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Present Status of Liquid Metal Research for a Fusion Reactor

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Abstract:

Although the use of solid materials as targets of divertor plasmas in Magnetic Fusion Research is accepted as the standard solution for the very challenging issue of power and particle handling in a Fusion Reactor, a generalized feeling that the present options chosen for ITER will not represent the best choice for a Reactor is growing up. The problems found for tungsten, the present selection for the divertor target of ITER, in laboratory tests and in hot plasma fusion devices suggest so. Even in the absence of the strong neutron irradiation expected in Reactor, issues like surface melting, droplet ejection, surface cracking, dust generation, etc., call for alternative solutions in a long pulse, high efficient fusion energy-producing continuous machine.

Fortunately enough, decades of research on plasma facing materials based on liquid metals (LMs) have produced a wealth of appealing ideas that could find practical application in the route to the realization of a commercial Power Plant based on Fusion Energy. The options presently available, although in a different degree of maturity, range from full coverage of the inner wall of the device with liquid metals, so that power and particle exhaust together with neutron shielding could be provided, to more conservative combinations of liquid metal films and conventional solid targets basically representing a sort of high performance, evaporative coating for the alleviation of the surface degradation issues found so far.

In this work, an updated review of worldwide activities on LM research is presented, together with some open issues still remaining and some proposals based on simple physical considerations leading to the optimization of the most conservative alternatives.

1. Introduction

Liquid Metals (LMs) 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 for lifetime and 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. However, many aspects still remain unresolved and integration of these proposals into a realistic scenario may be challenging.

The desirable characteristics of divertor in burning plasma devices are: Power handling at the level of tens of MW/m^2, particle exhaust (fuel and helium) at the level of several 10^{24} m^{-2} s^{-1}, impurity control (Zeff <1.5) and long lifetime, including fast recovery from type I ELMs and disruptions (in the range of GW/m^2 and duration of a few ms at most).

Divertor heat handling is extremely demanding in the fusion reactor [1,2]. The power flow from the main plasma is conducted along the field line of the separatrix surface and wet a narrow zone of the divertor plate. For the case of a Fusion Reactor with a fusion power of 3 GW for example [3], the estimated divertor power density is ~100 MW/m^2, which is not acceptable from the engineering viewpoint. Ongoing efforts are focused on the reduction of the divertor power density to an acceptable level (<10 MW/m^2) by geometry optimization e.g. snow-flake or super-X divertor concepts [4] and radiative cooling by impurities such as N_2, Ne and Ar which may require high impurity level at the edge plasma ($n_{Ar}/n_i = 0.9$ %, $Z_{eff} = 2.6$) [5].

Although ITER will use tungsten targets at the divertor, serious issues arising from the presence of transient heat fluxes like ELMs and disruptions together with neutron irradiation and its relatively high DBT transition temperature makes this material not the best choice for the divertor of any burning plasma experiments, and consequently, the use of liquid metals becomes sensible.

The structure of this paper is as follows. In chapter 2, a review of worldwide experience on the use of LMs is given, with particular emphasis on present machines. In chapter 3, some of the open issues from the scientific and technological points of view are addressed. In chapter 4, the implications of integrating the LM solution for the divertor with the rest of the components in a Reactor, along with some possible new solutions for the target design, are analyzed. Finally, in chapter 5, some conclusions on the feasibility of a LM solution for a future Fusion Reactor and required R+D work are presented.

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 biennual Symposia, whose next edition corresponds to the ISLA-4 to be held in Granada, Spain, next fall. A summary of worldwide activities and their evolution in the last five years can be found refs 6-8, corresponding to the Conference Reports of the three first symposia of the series celebrated so far.

In addition to this, the reader is also referred to devoted reviews presented in other, less specific conferences [9,10]

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 profit from 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 of 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. In this line, a liquid metal divertor was first proposed in the UWMAK-1 Design Report [11], mainly to provide strong particle pumping with free-falling liquid lithium. Still on this line of reasoning, the American ambitious project, APEX [12], explored several concepts based on free flowing liquid metals and salts for a Power Plant design. Thin and thick LM films, the latter adding first wall protection against neutron irradiation to the intrinsic benefits above mentioned, were analyzed in terms of physical and technological performance and reliability. Extensive modeling of critical issues like liquid film stability at the required flow velocities and MHD drag forces was performed. The idea of LM curtains, precluding the presence of continuous LM electrical circuits, was also put forward. Alternative cooling concepts, like EVOLVE [12] for the first wall based on lithium evaporation outside the main VV were also developed. Still in the USA, in the CDX-U project [13] a tray containing liquid Li was used as divertor lower plate. Although a strong improvement on plasma performance was achieved by strongly decreasing the recycling at the strike point, lithium splashing was realized to become a serious issue when using liquid metals with no extra holding force but gravity alone. Still within the flowing LM concept, the so-called LiMIT (Liquid Metal Infused Trenches) arrangement was developed by Ruzic and coworkers at the University of Illinois at Urbana-Champaign, Illinois [14]. 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. This concept was tested recently in the HT-7 tokamak [15] and it is planned to be tested soon in EAST. Recently, the possibility of enhancing the interaction between the LM in a pool with the divertor plasma by active convection by jxB force was proposed by Shimada and Hiorooka [16]. A set of electrodes inserted into the LM pool is used to activate convection into the liquid thus providing an improved distribution of the exhaust power within the target. Other proposals involving the use of circulating lithium in guide type structures can be found in [8,9].

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 [17,18] and ISTTOK [19] 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 [19].

Due to the serious issues found in the attempts to implement free moving LMs in a Magnetic Fusion environment, a second option came into play from the Russian teams: the capillary porous system (CPS) [20]. 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 on tens of microns can develop capillary pressures of the order of one atmosphere, high enough for preventing liquid splashing in the presence of 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. 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. Temperatures above 300ºC are typically required, while oxide free surfaces are mandatory in some instances [10,21]. The strong resistance that micro-porous systems offer to the movement of a liquid metal within them makes 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 the 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. 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. On the other hand, 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 [22]. A system inspired in the Heat Pipe concept [23] combining porous structures and in situ evaporation of lithium, but in separate volumes decoupled from the main plasma, was proposed by Nagayama several years ago [22].

Compared to evaporation, lithium radiation can become an excellent candidate for energy dissipation when introduced in a plasma. Although, 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 doesn’t reach the condition of coronal equilibrium due to its low residence time in the plasma makes non-coronal radiation estimates highly appealing. Figure 1 shows the predictions for the cooling rate of this element at several temperatures and different residence times into the plasma. Also shown is the expected value for DEMO plasma parameters. 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. 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 it, 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 [24-25]. Furthermore, Ono et al proposed the Radiative Liquid Lithium Divertor (RLLD)[26] and its active version (ARLLD) [27] 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 [27], 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.

In more conservative grounds, the combination of CPS structures with conventional cooling schemes is also a matter of active research. This is the case for the FTU activity on actively cooled CPS structures [28]. 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 ware as cooling fluid [8]. 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. Open physical issues

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. The reason for that is, in large extent, the impressive impact that lithium coatings have on plasma performance. Enhanced plasma confinement has been reported basically in all lithiated fusion devices, provided a significant part of the plasma facing surfaces are covered [30-34]. Thus for example, enhanced confinement in the H mode together with a decrease in the L-H threshold and in the power load to the target by a 50% was reported in NSTX [31]. Access to the H mode in the TJ-II stellarator was only possible after full lithiation of the first wall [33], while H mode by ICRH heating was achieved for the first time in EAST after significant coverage with lithium of the walls was carried out [33], to mention a few examples. However, no clear physical explanation for this conspicuous effect exits to date.

Most authors claim the strong pumping effect that Li has when exposed to a hot plasma, due to the eventual formation of lithium hydride predicted for temperatures below 700ºC, must be behind these observations. The decay of neutral density at the plasma periphery would lead to a decrease in the CX losses as well as an increase in the edge temperature, thus flattening the Te gradient at the SOL (lowering then the associated diffusive fluxes). Moreover, the resulting decreased edge density would allow for a deeper penetration of neutrals in the plasma and the concomitant displacement of the source term inwards. Although it is an empirical fact that edge temperature increases while edge density decreases upon lithiation, this result may not be of any use in a reactor divertor, on which a high recycling regime seems needed for low Te and strong pumping divertor efficiency [35]. However, other possible properties of lithium surfaces could be hiding behind the low recycling effect. Thus for example, it is known that lithium percolation into carbon materials makes the lifetime and the associated beneficial effect of Li coatings to be shortened, as compared to deposition on clean metallic surfaces. However, Taylor et al [36] reported enhanced D retention on mixtures of C/Li/O under carbonized/boronized walls in NSTX. Laboratory studies and MC modeling point to the possibility that atomic oxygen, brought to the surface by Li segregation in the carbon matrix, could enhance the bonding of D atoms to the atomic complex.

Aside from hydrogen uptake, alkali metals show some unique properties. Sputtering of this materials leads to the ejection of ions rather than neutrals, accounting for up to 2/3 of the total sputtered species [37]. One obvious implication of this property is a high redeposition of the sputtered material in the presence of the plasma sheath, even in the absence of ionization of the remaining neutrals in the surrounding plasma. Moreover, experiments at CIEMAT have shown that the secondary electron emission (SEE) yield of lithium surfaces by electrons increases by a factor of 5 in the presence of a plasma [38]. This high electronic SEE yield, up to 2.5, has a strong impact on the sheath potential of lithium elements exposed to a hot plasma. The exposure of twin limiters, (one made out of carbon, the other a lithium CPS system) in TJ-II under full lithiated walls confirmed the generation of inter-limiter currents at the SOL due to the development of different floating potentials on both limiters, otherwise exposed to the some local plasma parameters [39]. This effect vanishes if the same component (Li) is used on both limiters. At present it is not exactly known how a SEE yield >1 of a plasma facing material would affect the plasma performance, but enhanced plasma confinement was seen at positive bias voltages of the Lithium limiter at values above the nominal floating potential of ~3kTe. Although it is difficult to extrapolate these observations to a Reactor divertor, exploring the unique properties of liquid metal surfaces under all possible aspects may lead to new discoveries easing the implementation of the associated LM concepts in a Reactor.

Together with lithium, other elements with expected good performance from the neutron activation and transmutation point of view have been put forward as LM for fusion applications. This is the case of tin and gallium, both high Z elements with very low H retention capability. Gallium is the chemical element with the widest range of temperature in the liquid state and a very low vapor pressure at divertor relevant temperatures. However, one of the shortcomings of Ga is its very high corrosion activity on most of the candidates as supporting materials. After the rather unsuccessful experiments at T-3M [17] and ISTTOK [18] using Ga as a liquid curtain, activity on this element has declined. On the contrary, tin has attracted much attention as alternative to lithium. Experiments on tin-filled CPS samples at Magnum PSI and Textor have been carried out. Temperature enhanced sputtering and formation of a vapor cloud was observed when Sn samples were exposed to the divertor-type plasmas of Magnum PSI at FOM [40]. One of the critical issues found in these experiments was the strong effect that de-wetting of the LM on some spots of the CPS system has on its performance. Strong temperature spikes and hence thermal evaporation were found in the Sn-W mesh system. Furthermore, corrosion by Sn of the TZM disc used in the supporting structure was unexpectedly found. Interestingly, it was found that oxide reduction by H_2 or heat treatment was a pre-requisite for good wetting at moderate temperatures in Sn-Mo and Sn-W combinations. Activities in Latvia University and Red Star laboratories [8] on the topic have shown that the surface chemistry and wetting behavior for arbitrary combinations of LMs and porous structures made of refractory metals and stainless steel remains an open issue, badly missing systematic laboratory experiments if LMs are to be used as alternative options for a divertor target in a Fusion device.

One of the key issues on plasma facing material research is the tritium retention characteristics of the selected components. Thus, this issue has largely motivated the change from carbon to tungsten elements in ITER divertor targets, for example. Among the possible LM options above described, lithium is the element with larger retention of hydrogen isotopes, eventually leading to the formation of stable hydride with a fairly high decomposition temperature (690ºC). A lot of work has been devoted in order to assess if LiH will be formed under plasma exposure at temperatures compatible with tolerable vapor pressures, ~up to 480 ºC based on the 1% contamination limit of the divertor flows. Extensive work at Ciemat on exposure of hot lithium to D_2 atmospheres has proved that under the low pressures existing in the divertor chamber, no LiH formation takes place [41]. Moreover, no uptake of H in any of its possible chemical states (solved, trapped, bonded) was seen at exposure temperatures above 500ºC [42]. For plasma exposures in TJ-II, precluding D retention on CPS LL limiters requires temperatures between 400 and 500 C [43], as found in other devices [24]. This relatively low temperature may be associated to unavoidable surface oxidation leading to an enhanced retention but a lower binding energy of trapped hydrogen on Li surfaces [44]. In relation to this, experiments at PILOT PSI have been recently initiated to check for any possible flux dependence on retention.

Even if T retention is not an issue for lithium at relevant divertor temperatures, excessive evaporation may become a showstopper. Certainly, the degree of re-deposition (see below) must be evaluated before defining a critical temperature value. In any case, low Z, low retention and low P_{vap} solutions may exist. Thus, Li/Sn alloys with a Li content <30% at. were proposed as attractive alternatives to pure Li in the APEX project [12]. The reason for that was the strong surface segregation of Li atoms in the alloy, making them basically a pure lithium element when exposed to the plasma while keeping the low vapor pressure and very low H retention characteristic of tin [45]. Based on this, extensive work has been initiated in several European laboratories under the auspices of the Eurofusion Consortium to fully characterize this alternative LM. Ongoing research focuses on lithium segregation at the melting point (300-350 ºC depending on composition) as well as H retention and sputtering characteristic in hot and divertor-type plasmas.

4. Integrating LM solutions into a Fusion Reactor Design.

Depending on the degree of exploitation of the unique properties of LMs displayed above, allowed in the design of a Fusion Reactor, different integration issues will arise. A full use of the potential of LM as circulating fluids, and hence of power and particle exhaust or even neutron shielding, poses huge challenges to present Power Plant engineering and this option remains as a promising solution for future generations for now. Realistic approaches then must look at localized, slow flowing liquid or CPS designs. Wetting and flow instabilities remain rather unsolved problems for the designs of flowing liquid concepts as pointed out by several teams [6-8]. The exception could be the LiMIT concept, of proven potential in several test experiments, but a conflict between broad and narrow trenches, the first allowing for higher liquid flows and the second providing stability vs. plasma transients and splashing, still exists. Since these issues are common to all microstructure-base designs, a general analysis of such systems will be made in the following.

The condition to be fulfilled by a divertor structure including LM and porous systems are: 1) stability of LM *vs.* MHD induced forces, 2) fast refilling of the surface film after strong loads and 3) good thermal characteristics. While the first point calls for small pores, the second one poses a limit to their minimum size and the third one to the thickness of the CPS layer. So, the most conservative approach would be using a CPS structure only for surface protection of a more standard target material, as tungsten. This option was recently analyzed by Coenen et al [10]. By using the RACLETTE code, and imposing a maximum temperature below the LM boiling point, the behavior of structures consisting on a 10 mm, LM filled CPS sitting on a 4.4 mm W substrate with a 1.1mm Cu tube with water cooling were simulated under steady state and transient loads. Maximum values of 25 MW/m^2 and 10 MW/m^2 for Sn and Li respectively were deduced. These values are reduced by a factor of 2.5 if maximum temperatures for each material are restricted to associated impurity fluxes of 1% of the total flux to the divertor, set at 1.10^{24} m^{-2}s^{-1}. However, no analysis on CPS structural optimization was performed by these authors.

Since liquid metals show a systematic lower thermal conduction coefficient than W, the question of how thick the CPS should be is worth addressing. The CPS structure has two main functions: holding the LM in place and refilling the surface by porous transport. These two goals call for different porous sizes, something impossible if a simple porous mesh is used. Small pores are best suited for the first function, while transport through Poiseuille flow becomes very restricted in small pore diameter. Thus, drying of the CPS surface may happen if the underlying porous array is not able to refill the surface at a rate high enough, depending on the frequency of ELMs, for example.

The flow across a capillary follows Poiseuille equation:

1) $Q\ (m^3s^{-1}) = \pi/8.\ (\Delta P.r^4/\eta.l)$ (MKS units)

and the associated work for the transport is

2) $W\ (\text{Watts}) = Q.\Delta P = Q^2.8\eta.l/\pi.r^4$

Where ΔP stands for the pressure difference on both sides, η for the viscosity of the LM, r is the pore radius and l the length of the path across the mesh. Note that l can be significantly larger than the nominal thickness of the CPS structure if a tortuous way needs to be walked by the LM from the underlying pool to the CPS surface. As seen, a fourth-power dependence on the porous size appears in the above equations. In the absence of other driving forces, as could be an extra pressurization in the pool, capillary pressure, $\Delta P=2\sigma/r \cos\theta$, provides the work required in transporting the LM across the CPS at a rate of Q. The minimum value of Q required during vaporization is

3) $\Gamma_{vap}(\text{moles/s}) = Q.\rho/A$

with ρ in g/cc and A the atomic weight of the element in g/mole.

In the extreme case of full vaporization of the CPS LM content (by strong ELMs for example), replenishing time becomes an issue. By using eq. 1, this time is

4) $t = l/v_{flow} = l/(Q/\pi r^2)$,

For a Q value driven by the capillary pressure and assuming perfect wetting ($\cos\theta = 1$), eq.4 becomes

5) $t = 4l^2 \eta / r.\sigma$

which reproduces the equation proposed by Washburn for full wetting ($\cos\theta = 1$) conditions [46]. As seen in eq.5, small thickness and big pore size are required for the fast replenishment of a dry CPS structure, as somehow expected. Thus for example, for liquid lithium with σ=0.4Nw/m and η=0.5 mPa.s, a 10 mm thick CPS structure with pores of r=10μm will show a time response of 50ms sec, i.e, full refilling between type I ELMs at f=20Hz, assuming a straight path of the L across the porous structure. Note that this time applies to the refilling of the depleted by transport across the CPS structure, not from non-depleted surrounding regions at the surface. This simple model, however, needs experimental validation for the specific materials and geometry to be used in the final design. In this respect, data for lithium wicking on TZM and SS supports were recently reported by Lin et al [47] on laser micro-textured surfaces with pore size of <250 μm. Although not exactly the same geometrical system, times significantly higher than those predicted by eq. 5 were experimentally found, probably due to incomplete wetting even at the temperature of 866K used in this work.

Finally, good thermal conductance for the CPS structure is required. This implies a small thickness and a moderate degree of porosity. Recent studies in a sintered metallic matrix [48] show that its thermal conductivity, K, degrades very quickly with porosity and there is a critical value of ~20% that should be avoided. Although different physical systems, there are reasons to believe that porosity will also degrade the conductivity of W structures in the CPS design. Nonetheless, experiments on lithium filled porous molybdenum at the University of Illinois showed that if 80% porous Mo foam is embedded with liquid lithium, the resulting thermal conductivity is just given by the relative fraction of each material and its corresponding thermal conductivity in a simple additive way [49]. On the contrary, when defective wetting between both components happens, some times due to the development of some chemical compound in the interface, very low values of K are to be expected. In NSTX for example, only a 5% of the expected K was deduced in porous Mo–Li samples [50]. Figure 2 shows the evolution of the three relevant parameters, capillary pressure, refilling time and thermal conductivity depending on porous size/arrangement.

A farther step in the system optimization is obtained if the liquid metal can be also used for cooling purposes, as it is very often the case for Fission Reactors and other analogous systems. In this case, the dangerous situation of having water and liquid lithium (highly reactive) in close proximity is avoided and at the same time, refilling the CPS structure is very much eased. Instead of the single channel, hypervapotron design chosen for ITER target cooling [51], a multi-channeled array filled with liquid metal, proven very successful in cooling of microelectronic devices [52], is here proposed. The diameter of the cooling channels, in the range of mm, has to be decided in terms of pressure drop development along the target element and required pumping power. Small pores connect some of the cooling channels to the micro-textured surface, thus providing the required refilling for the compensation of evaporative losses. Figure 3 shows the two designs based on these considerations, termed ELMAC and ILMAT, respectively. Incidentally, a very similar concept to ELMAC was recently proposed by the NSTX team in combination to a T-tube arrangement [53]. In all cases, direct micro machining of the surface will avoid the development of interfacial thermal resistance, a well-known deleterious effect arising under defective wetting conditions [54]. In this respect, recent tests on laser textured TZM and SS surfaces at Princeton have shown the way to optimize the transport of liquid metals by a proper pattern of micro-channels along and across the surface [47]. However the potential problem of surface corrosion or embrittlement of W by the continuous flow of liquid Li has to be sorted out before opting for this integrated, high power-removal rate solution.

Finally, the presence of more than one plasma-facing component in a Fusion device leads unavoidably to the formation of co-deposits as well as an assortment of mutual interactions that should be taken into account from the very beginning. Although a full lithium FW would be ideally suited for a liquid lithium divertor solution, excessive evaporation at the Reactor FW relevant temperatures makes this impractical at least for lithium. Even if a suitable geometrical arrangement of pores at the first wall structure providing decreased evaporation rate, as suggested by recent laboratory experiments [55], could be found, the complexity of the system, specially in a modular design, will jeopardize the full Reactor integrity. Therefore, assuming the more conventional full W or Eurofer FW at high temperature (>600ºC), issues arising from the interaction of Li (or any other candidate) ions and the first wall material must be addressed. From a first consideration, three topics are readily spotted. One is the effect of FW erosion, mainly at the low field side, and transport of the wall material to the inner divertor through the inner SOL, as experimentally verified in the JET ILW operation [56]. This could lead to a prompt, partial clogging of the CPS structure at that point together with strong LM contamination. Second, a LM rich SOL is likely to be generated under steady state plasma conditions. Since sputtering by Li ions (the lowest one within the LM choice) is significantly higher that by plasma particles, ejection of FW material through the weakly screening SOL into the plasma may pose a serious problem from the plasma purity point of view. Finally, the combination of temperatures at the divertor and at the FW has a direct impact on the recycling of the LM within the vacuum vessel. For a FW temperature significantly higher than that at the CPS divertor, no condensation on the FW is to be expected. Please note that this aspect has no precedent in present Fusion devices, on which lithium component operation leads to a systematic formation of highly deuterated cold lithium deposits. In the absence of wall pumping, suitable condensers at temperatures precluding the uptake of T must be envisaged. At this stage of knowledge, some of these potential issues are difficult to assess and devoted research seems necessary in the short term.

5. Summary and Conclusions.

Finding the right material for the plasma facing components of a Fusion Reactor is doubtlessly challenging. At present there is no certainty about the performance of the ITER selected combination in a future Reactor, but enough experimental evidence exists to foster intensive research on alternative solutions. Among them, liquid metals offer appealing characteristics but their use requires a change in the paradigm of the PWI research made to date. Fortunately enough, a slow, step-by-step transition from the present solid target-based solutions to the LM approach seems feasible. Contrary to some believes most of the experience gained on W research, for example, has a direct application to LM solutions if this material is used as the substrate supporting the CPS arrangements. In that sense, an “advanced liquid metal coating” concept better describes the resulting target component in the most conservative design. Two conceptual models of a divertor target, ELMAC (evaporable liquid metal advanced coating) and ILMAT (integrated liquid metal advanced target), based on this concept are here proposed. It is expected that a liquid metal coating can effectively protect the underlying component from any kind of surface damage, including that arising from the high particle flux of plasma particles (blistering, fuzzy and bubble formation, etc.) in addition to surface melting and cracking, effects which are known to be behind the full destruction of solid materials at long plasma exposure times.

A large degree of maturity is being achieved in the last years’ research on LMs in particular for the CPS concept. Machines like NSTX, FTU, EAST and KTM, among others, have a scientific program likely to enlighten many of the presently existing shadows. New LM candidates remain still unexplored and a plethora of “out of the box” ideas is continuously generated in the LM collectivity. However, the Fusion community is facing one of the greatest challenges ever undertaken and a lot of work still remains to be done in a rigorous, realistic way. A competitive LM Fusion engineering has to be developed in the meantime, able to cope with some of the challenges imposed by the new demands if a Fusion Reactor is planned in a few decades from now.

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References.

[1] R.P Wenninger et al., Nucl. Fusion 54 (2014) 114003

[2] H. Zohm et al., Nucl. Fusion 53 (2013) 073019

[3] K. Tobita et al., Nucl. Fusion 49 (2009) 075029,

[4] F. Piras et al., Plasma Phys Control Fusion 51 (2009) 055009

[5] N. Asakura et al., Nucl. Fusion 53 (2013) 123013.

[6] Y. Hirooka et al Nucl. Fusion 50 (2010) 077001

[7] M. Ono et al Nucl. Fusion 52 (2012) 037001

[8] G. Mazzitelli et al Nucl Fusion 55 (2015) 027001

[9] Y. Hirooka et al. TOFE-2014 Proceedings. Fusion Science & Technology, in press.

[10] J W Coenen et al. Phys Scr. T159 (2014) 014037

[11] B. Badger et al., ‘UWMAK-I – A Wisconsin Toroidal Fusion Reactor Design’ UWFDM-68 (1974)

[12] M.A. Abdou et al. Fusion Eng. Des. 54 (2001)181

[13] R Majestic et al. Fusion Eng. Des. 72 (2004) 121

[14] D. N. Ruzic et al., Nucl. Fusion vol. **51** (2011)102002

[15] G Z Zuo et al. Fusion Eng. Des. 89 (2014) 2845

[16] M Shimada and Y Hirooka. Nucl Fusion.54 (20014) 122002

[17] S.V. Mirnov et al., J. Nucl. Mater. 196-198 (1992) 45.

[18] S.V. Mirnov et al., Fusion Eng. Des. 81 (2006) 113.

[19] R B Gomes et al Fusion Eng. Des. 83 (2008) 102

[20] V Evtikhin et al. Fusion Eng. Des. 49-50 (2000) 195

[21] T W Morgan et al. http://dx.doi.org/10.1016/j.jnucmat.2014.11.085

[22] Y. Nagayama. Fusion Eng. Des. 84 (2009)1380

[23] I. Kirillin, Liquid Metal Coolants for Heat Pipes and Power Plants, 1990 Hemisphere Publ. Corp.

[24]] V Evtikhin et al. Plasma Phys Control Fusion 44(2002) 955

[25] S V Mirnov et al. Nucl.. Fusion 51 (2011) 073044

[26] M Ono et al. Nucl. Fusion 53 (2013) 113030

[27] M. Ono et al. Fusion Eng. Des. 89 (2014) 2838

[28] G. Mazzitelli et al., J. Nucl. Mater. (2015), http://dx.doi.org/10.1016/j.jnucmat.2014.12.050

[29] I. Lyublinski et al. Fusion Eng. Des. 87 (2012)1719

[30] D K Mansfield *et al Nucl. Fusion* 41 (2001) 1823

[31] R. Maingi et al., Phys.Rev. Lett. 105 (2010) 135004.

[32] J Sanchez et al. Nucl. Fusion 48 (2009)104018

[33] X.J. Zhang et al. Nucl. Fusion 52 (2012) 032002

[34] V. Pericoli Ridolfini, et al. Plasma Phys. Control. Fusion, 49 (2007) S123

[35] Chr. Day, et al., Towards a physics-integrated view on divertor pumping, Fusion Eng. Des. (2014), http://dx.doi.org/10.1016/j.fusengdes.2014.04.077

[36] C N Taylor et al. Physics of Plasmas 21 (2014)057101

[37] J P Allain et al. Phys Rev.B 76 (2007) 205434

[38] E Oyarzabal et al. J Nucl Mater. **452** (2014) 37

[39] F L Tabarés et al. "Liquid Lithium Limiter biasing experiments in the TJ-II stellarator" J. Nucl. Mater. 2014. http://dx.doi.org/10.1016/j.jnucmat.2014.11.090

[40] T.W. Morgan et al., J. Nucl. Mater. (2014), http://dx.doi.org/10.1016/j.jnucmat.2014.11.085

[41] A. B. Martin-Rojo et al. Fus Eng Design **89** (2014) 2915

[42] E. Oyarzabal, et al.J. Nucl. Mater.2014.http://dx.doi.org/10.1016/j.jnucmat.2014.10.088

[43] F.L. Tabarés et al."Studies of Plasma-Lithium Interactions in TJ-II". Proc. IAEA Conference, San Diego CA. 2012. P5/36

[44] C. N. Taylor, J. P. Allain, et al. J. Nucl. Mater. 415 (2011) S777

[45] S. Sharafat and N. Ghoniem 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

[46] Washburn, E. W. Physical Review, 1921.

[47] T F Lin et al. J. Nucl. Mater 433 (2013)55

[48] A. E. Gheribi et al, APL Materials 2 (2014) 076105

[49] M. A. Jaworski et al, J. Nucl. Mater.378 (2008) 105

[50] T. Abrams et al. J. Nucl. Mater. 433 (2013)

[51] R D Boyd. Fus. Sci. Technol.67 (2015)1

[52] Y Liu et al. Int. J. Heat Mass Transfer. 80 (2015) 605

[53] M A Jaworski Plasma Phys. Control. Fusion **55** (2013) 124040

[54] G Balasubramanian and I.K Puri. Appl Phys Letters 99 (2011) 013116

[55] E. Oyarzabal et al. Proc. PFCM. Aix en Provence (2015)

[56] S.Brezinsek et al. Nucl. Fusion **55** (2015) 063021

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 (Nw/m) at T_m	0.4	0.55	0.69
Dynamic viscosity	η (10^{-3} 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	κ(W/m/K) at T_m	45	30	50.9
Molar Heat Capacity	C_m (J/mol/K)	24.86	27.11	25.86

Figure 1.

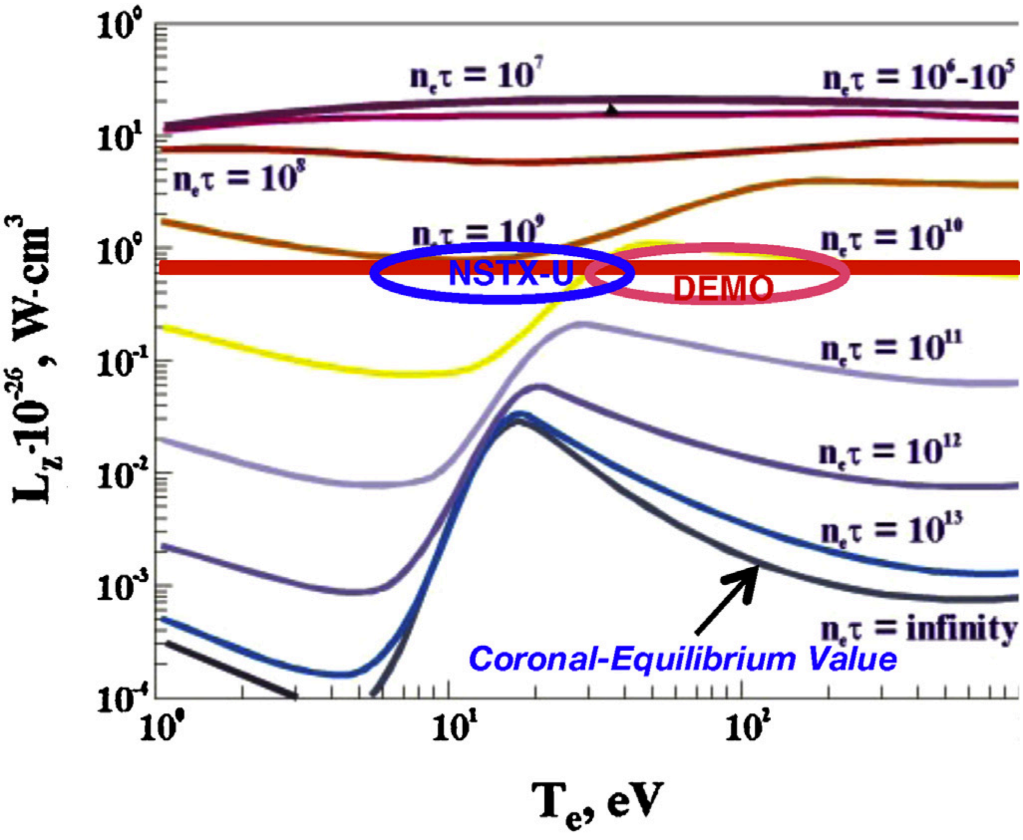
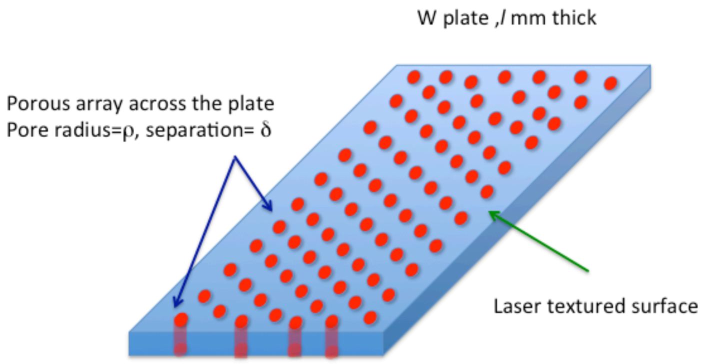


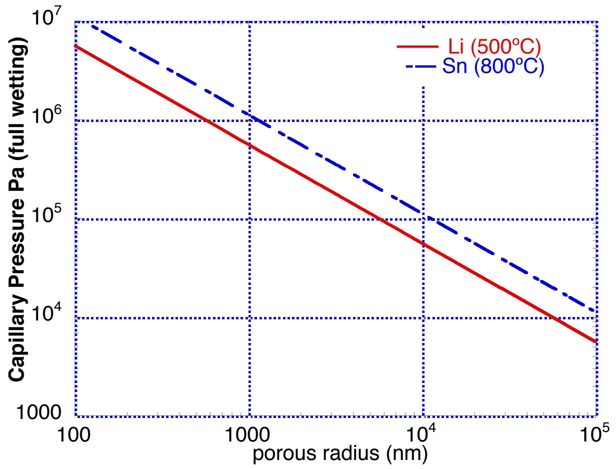
Fig 1. The Li non-equilibrium and coronal radiation (ne .τ= infinity) power per one atom and one electron as a function of electron temperature and ‘non-stationary parameter ne.τ'. From ref 27. Values of the cooling rate, L_z, for the expected conditions in DEMO and NSTX-U are given.

Figure 2.

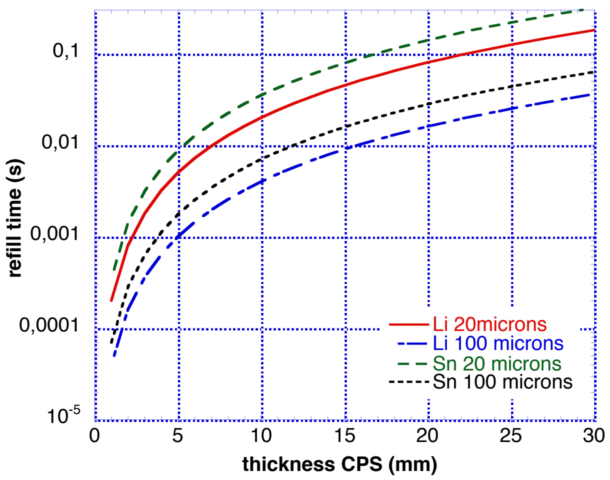
Dependence of some critical parameters on porous size for the selection of Capillary Porous supports for liquid metals in Fusion Devices. See text.



2.a) Sketch of geometry used for the calculations



2.b) Maximum capillary pressure vs pore size for Li and Sn at 500 and 800 ºC respectively



2.c) Minimum refilling time vs CPS thickness for two porous sizes (radius) and the same conditions as in 2a.

Fig 3. Two possible designs for liquid metal- protected targets in a Reactor Divertor.