for the refilling of the CPS structure. Although this behavior seems feasible for lithium, tin operation at divertor temperatures above those of the vacuum vessel may be required by the divertor operation design, as commented above. Dripping of the condensed Sn by gravity along the surface of the first wall must be taken into account (and facilitated) if this is the case. Also, since some of the vapor would eventually pumped out by the vacuum system, devoted condensers, at temperatures below that of

the divertor but high enough to guarantee no tritium uptake must be foreseen. Note here that this temperature can be well below that of the divertor as far as the ambient pressure at the required location is much lower, likely in the sub-Pascal regime.

Material mixing issues are present in all fusion devices nowadays. This implies codeposition of D/Be layers on tungsten for ITER, for example, and no single solution, other than the trivial use of one single component for all the PFC, exist. For a reactor design with hot W (or SS) first wall and a LM divertor, transport of the eroded FW components to the divertor would take place and issues concerning LM contamination and, eventually, clogging of the porous structure should be considered. Erosion of the high Z components of the first wall will be enhanced by the liquid metal elements incorporated into the main plasma and implantation of Li or Sn into W may significantly affect its thermo-mechanical properties. In this respect, experiments studying the interactions of hot Li-W layers exposed to H_2 and Li-seeded H_2 glow discharge plasmas have been recently initiated at Ciemat [67]. Although a costly solution, the possibility of covering the FW by LiSn (for a Li divertor) or Sn (for a pure Sn one), both having a moderate vapor pressure at the FW operation temperature, remains as a way out to circumvent material mixing issues.

Under continuous operation, refilling of CPS structure with liquid metal must be provided in order to compensate for evaporative losses. The rate of such refilling will be critically determined by the redepostion efficiency and likely it will not pose problems associated with fast circulation of liquid metals under strong magnetic fields. An optimized design of CPS geometry will mitigate the risk of drying out under evaporative fluxes expected during hot plasma operation, particularly high for those induced by heat transients like ELMs.

Finally, and although this is not meant to be an exhaustive list of pending issues, for a liquid lithium water-cooled target, safety issues may be a concern. The present database does not allow an accurate estimate of the overall hydrogen retention induced by a liquid Li or Sn CPS target. For Li, with no direct measurements, the influence of plasma driven retention is not fully investigated yet. For Sn, bulk hydrogen retention and codeposition are expected to be much lower, but needs further investigation. In the absence of redeposition on the first wall, as expected for the considerations deployed above, the maximum amount of Li allowed in a reactor will be eventually determined by safety issues related to the formation of explosive H_2/air mixtures in case of massive water leaks from the cooling circuit. For a 4% H_2/air mixture (flammability limit) and the reactor volume given in Ref 4, a maximum of 28 liters of liquid Li is obtained, while for the explosion lower limit (18% H_2/air) this amount increases up to 126 l. On the other hand, for a 5% retention of T/D and assuming equal T and D concentration in the liquid lithium at 550 ºC, 750 g in the vessel T limit translates into 140 l of liquid Li. For reference, in a divertor area covered with a 10 cm wide Li element (on each, the HF and LF sides) a 100 l volume represents a maximum thickness of a pure liquid Li layer

of ~1cm, thus providing enough room for a local liquid lithium reservoir required for refilling purposes.

To summarize, in order to close the design of a CPS-LM target for a fusion reactor, urgent research on the topics listed below is highly recommended:

- Performance of CPS-LM arrangements under high (20 MW/m2) steady and fast (ELM like) transient heat loads. Assessment of the vapor shielding effect.
- Modeling of the plasma response in the presence of contaminants from the LM target. This modeling should provide quantitative values for the maximum flow of liquid metal species allowed into the plasma without degradation of confinement or excessive dilution of the central DT fraction and therefore, the need of injecting extra radiators (Ar, Ne).
- Optimization of LM transport into the CPS to provide a fast refilling of the surface. Redeposition, implying a refilling from the surface, must be properly accounted for when considering optimized geometry for the CPS matrix.
- Effect of contamination on the fuel retention characteristics of LM's. Intrinsic impurities (N, O, C) and those produced in the FW-plasma interaction should be considered.
- Interactions between the FW components and the LM elements. The mutual, deleterious effects must be assessed, and a FW design easing the recovery of the evaporated LM should be envisaged.
- Long-term stability of the CPS-LM system under the neutron irradiation foreseen for a fusion reactor. Chemically induced effects as well as impact on tritium retention must be evaluated.

5. Conclusions.

Divertor target concepts based on liquid metals held in capillary porous systems have been extensively tested in the last years in a variety of experiments. Nevertheless, most of the present experience on liquid metal performance under the exposure to high power fluxes has been obtained in fusion limiter devices, on which much higher electron temperatures and lower neutral pressures are present in front of the material elements.

Therefore, under the lack of a devoted facility specifically oriented to close the existing gaps for the implementation of liquid metal-based solutions to the power exhaust issue of a divertor-based fusion reactor, an important share of the pending work belongs to modeling activities. It must be kept in mind, however, that some of the open issues are not specific to the use of LM-based targets but common to more conventional solutions based on solid PFC concepts. This is the case, for example, of combining a very hot FW with normal divertor operation, never attempted before in the existing fusion facilities, not to mention the presence of high neutron doses, very long pulse operation and the cooling circuit design able to handle the expected thermal loads at the divertor target of a fusion reactor.

Only a focused effort on the topics here identified and on any others not yet deployed will bring liquid metal target concepts to the level of maturity required for a credible, alternative reactor divertor design.

Acknowledgements

The authors are indebted to the Eurofusion PFC and DTT teams on liquid metal research for fruitful discussions and suggestions.

This work was partially financed by the Spanish "Ministry of Economy and Competitivity" under project ENE2014-58918-R

This work has been carried out within the framework of the Eurofusion Consortium and has received funding from the Erratum research and training program 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Fusion Electricity – A roadmap to the realization of fusion energy, F. Romanelli et al., EFDA, 2012

[2] Linke J. 2006 Trans Fus Sci. Technol 49 455

[3] Nygren R.E. et al 2011 J. Nucl. Mater. 417 451

[4] Wenninger R. P. et al 2014 Nucl. Fusion 54 114003

[5] You J. H. et al. Conceptual design studies for the European DEMO divertor: Rationale and first results, Fusion Eng. Des. (2015), http://dx.doi.org/10.1016/j.fusengdes.2015.11.012

[6] Federici G. et al. 2015 Fus Eng Design http://dx.doi.org/10.1016/j.fusengdes.2015.11.050

[7] Stork D. et al. 2014 J. Nucl Materials 455 277–291

[8] Hirooka Y. et al. 2010 Nucl. Fusion 50 077001

[9] Ono M. et al. 2012 Nucl. Fusion 52 037001

[10] Mazzitelli G. et al 2015 Nucl Fusion 55 027001

[11] Evtikhin V et al. 2002 Plasma Phys Control Fusion 44 955

[12] Ren J. et al. Fus Eng Design 102 (2016) 36–43

[13] Vertkov A. V. et al. 2012 Fus. Eng and Design 87 1755– 1759

[14] Hirooka Y. et al. 2015 Fus Sci Technol. 68 477

[15] Coenen J. W. et al. 2014 Phys Scr. T159 014037

[16] Ruzic D. N. et al., 2011 Nucl. Fusion 51 102002

[17] Mirnov S.V. and Evtikhin V. 2006 Fusion Eng. Des. 81 113.

[18] Gomes R. B. et al. 2008 Fusion Eng. Des. 83 102

[19] Fiflis P. et al."Wetting properties of liquid lithium on select fusion relevant materials" Fusion Eng. and Design 89 (2014) 2827.

[20] Morgan T. W. et al. 2015 J. Nucl Mater 463 1256
[21] Nagayama Y. 2009 Fusion Eng. Des. 84 1380
[22] Kirillin I. 1990 Liquid Metal Coolants for Heat Pipes and Power Plants, Hemisphere Publ. Corp.
[23] Ono M. et al. 2013 Nucl. Fusion 53 113030
[24] Mirnov S. V. et al 2011 Nucl. Fusion 51 073044
[25] Ono M. et al. 2014 Fusion Eng. Des. 89 2838
[26] Goldston R. et al 2016 Phys. Scr. T167 014017
[27] Mazzitelli G. et al 2015 J. Nucl Mater 463 1152
[28] Vertkov A. et al. 2016 Fus Eng Design. Proceedings of ISLA-4. In press
[29] Lyublinski I. et al. 2012 Fusion Eng. Des. 87 1719
[30] Maingi R. et al. 2010 Phys.Rev. Lett. 105 135004
[31] Veleckis E. et al 1974 J. Phys. Chem. 78 1933
[32] Smith F. J. et al. 1979 J. Inorg. Nucl. Chem. 41 1001
[33] Baldwin M. et al. 2002 Nucl. Fusion 42 1318
[34] Furuyama Y. et al. 2003 J Nucl Mater 313-316 288
[35] Pisarev A. et al. 2013 J. Nucl. Mater. 438 S1076
[36] Oyarzabal E. et al. 2015 J. Nucl Mater 463 1173
[37] Martin-Rojo A.B. et al. 2014 Fus. Eng Design 89 2915
[38] Oyarzabal R. et al 2016 Fus Eng Design. Proceedings of ISLA-4. In press
[39] Bi H. et al. Plasma Fus. Research. 11 (2016) 2405026.
[40] Tabares F L et al. 2012 Proc. 24th Int. Conf. on Fusion Energy (San Diego, 2012) http://wwwnaweb.iaea.org/napc/physics/FEC/FEC2012/index.htm
[41] Brooks J.N. et al. 2001 J.Nucl.Mater. 290-293 185
[42] Neff A.L. et al. 2015 J Nucl Mater. 463 1147
[43] A.M. Capece, et al., J. Nucl. Mater. 463 (2015) 1177.
[44] Sharafat S. and Ghoniem N. 2000 Summary of thermo-physical properties of Sn and compounds of Sn–H, Sn–O, Sn–C, Sn–Li, Sn–Si and comparison of properties of Sn, Sn– Li, Li, Pb–Li Technical Report UCLA-UCMEP-00-31 University of California, LA
[45] Loureiro J. et al. 2016 Fus Eng Design. Proceedings of ISLA-4. In press.
[46] Loureiro J. et al . Proc. PSI 16 Rome. To apear in Nucl Mat Energy
[47] Tabares F L et al . Proc. PSI 16 Rome . To apear in Nucl Mat, Energy
[48] Allain J. P. et al. 2007 Phys Rev.B 76 205434
[49] Doerner R. et al 2001 J Nucl Mater. 290-293 166
[50] Abrams T. et al. 2015 J Nucl Mater. 463 1169
[51] Skinner C. H. et al. 2009 J Nucl Mater 390–391 1005
[52] Coventry M. D. et al 2003 J Nucl Mater 313–316 636
[53] Doerner R. et al. 2004 J Appl Phys 95 4471
[54] Abdou M. 2001 Fusion Eng. Des. 54 181

[55] Allain J. P. 2001 Thesis. KINEMATIC AND THERMODYNAMIC EFFECTS ON LIQUID LITHIUM SPUTTERING. University of Illinois, Urbana-Champaign
[56] Rognlien T. D. and Rensik M. E. 2002 Phys Plasmas 9 2120
[57] Rognlien T. D. and Rensik M. E. 2002 Contrib. Plasma Phys. 2-4 193
[58] Pelka G. et al."TECXY study of a liquid lithium divertor for DEMO", Contr. on Plasma Physics . In press
[59] Pericoli Ridolfini V. et al. 2007 Plasma Phys. Control. Fusion, 49 S123
[60] van Enden, et al., Phys Rev Lett. 116 (2016) 135002.
[61] Tabarés F L 2015 Plasma Phys. Control. Fusion 58 014014
[62] Taylor C. N. et al. 2014 Physics of Plasmas 21 057101
[63] Reed C. B. "Lithium Safety and Material Compatibility" in Lithium;Technology, Performance and Safety, 2013. Ed F L Tabarés. Nova Sci Publishers. NY.
[64] Oyarzabal E. et al. 2014 J Nucl Mater. 452 37
[65] Campanell M.D. et al 2012 Phys. Rev. Lett. 108 255001
[66] Tabarés F. L. et al 2015 J Nucl Mater. 463 1142
[67] de Castro A. et al. 2016 Fus Eng Design. In press

Table I. Properties of most relevant liquid metals for Fusion Applications

	Symbol (units)	**Li**	**Sn**	**Ga**
Atomic number	Z	3	50	31
Atomic weight	A	6.94	118.7	69.72
Mass density	ρ (10^3 Kg/m^3)	0.57	6.99	6.095
Melting point	T_m (ºC)	180.5	231.9	29.8
Boiling point	T_b (ºC)	1347	2270	2403
Surface tension	σ (N/m) at T_m	0.4	0.55	0.69
Dynamic viscosity	η ($10^{\square\square}$ Pa.s) at T_m	0.25	1.85	0.95
Latent Heat of vaporization	ΔH_{vap} (kJ/mol)	147	296	256.1
Thermal conductivity	$\kappa\square\square\square\square/\square\square$ at T_m	45	30	50.9
Molar Heat Capacity	$\square_{\square}$ (J/mol/K)	24.86	27.11	25.86

Table II: Table II. Saturated solubility and corresponding equilibrium pressures for the X-Li (X=H,D,T) system at several temperatures. The flux of Li evaporation is also indicated.

T °C	T K	H sol. %	D sol. %	P_{Li_2X} H Pa	P_{Li_2X} D Pa	P_{Li_2X} T Pa	Vap Flux (10^{22} m^{-2} s^{-1})
400.0	673.0	1.240	1.1273	0.097	0.1457	0.171	0.04
450.0	723.0	2.141	2.2247	1.072	1.5995	1.877	0.280
500.0	773.0	3.445	4.0208	8.628	12.873	15.10	1.440
550.0	823.0	5.231	6.7626	53.90	80.410	94.36	5.900
600.0	873.0	7.572	10.716	272.9	407.21	477.8	20.78

Figure Captions:

Fig. 1. Evaporative fluxes for Li, Sn and LiSn alloys (0.8 Sn)

Figure 2 : Response of a Li-filled CPS structure to 22 plasma pulses of 4 MJ/m^2 and 0.2-0.5 ms duration in a QSPA device. From left to right: unexposed, exposed w/o lithium, exposed with Li. From Ref. 11.

Fig 3. Sieverts' plots for the D/Li system at several temperatures. Adapted from Ref. 37.

Fig 4. Equilibrium pressure and saturated solubility of H,D and T on lithium at temperatures between 400 ad 650 ºC. Values of P and c_H at 550 ºC are highlighted. Also shown (P_{ex}), the experimental values obtained for a H_2/Li system at Ciemat (Ref 41).

Fig. 1. Evaporative fluxes for Li, Sn and LiSn alloys (0.8 Sn)

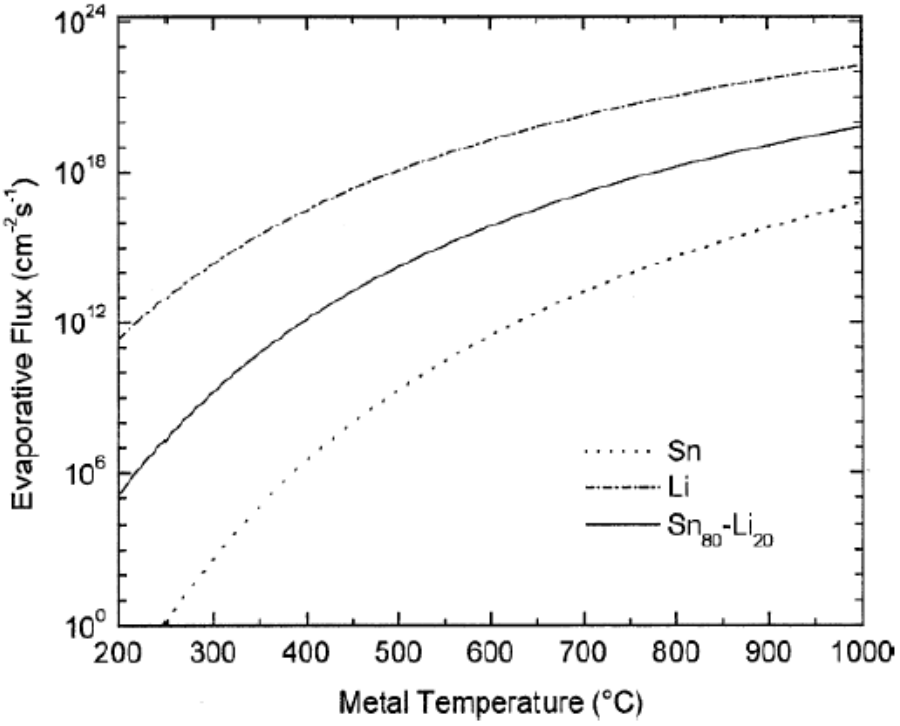
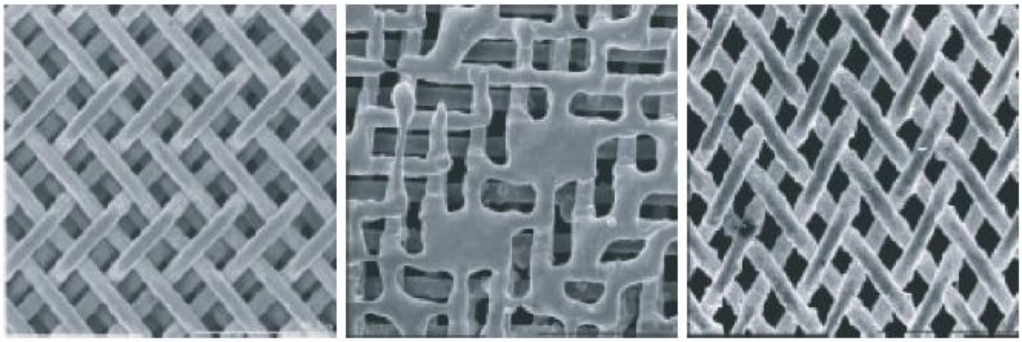


Figure 2



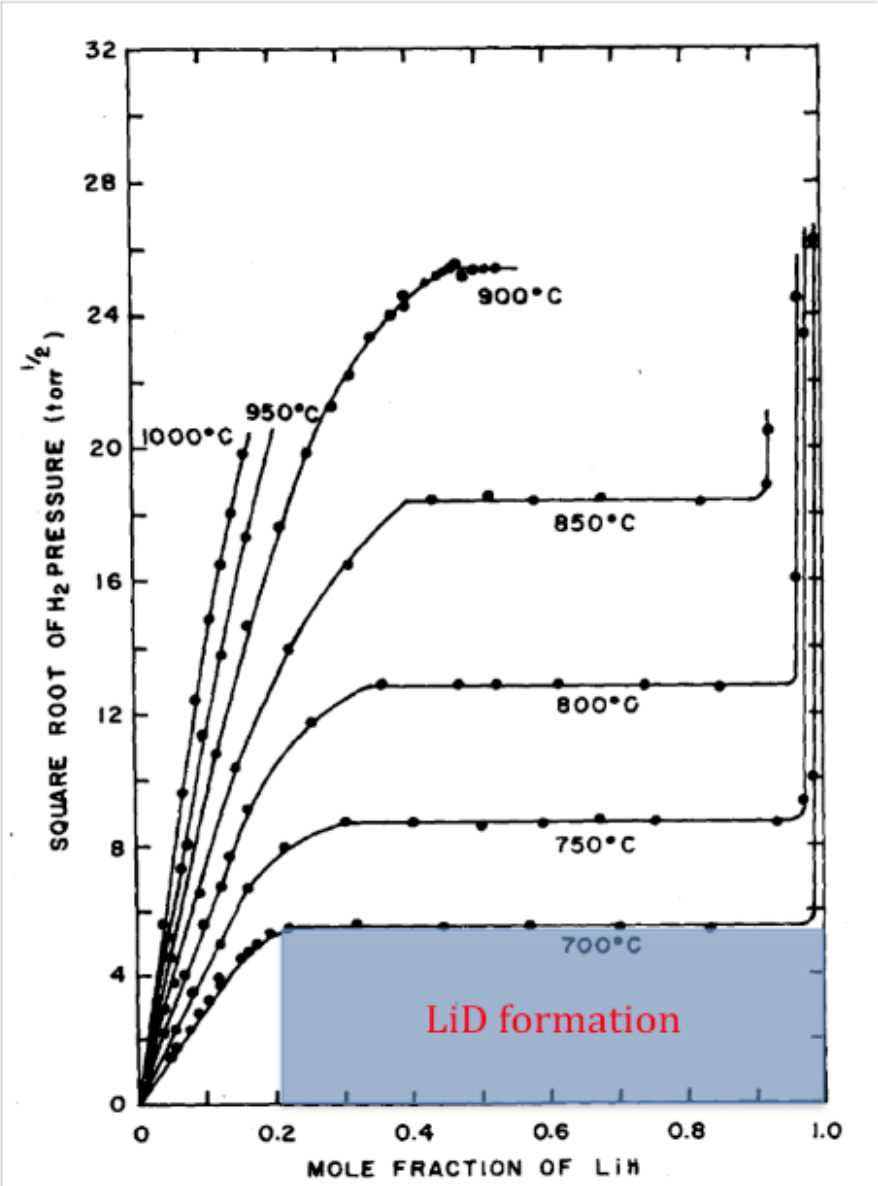
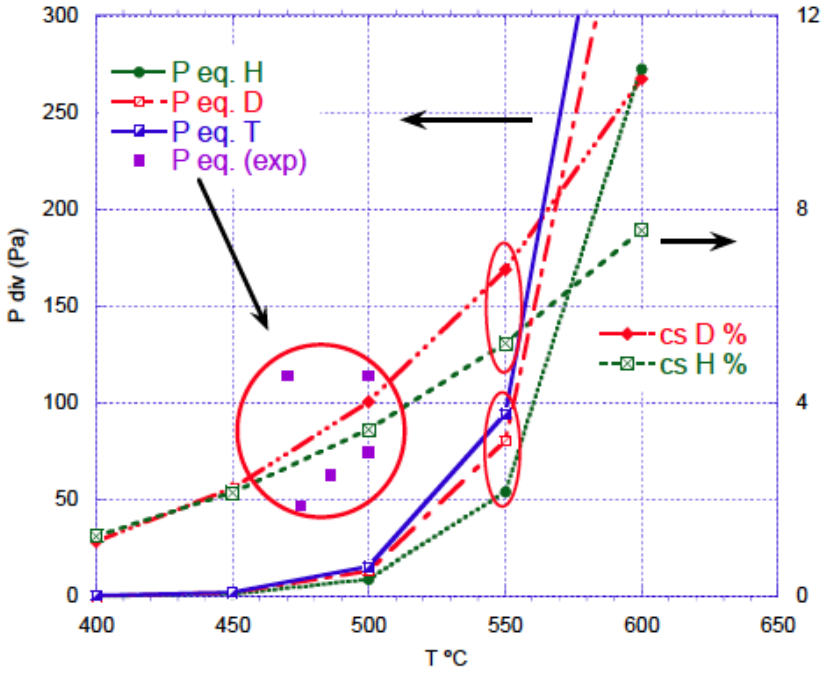

32
28
24
20
16
12
8
4
0
0
0.2
0.4
0.6
0.8
1.0
SQUARE ROOT OF H_2 PRESSURE ($torr^{1/2}$)
MOLE FRACTION OF LiH
900°C
950°C
1000°C
850°C
800°C
750°C
700°C
LiD formation

Figure 3.

Figure 4.


P eq. H
P eq. D
P eq. T
P eq. (exp)
cs D %
cs H %
P div (Pa)
T °C
300
250
200
150
100
50
0
12
8
4
0
400
450
500
550
600
650