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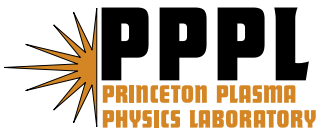
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Liquid Metal Walls, Lithium, And Low Recycling Boundary Conditions In Tokamaks

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Abstract. At present, the only solid material believed to be a viable option for plasma-facing components (PFCs) in a fusion reactor is tungsten. Operated at the lower temperatures typical of present-day fusion experiments, tungsten is known to suffer from surface degradation during long-term exposure to helium-containing plasmas, leading to reduced thermal conduction to the bulk, and enhanced erosion. Existing alloys are also quite brittle at temperatures under 700°C. However, at a sufficiently high operating temperature (700 – 1000 °C), tungsten is self-annealing and it is expected that surface damage will be reduced to the point where tungsten PFCs will have an acceptable lifetime in a reactor environment.

The existence of only one potentially viable option for solid PFCs, though, constitutes one of the most significant restrictions on design space for DEMO and follow-on fusion reactors. In contrast, there are several candidates for liquid metal-based PFCs, including gallium, tin, lithium, and tin-lithium eutectics. We will discuss options for liquid metal walls in tokamaks, looking at both high and low recycling materials. We will then focus in particular on one of the candidate liquids, lithium.

Lithium is known to have a high chemical affinity for hydrogen, and has been shown in test stands¹ and fusion experiments^{2,3} to produce a low recycling surface, especially when liquid. Because it is also low-Z and is usable in a tokamak over a reasonable temperature range (200 – 400 °C), it has been now been used as a PFC in several confinement experiments (TFTR, T11-M, CDX-U, NSTX, FTU, and TJ-II), with favorable results. The consequences of substituting low recycling walls for the traditional high recycling variety on tokamak equilibria are very extensive. We will discuss some of the expected modifications, briefly reviewing experimental results, and comparing the results to expectations.

Keywords: Liquid metals; Plasma-facing components, Plasma-material interactions; Lithium

PACS: 52.25.Xz, 52.40.Hf, 52.55.Fa, 52.55.Rk

INTRODUCTION

At the present time, the material of choice for conventional, solid plasma-facing components in a fusion reactor is tungsten, which would be operated at a wall temperature above the ductile to brittle transition, in excess of 700 °C. Even tungsten, however, requires significant materials development, in order to ensure that the plasma-facing components (PFCs) have adequate lifetime under the combined flux of neutrons and plasma at the reactor wall. Structural materials, such as reduced activation ferritic/martensitic (RAFM) steels, have shown promise in high neutron dose environments,⁴ but for reactor PFCs steels are not generally considered attractive. Significant development and testing of nanocomposited or other variants of tungsten are required to qualify this material for reactor PFC applications.

Even if neutron-tolerant variants of tungsten suitable for low-moderate neutron wall loading are developed, however, the existence of just this single candidate material for a PFC strongly restricts fusion reactor design options. There is, for example, no path to a compact, high beta, high wall loading fusion reactor concept, in the absence of a suitable wall material or construction. For lower wall loading concepts, the need for regular replacement of the PFC inventory will be a significant operational cost driver for fusion reactors. The erosion rate of tungsten, when used as a divertor target, is also too high to allow the use of thin-walled constructions. Thin PFCs have the advantage of low thermal impedance between the heat load and the coolant (for “hypervapotron” or heat pipe-like approaches). The maximum allowable rate of heat removal through a thick (one to a few centimeters) tungsten divertor tile sets an upper limit of approximately 20 MW/m² for power loading in tokamak divertors. This limit also imposes significant restrictions on fusion reactor designs.

If reactor PFCs could be renewed in-situ, then many restrictions on the choice of materials – for example, the allowable erosion rate - may be relaxed. An approach to a renewable PFC is to incorporate a layer of liquid metal as the plasma-facing surface. The design of a liquid metal PFC was the focus of the ALPS (Advanced Liquid Plasma-facing Surface) and APEX (Advanced Power EXtraction) programs in the United States starting in the late 1990s.⁵ Although molten salts (e.g FLiBe, a fluorine-lithium-beryllium salt) were briefly considered as candidate materials, the leading candidates for liquid PFCs were metals with melting points near or below 200 °C, and low vapor pressure over a wide temperature range.

The use of a constantly renewed liquid metal surface would allow the design of a much thinner interface between the PFC surface and the coolant, since the erosion lifetime requirements are reduced to the fluid replacement time - which would likely not exceed 10 – 100 seconds. In contrast, it would be impractical and costly to replace solid PFCs on a timescale shorter than a year, and the downtime associated with even yearly replacement would be considerable. Therefore, the use of even slowly flowing liquid metals raises the possibility of thin-walled divertor target constructions which can be intensely cooled, and could tolerate heat loads in excess of 20 MW/m². Alternative approaches, which may also tolerate very high heat loading, include fast-flowing liquid metal jets or films. In jet or fast-flowing design concepts, heat is removed with the flowing liquid metal, which is therefore “self-cooled”; no separate coolant loop would be employed. Another form of “self-cooling” which applies to liquid lithium PFCs is evaporative cooling. Lithium forms a vapor shield at very high heat flux; the associated self-shielding has been shown to permit operation of liquid lithium PFCs at very high localized heat loads, even under long-pulse conditions.⁶ Any such construction, whether a thin slowly flowing system or a thick fast-flowing jet or film, must, of course, be able to withstand disruptive forces, although the liquid metal PFC itself could presumably be reformed after a disruption, even if significant liquid loss through evaporation occurred.

Finally, the use of liquid metals may imply a simplified test cycle for reactor PFCs. Liquid metals are not subject to neutron damage, although the substrate along which they flow is. Conversely, the substrate is not subject to plasma-material interactions (PMI), although it must have a sufficient lifetime in a fusion neutron environment. The use of liquid metal PFCs separates PMI from neutron damage issues, so that the liquid

metal can be adequately tested in a nonnuclear tokamak, while the supporting structural system could, in principle, be tested in a fusion materials irradiation facility, which lacks the PMI component. For PMI testing, plasma exposure times which exceed the time it takes the liquid metal to flow from inlet to outlet (the residence time of the fluid in the tokamak) are unnecessary. This also reduces the required pulse length for PMI testing to 10 – 1000 seconds, and eliminates the need for high duty factor operation.

The primary problem with liquid metal PFCs is, of course, the difficulty of introducing the liquid metal to a tokamak, producing stable, constrained flow across the confining magnetic fields, even in the presence of plasma MHD activity, and finally removing the liquid metal from the tokamak for cooling or other processing. Because of the difficulties associated with generating such flow in a fusion system, and the fact that the tokamaks which are currently testing liquid metal PFCs have pulse lengths on the order of a second or less, near term experiments have focused on static liquid metal systems. Static liquid metal systems require renewal of the PFC between discharges only.

Liquid Metals for PFCs

The most promising liquid metals for PFC applications are lithium, gallium, and tin. Lithium and tin also form a eutectic, in the range of 80% tin - 20% lithium, which has possible advantages over either pure metal. At this time, however, most of the tokamak experiments in the world, which have employed liquid metals as PFCs, have concentrated on lithium, although a few experiments have been performed with gallium. Neither tin nor a tin-lithium eutectic has been investigated in a tokamak.

The physical properties of lithium, gallium, and tin in general differ significantly, although all three metals have melting points within 150 °C. Table 1 summarizes the relevant properties of all three metals.

Table 1. Properties of candidate liquid metals.

	Lithium	Gallium	Tin
Atomic number	3	31	50
Atomic weight	6.9	69.7	118.7
Melting point (° C)	180.5	29.8	232.0
Boiling point (° C)	1342	2204	2602
Liquid density (g/cm ³)	0.5	6.1	7.0
Sp. heat capacity (J/g °C)	3.58	0.37	0.23
Thermal conductivity (W/m°C)	40.6	84.8	66.8
Electrical resistivity (140 nΩ-m)	93	140	115
Temperature at which vapor pressure = 10 ⁻⁷ Torr (° C)	400	900	1000

Lithium, gallium, and tin span a wide range in atomic number, from the lowest Z of any solid (for lithium) to an atomic number in excess of molybdenum (for tin). The

specific heat capacity spans more than an order of magnitude, from tin (0.23 J/g°C) to lithium, which at 3.58 J/g°C has the highest specific heat of any material which is solid at room temperature. The limit in practical operating temperature for each of the metals is determined in part by the vapor pressure. An approximate limit is set by the temperature at which the equilibrium vapor pressure of the liquid equals 10^{-7} Torr; this limit is low for lithium (400 °C), but exceeds the maximum expected operating temperature for PFCs in a reactor for either gallium (900 °C), or tin (1000 °C).

A more relevant limit for operating temperature is set by the evaporation rate of the liquid metal PFC, which can be directly related to the plasma impurity influx. Evaporation rates for lithium, gallium, and tin, as well as a tin (~80%) – lithium (~20%) eutectic, are shown in Figure 1.⁷ The evaporation limit, and therefore the temperature limit, depends on where and how the PFC is employed. For example, the highest tolerance for an evaporative influx is in the divertor, which can be physically separated from the last closed flux surface (LCFS) by a significant distance, baffles, etc. A wall PFC is in closer proximity to the LCFS. For a wall PFC, the evaporative limit is also different for high recycling (“HR”) and low recycling (“LR”) equilibria, due to the difference in edge plasma temperature and therefore the sputtering yield – which adds to the edge impurity source. Again, the operating temperature limit for lithium is seen to be significantly below that for gallium or tin. It will be important to confirm these temperature limits in future experiments with liquid metal PFCs.

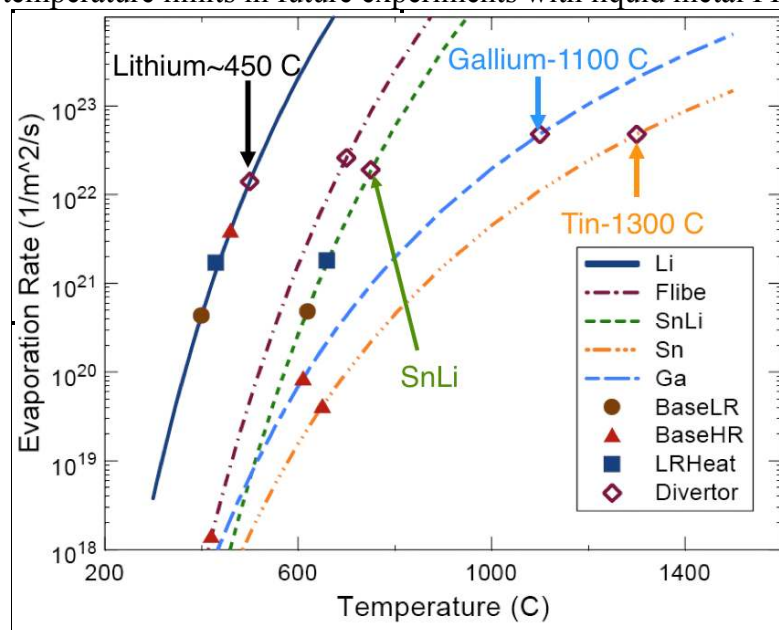


FIGURE 1. Evaporation rates and resultant temperature limits for liquid metal PFCs for either divertor or wall applications. The temperature limits depend on the resultant recycling coefficient (either “HR” for high recycling, or “LR” for low recycling equilibria). Flibe (a salt) is not considered here.

Not all vacuum-compatible structural materials are compatible with liquid metals. Virtually all metals are more chemically active when liquefied. In general, liquid gallium is the least chemically aggressive of the three, while the alkali liquid lithium is the most aggressive. For example, gallium alloys with many metals, but does not readily attack ceramics. Tin is compatible with alumina and quartz, even at elevated

temperatures, and with all the refractory and many common metals. Lithium is compatible with all the refractories, as well as vanadium, niobium, and steels over the applicable temperature range (less than 450 °C), provided that impurities such as nitrogen are eliminated as the lithium is recirculated. But lithium attacks most ceramics above 400 °C, and will rapidly and destructively invade materials such as quartz or alumina. Notable exceptions to this rule are yttria (Y₂O₃) and erbium oxide (Er₂O₃). Both of these ceramics have extremely high binding energies, and are resistant to attack by liquid lithium to temperatures of 600 – 700 °C.

Finally, although sodium is not suitable as a PFC, since it has unacceptably high vapor pressure when liquefied, it is of interest as a liquid metal coolant. Sodium is usable with many ceramics, and has been employed as a coolant in experimental fast fission reactors for decades.

Since a successful fusion reactor must convert heat to electricity at high thermodynamic efficiency, and since high power conversion efficiency requires a high temperature working fluid, most recent reactor designs have featured wall temperatures in the 600 – 800 °C range.⁸ This requirement would eliminate consideration of lithium as a PFC, were it not for the fact that of the three liquid metals considered here, lithium has by far the highest chemical affinity for isotopes of hydrogen, and is the only liquid metal which offers the possibility of greatly reduced hydrogen recycling. Test stand experiments have found no evidence of deuterium absorption on tin, and only weak retention of atomic deuterium in gallium,⁹ but experiments with lithium have demonstrated that retention of deuterium can occur up to an atomic ratio of 1:1.¹ These results, from the PISCES linear test stand, are shown in Figure 2.

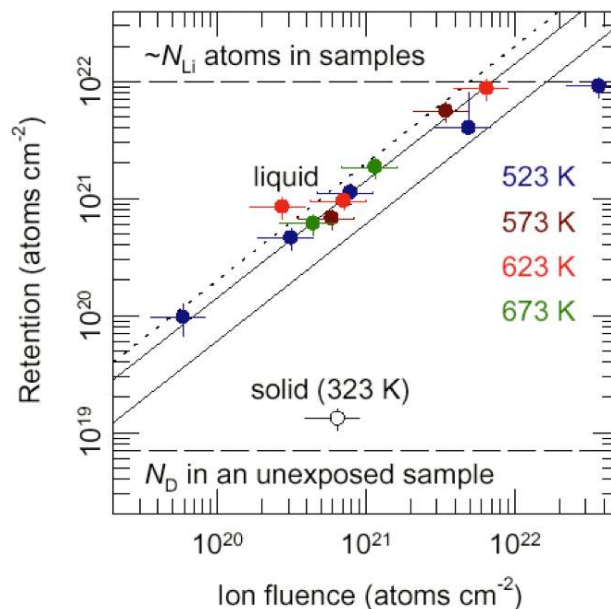


FIGURE 2. Retention vs. deuterium fluence on lithium in the PISCES experiments. For the liquid (at a temperature of 523 °K or above), deuterium is retained up to a 1:1 atomic ratio by lithium. Retention drops significantly for the solid, when only the surface layers of lithium are accessible.

Although solid lithium coatings have been used for wall conditioning in tokamak experiments since the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory (PPPL),¹⁰ and recently in the National Spherical Torus eXperiment (NSTX, also at PPPL),¹¹ it is only with a liquid PFC that the full lithium inventory is available for deuterium pumping. The diffusivity of deuterium in liquid lithium is high – of order $10^{-4} \text{ cm}^2 \text{ sec}^{-1}$ over the temperature range of 300 – 400°C,¹² but is negligible in solid lithium. Experiments in T11-M at TRINITI, Troitsk, Moscow¹³ the Current Drive eXperiment – Upgrade (CDX-U, at PPPL),³ and the Frascati Tokamak Upgrade (FTU, at ENEA Frascati)¹⁴ have all employed liquid lithium as a PFC, to varying degrees. Near-term experiments in the Lithium Tokamak eXperiment (LTX, at PPPL)¹⁵ and NSTX¹⁶ will make more extensive use of liquid lithium PFCs.

Lithium would not be a serious candidate for a liquid metal PFC, due to its low operating temperature limit, if it did not offer the possibility of very low recycling.

Recycling and the Properties of Lithium

The recycling coefficient R is defined as:

$$R \equiv \frac{\text{flux of neutrals from the wall which fuel the plasma}}{\text{flux of deuterons from the plasma into the wall}}$$

Recycling has a strong effect on the edge plasma conditions. Most of the power exhaust across the last closed flux surface of a tokamak is convective; power is conveyed from the confined plasma to the wall via the particle flux to the wall, at least in the absence of a strongly radiating edge. For a nonrecycling wall, the edge particle population is determined by particle confinement, and transport across the LCFS, alone – particles are not sourced from the wall via recycling. For a high recycling wall, the edge particle population consists of losses plus the recycling source. Since fueling a tokamak with an edge gas source is inefficient (typical edge fueling efficiencies are in the range of 10%), particles undergo multiple recycling events in the edge before penetrating to the core. Thus the edge particle population in a high recycling tokamak is very large compared to the tokamak fueling requirements. The edge fueling source in a high recycling tokamak dominates over any core fueling, by a significant factor.

The power input to the tokamak is fixed by Ohmic + auxiliary power input + fusion (alpha) power, if any. Thus, the power carried per particle in a low or nonrecycling tokamak, and therefore the edge temperature, is much higher than the power per particle (and the edge temperature) in a high recycling tokamak. A higher edge temperature may lead to enhanced sputtering of the PFCs, but it is also associated with higher performance in virtually all tokamak experiments. A reduction in recycling virtually always results in enhanced core plasma performance. As yet, no confined plasma has been operated in the very low recycling regime, where the wall particle source is negligible compared to the core particle source.

We denote the particle confinement time as τ_p , and the *effective* particle confinement time as τ_p^* - this is just the characteristic density decay time, in the absence of external particle fueling. Thus:

$$\tau_p^* \equiv \frac{\tau_p}{1 - R}$$

Nonzero recycling increases the effective particle confinement time τ_p^* . If $R \sim 1$, then the particle density in a tokamak discharge will not decrease, when external fueling is terminated, since all particles which escape confinement are recycled. Mechanisms for recycling include collisional processes such as reflection or backscattering from the surface of the PFC, or plasma-induced desorption from gas-saturated surface layers on the PFC.

The importance of adsorbed gas on the surface of the PFCs is clear if we realize that the number of particles in just a monolayer on the surface of the PFCs exceeds the total particle population of a typical tokamak discharge. Taking TFTR as an example, we can form the ratio of the number of particles in a surface monolayer (with a density typically 10^{16} cm^{-2}) to the number of particles in a typical discharge:

$$\frac{\langle n_e \rangle 2\pi^2 R_0 a^2}{10^{16} \text{ cm}^{-2} \cdot 4\pi^2 R_0 a} \approx \frac{3 \times 10^{13} \text{ cm}^{-3} \times 100 \text{ cm}}{2 \times 10^{16} \text{ cm}^{-2}} = 0.15$$

Where R_0, a are the major and minor radius of the plasma, respectively, and the average density of the discharge is taken as $3 \times 10^{13} \text{ cm}^{-3}$. Since there may be many monolayers of adsorbed gas on the surface of the wall, the wall inventory will almost certainly dwarf the plasma particle inventory. In a steady-state, high recycling tokamak, therefore, recycling is the dominant fueling source for the discharge.

Since liquid lithium has a very strong affinity for isotopes of hydrogen, and does not form hydrogen-rich surface layers because of the high diffusivity of hydrogen, the sole remaining mechanism by which hydrogen can be recycled from liquid lithium is direct reflection.

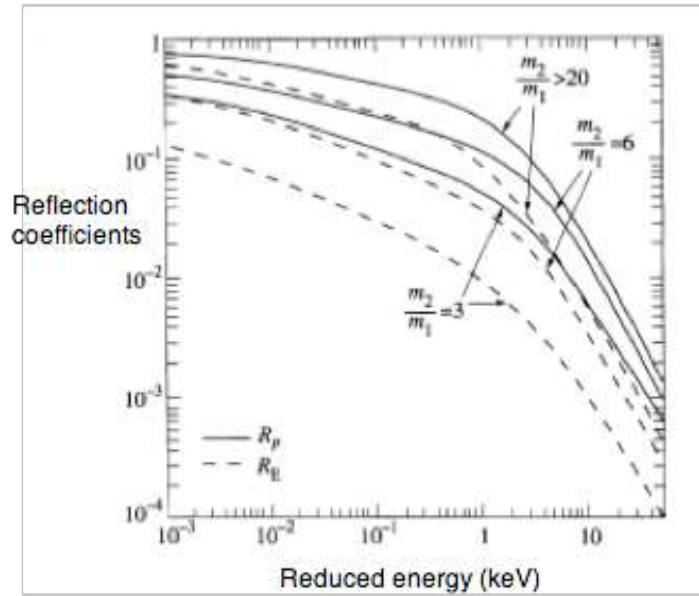


Figure 3. Probability of direct reflection (solid line) of an incident ion of mass m_1 from a surface composed of atoms with mass m_2 , as a function of the reduced energy. The dashed line indicates the fraction of the incident energy retained by the reflected particle.

Direct reflection is due to hard-sphere collisions between the incident ion and the atoms forming the wall PFC; it produces an irreducible minimum, energy dependent,

recycling coefficient. The probability of direct reflection as a function of the reduced energy is shown in Figure 3.^{17,18} Here the reduced energy is defined as:

$$\varepsilon \approx \frac{32.5m_2E}{(m_1 + m_2)Z_1Z_2(Z_1^{2/3} + Z_2^{2/3})^{1/2}}$$

Where (1) denotes the incident ion and (2) the target atom. Values of ε for deuterium incident on several PFC materials are shown in Table 2.

Table 2. Reduced energy for deuterium incident on several wall materials.

For D incident on:	Reduced energy
Li	$\varepsilon=4.78$ E
C	$\varepsilon=2.24$ E
Mo	$\varepsilon=0.21$ E
W	$\varepsilon=0.10$ E

For a given incident energy, the probability of direct reflection of deuterium from high-Z materials such as molybdenum or tungsten is considerably higher than from a low-Z material such as lithium. For 100 eV deuterium incident on lithium the probability of direct reflection drops to approximately 10%. It is important to note that the range of the incident deuteron in the wall material is very short; reflection occurs in the uppermost few hundred Ångstroms of the surface. Thin surface layers of oxygen or carbon on either a low Z material like lithium, or a high Z material like tungsten, strongly affect the probability of direct reflection. Also, the estimate shown in Figure 3 assumes that the particle is incoming at normal incidence. Off-normal incidence produces a higher probability of reflection. For a particle population with an average angle of incidence of 45°, the probability of reflection of an incoming 100 eV deuteron from a lithium surfaces doubles, to 20%. The probability drops to less than 10% for an incident energy in excess of 300 eV.¹⁹

Although recycling usually refers to a process involving the plasma ions, electrons are also “recycled” via secondary electron emission. Secondary electron emission is an important process, which can strongly cool the edge plasma. The power flow from the edge electron population to the wall/limiter/divertor is given by:

$$q_{pe} \approx (2kT_e + e\phi_0) \frac{0.6n_e c_s}{(1 - \delta_e)} - e\phi_0 \delta_e \frac{0.6n_e c_s}{(1 - \delta_e)}$$

Where q_{pe} is the power lost by the electron population, $\phi_0 = -\alpha(kT_e/e) \equiv$ the sheath potential at the wall/limiter/divertor, with α typically ~ 3 , c_s = the sound speed, and δ_e is the secondary electron emission coefficient. Some materials, such as boron (which is a common ingredient in tokamak wall conditioning) have very high secondary electron emission coefficients. Interestingly, lithium has the lowest secondary electron emission coefficient of any metal. The secondary electron emission coefficients as a function of primary energy for lithium, tin, and platinum (also a copious emitter) are shown in Figure 4.²⁰

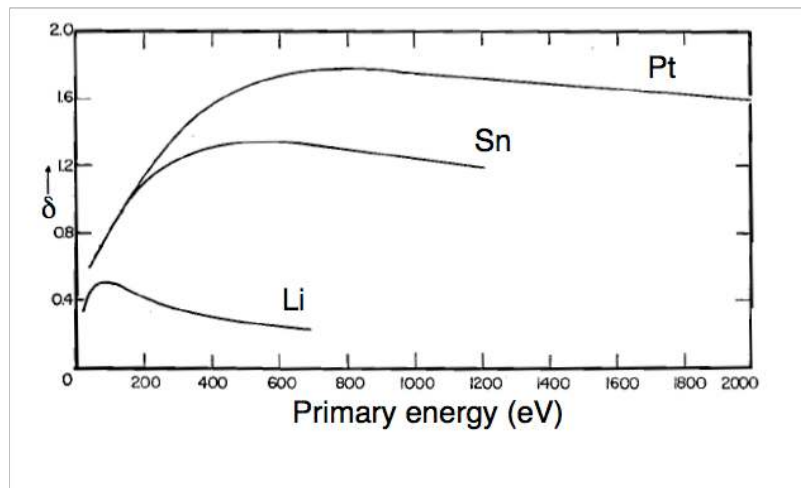


Figure 4. Secondary electron emission coefficients as a function of primary electron energy, for normal incidence on lithium, tin, and platinum. Measurements were performed with solid targets, however, no significant changes would be expected for a liquid target.

Figure 4 is relevant to unmagnetized emission; the effect of a magnetic field on secondaries is very difficult to model. As is the case for ion reflection, off-normal incidence has an effect on secondary emission, but the principal change is a modest shift in peak emission to higher primary energies.

Since lithium has the lowest atomic weight of any solid, sputtering by energetic deuterium, tritium, or helium could produce a large edge impurity source. In Figure 5 is shown the sputtering yield for deuterium incident on lithium at an angle of 45° , over the energy range of 10 – 1000 eV.¹⁹ The experimental results shown are for sputtering from a solid surface; it is very possible that sputtering from a liquid would better match modeling for a smooth surface.

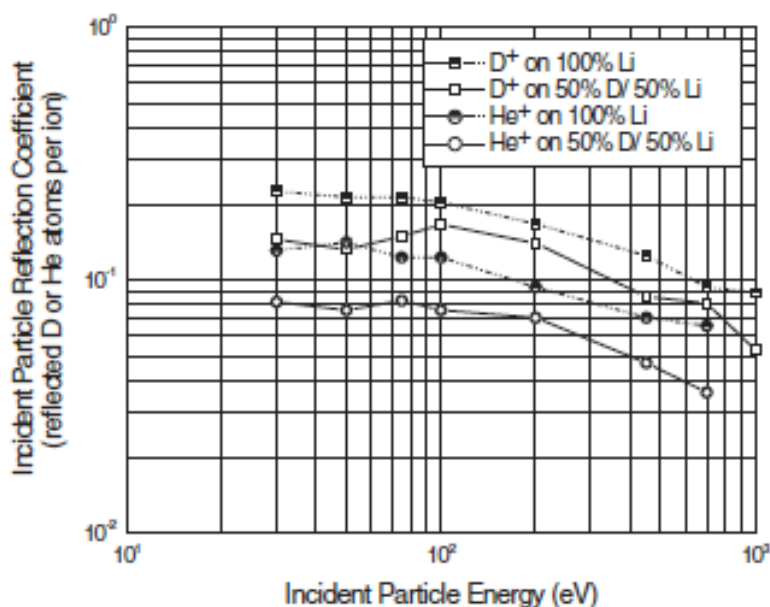


Figure 5. Sputtering of lithium by deuterium as a function of energy, for a 45° angle of incidence.

Although most sputtered PFC materials leave the surface as neutral atoms, the fraction of lithium which is sputtered as an ion is of order 60% for incident ion energies in the range of 0.5 – 1.0 keV (for incidence at 45°). Material sputtered as an ion will most likely be promptly redeposited. In addition, the low ionization energy of lithium increases the probability that even neutral lithium will be ionized in the wall sheath, and redeposited on the wall. Redeposition of a high fraction of sputtered lithium may explain why tokamak experiments which employ lithium wall conditioning typically operated with very low core plasma lithium impurity concentrations. In NSTX, the core lithium concentration is typically 0.1%.²¹ In TFTR, which employed a lithium coated wall limiting a hot (~keV) edge plasma, the core concentration of lithium was 0.5%.²²

Interest in low recycling discharges has driven recent experiments to the use of solid lithium as a wall conditioning technique, and the deployment of liquid lithium PFCs, despite the inherent difficulties of dealing with a liquid metal in a tokamak environment. Gallium and tin have barely been tested, but systems for the deployment of flowing liquid lithium walls in a tokamak would be very similar to systems for the deployment of flowing gallium or tin. Also, gallium or tin liquid metal PFCs would not have as restrictive an operating temperature limit as does lithium, nor do they accumulate deuterium and tritium from the discharge. The experience being gained at present with liquid lithium PFCs can certainly be extended to the use of other liquid metals.

Lithium Wall Conditioning and Liquid Lithium PFC Experiments

Here we will touch on a few highlights of experiments with lithium wall conditioning, wall coatings, and partial liquid lithium PFCs. The first large experiment to employ lithium wall conditioning through pellets, coatings, and edge injection was TFTR, starting in the late 1980s, and continuing through the termination of the TFTR project in 1997. TFTR was a limited, not a diverted, tokamak, so the improved confinement mode developed for high performance discharges was termed the supershot.²³ Production of a supershot discharge required a reduction in wall recycling, either through aggressive discharge cleaning to remove the wall hydrogen inventory in the carbon tiles, or through a combination of discharge cleaning and lithium wall coatings. The minimum documented recycling coefficient achieved in lithium-conditioned supershots was 0.7 – 0.85 (depending on whether the recycling coefficient was evaluated at the last closed flux surface, or the wall).²⁴ This represents a comparatively large reduction in recycling for a large tokamak, and was found to result in a significant enhancement in plasma performance. Figure 6 is a plot of the energy confinement time, normalized to the L-mode confinement scaling law,²⁵ for TFTR supershots which did (diamonds) or did not (squares) employ lithium pellets or wall coatings for conditioning and recycling reduction.²⁶ The arrow highlights discharges with extensive lithium wall coatings, which achieved a confinement enhancement factor, over L-mode scaling, of 3.3. The average confinement enhancement for supershots with discharge-cleaned carbon walls was 1.5. The record confinement time for TFTR, 330 msec, was achieved through extensive lithium wall conditioning and coatings.¹⁰

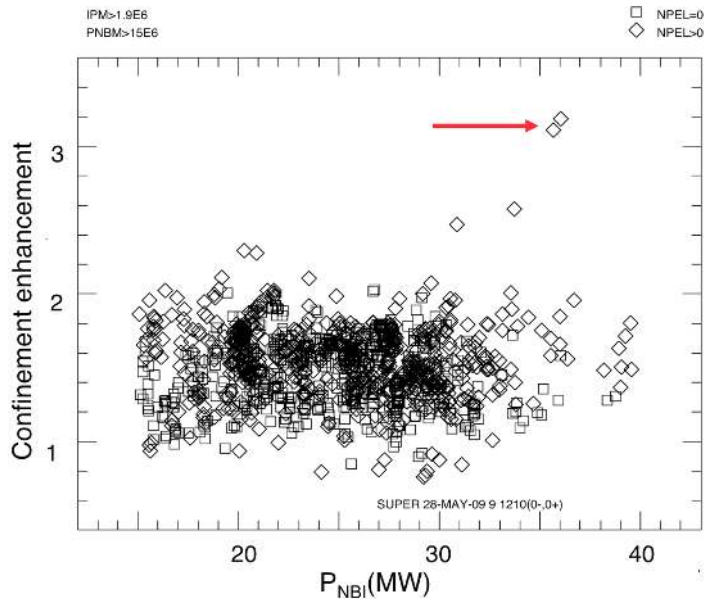


Figure 6. Scatter plot of energy confinement time enhancement, over L-mode scaling, for TFTR discharges with lithium pellets and wall conditioning (\diamond) and for cleaned carbon walls (\square).

More recently, the NSTX device has employed lithium gettering as a technique to reduce recycling and condition the carbon walls of the device. In this experiment, lithium is evaporated from an oven source to form a thin surface coating on the carbon PFCs. Coatings only a few microns thick are sufficient to ensure that plasma ions will interact only with the coating, and not with the underlying carbon tile. The technique is not unlike titanium gettering, which was, and still is, commonly used in smaller fusion experiments with stainless steel walls, except that lithium has much lower atomic number than titanium, and is more effective at pumping water and hydrogen. The lithium coatings produced in NSTX have been solid, although experiments with liquefied coatings are scheduled to begin in 2010.

The use of lithium wall coatings also resulted in enhancements to the energy confinement time in NSTX, especially in the electron loss channel.²¹ A number of other effects on the discharge, including the elimination of edge-localized modes (ELMs) with sufficient lithium coating, have been observed.²⁷ The NSTX group has also investigated techniques for lithium wall conditioning which may be extensible to long pulse or even steady-state operation.²¹

The first experiment with a liquid, rather than a solid, lithium limiter was conducted on the T11-M device, starting in the late 1990s.²⁸ The T11-M capillary porous (CPS) system employed multiple layers of molybdenum mesh to retain lithium via wetting and surface tension against motion induced by plasma-generated MHD forces on the liquid metal. A system based on the T11-M development, but larger and more extensive, has been more recently employed in the FTU tokamak, starting in 2006.^{14,29} A photograph of the FTU liquid lithium limiter system, prior to installation, is shown in Figure 7. In FTU, the lithium limiter system has mainly been used as a lithium source for wall coatings, rather than as the primary plasma limiting surface. Beneficial

effects observed on FTU during lithium experiments include a reduction in the plasma Z-effective, and an extension of the operational plasma density window somewhat beyond the Greenwald limit.²⁹



Figure 7. Photograph of the FTU liquid lithium limiter . The multilayer molybdenum mesh retention system is at top, in three sections, with the lithium reservoirs and heating system into each section, below the mesh surface.

Porous metallic systems to retain liquid lithium have also now been installed in NSTX¹⁶ at PPPL, although the NSTX approach employs a porous plasma-sprayed molybdenum surface rather than layers of molybdenum mesh. The use of plasma sprayed porous metal technology was developed for the LTX device at PPPL, and is applicable to large-area surfaces with complex shapes.

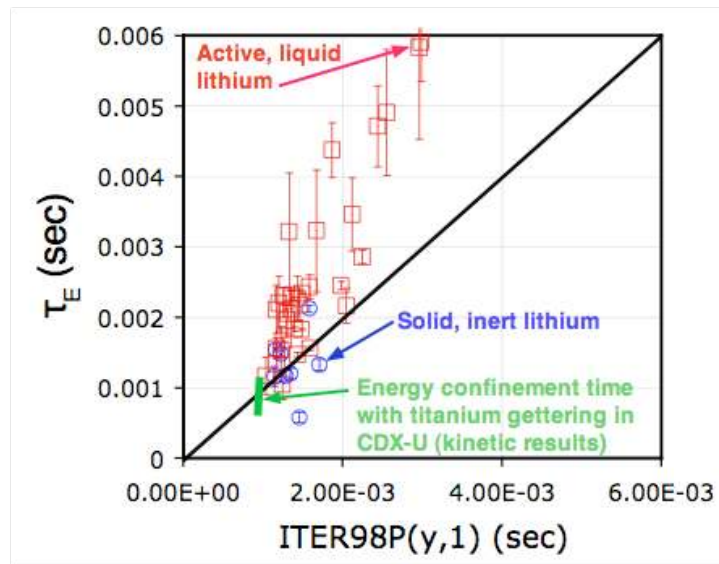


Figure 8. Energy confinement time, compared to ITER98P(y,1) scaling, for CDX-U in the case of solid, passivated lithium (blue points) and for active, liquefied lithium (red points).

The first experiment to employ a large-area liquid lithium limiter as a tokamak PFC was conducted on the CDX-U device, also at the Princeton Plasma Physics

Laboratory, from 2001 through 2005.³⁰ The CDX-U design employed an electrically heated toroidal tray, which was filled with liquid lithium. The tray provided an exposed area of liquid lithium of 2000 cm² as the lower plasma limiting surface, and was typically operated at a temperature of 300 – 400 °C during plasma discharges. The global recycling coefficient for CDX-U discharges which used the liquid lithium tray as a limiter were found to be in the range of 50 – 70%.³ A large increase in energy confinement – a factor of six - was found for low recycling discharges in CDX-U using the liquid lithium tray, compared to high recycling discharges in which the tray was either not filled with lithium, or not heated. The energy confinement results for CDX-U, compared to ITER98P(y,1) ELMy H-mode scaling,³¹ are shown in Figure 8. A summary of results from fusion experiments with liquid lithium PFCs has recently been published.³²

Further Development of Liquid Metal PFCs

There are many research topics still to be explored in liquid metal PFCs, including the need to deploy and test high recycling liquids in tokamaks, and a strong need to develop flowing systems, with stable, reliable, wall-adhered flows. The CPS system tested on T11-M and FTU employs an internal lithium reservoir which replaces any evaporative losses from the plasma-contacting lithium-filled mesh; this can be considered a demonstration of very slow flow, for replenishment only. However, liquid lithium systems with significant flow rates have only been demonstrated on test stands, such as the LIMITS facility at Sandia National Laboratory in the U.S.³³ An early, successful, exploration of a gallium jet-droplet limiter took place in the T3-M tokamak in the late 1980's.³⁴

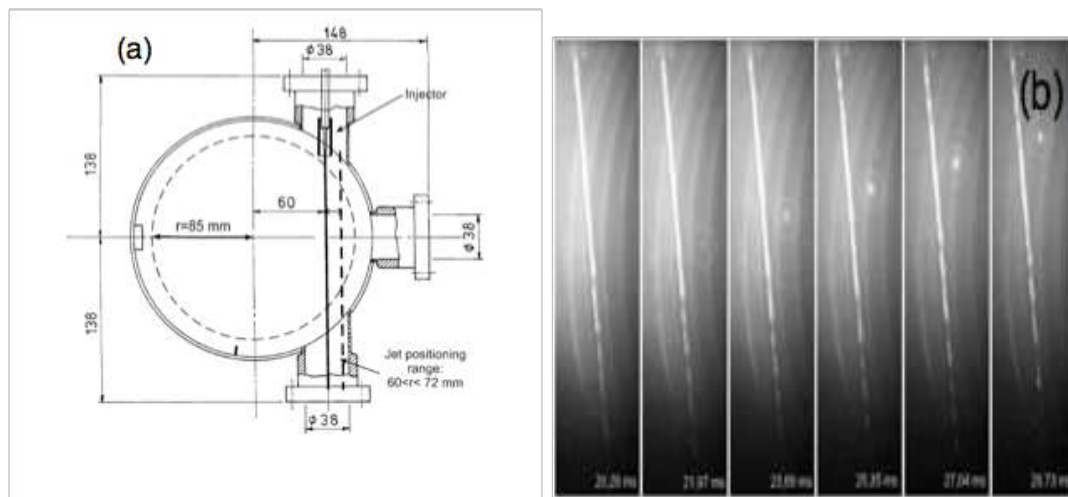


Figure 9. (a) Arrangement of the gallium jet limiter experiment in ISTTOK, and (b) fast camera images of the gallium jet in operation. Tokamak discharges with the gallium jet limiter exhibited similar levels of radiation to discharges operated against a carbon rail limiter.

The only recent test of gallium as a PFC in a tokamak was in the small ISTTOK device, which successfully employed a liquid gallium jet as a limiter.³⁵ An elevation

view of ISTTOK showing the installation of the jet, and a series of frames from a fast visible light camera showing the jet in operation, are shown in Figure 9(a & b).

Experiments in the formation and flow of liquid metals, other than lithium, on test stands, with magnetic fields relevant to spherical tokamaks such as NSTX, have been performed at the University of California at Los Angeles (UCLA). Tests with 20 centimeter wide, centimeter-deep channels with liquid metal flow velocities of 1 – 5 m/sec. show evidence of hydraulic shock formation in the presence of a magnetic field component normal to the surface of the fluid.³⁶ Alternative schemes which employ $\mathbf{J} \times \mathbf{B}$ forces to constrain the liquid metal flow to a guide wall conformal to the last closed flux surface of the tokamak have been proposed,³⁷ but not demonstrated. Flows along flux surfaces would avoid issues with shocks and turbulence generated by surface-normal magnetic fields.

Approaches to cooling liquid metal PFCs from behind, in the case of slow flows, which are not self-cooled, are being explored. Liquid lithium has been shown to effectively self-generate flows which can dissipate very high heat loads – up to 60 MW/m² for 300 seconds in tests with a small electron beam system in the CDX-U experiments.³⁰ Experiments with electron beam heating of liquid lithium targets at the University of Illinois have produced similar results, along with evidence that thermoelectric effects – the self-generation of flows through thermoelectric currents and the resultant $\mathbf{J} \times \mathbf{B}$ forces – are probably responsible.³⁸ CPS systems have demonstrated similar capabilities – 25 MW/m² steady state, and greater than 50 MW/m² transiently, with an estimated maximum heat flux in excess of 100 MW/m², although at high surface temperatures and correspondingly high evaporation rates.⁶

One of the harshest tests of heat dissipation in a liquid lithium system will be provided by the International Fusion Materials Irradiation Facility (IFMIF), in which fast-flowing liquid lithium (albeit without magnetic field) will be used as the target for a 10 MW continuous deuterium beam, with a local power density of 1 GW/m².³⁹ This is a self-cooled system, as described previously, with lithium flow rates up to 20 m/sec. IFMIF, of course, is intended to produce a high duty factor source of 14 MeV neutrons via the D-Li stripping reaction, so the nozzles, flow formers, and substrates employed for the liquid lithium target will inevitably be tested for simultaneous neutron irradiation and lithium tolerance during the course of operations.

Several tokamak experiments plan expanded tests of liquid lithium PFCs in the next few years. These include FTU, which is constructing a 90° toroidal CPS system, NSTX, which has installed a fully toroidal, heated, outer divertor segment using porous molybdenum to retain liquid lithium, and LTX, which will be operating with a 5 m², full liquid lithium thin-film wall in 2010. Success with static liquid lithium PFC tests would encourage continued development of flowing, continuously renewed liquid metal systems.

Finally, numerical modeling of flowing liquid metal tokamak PFC systems has not been discussed here. In fusion reactor design studies, liquid metal MHD effects and flows have long been considered, both analytically and numerically, in connection with tritium breeding blankets. Recent efforts at UCLA and HyperComp Corporation have produced relevant MHD models for open-channel flow of liquid metals in tokamak magnetic fields; a summary of this work and other modeling of liquid metal MHD flows has been given by Morley.⁴⁰

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