

# High-temperature, liquid metal plasma-facing component research and development for the NSTX-U

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## Abstract:

Liquid metal plasma-facing components are actively studied as a possible plasma-facing component (PFC) material in current and future fusion experiments. Liquid lithium, in particular, offers a low-Z plasma-facing material in addition to the other properties of liquid metal PFCs: self-healing, renewable, and immunity to neutron damage. Experiments with liquid lithium are challenging due to the reactive nature of the metal which leads to the rapid formation of oxide and carbonate layers when exposed to air. The complexity of implementing liquid PFCs recommends a graded approach with pre-filled divertor targets as an intermediate technology. Successful experiments with lithium require a strategy for minimizing or eliminating the surface contaminants that are compatible with experimental conditions. Preliminary experiments on the use of a sacrificial, removable metal layer for use with lithium-based divertor targets have been conducted indicating feasibility of the concept.

## 1 Introduction

Liquid metal plasma-facing components (PFCs) are a potential technology for use in present and future experimental fusion devices. The novel features of a liquid metal PFC are that it provides a self-healing, renewable surface, eliminates the issue of surface cracking due to thermomechanical stresses induced by transient events, and neutron damage is separated from plasma-induced damage effects[1]. In the case of liquid lithium, the plasma-facing material also presents a low-Z surface and the capacity for absorption and subsequent transport of the fusion fuels[2]. These latter qualities make experiments with lithium attractive for current devices[3].

Recent studies of lithium surface conditioning have highlighted the sensitive nature of the surface. Studies of surface composition on exposure to common vacuum contaminants showed rapid conversion of the surface to an oxide[4]. The conversion to an oxygen- and carbon-bearing surface is also exhibited in tokamak contexts where these impurities show no differentiation whether the substrate is graphite or metallic in nature[5]. Further, modeling[6] and experiments[7] of these surfaces indicates both qualitative and quantitative differences in various phenomena such as hydrogenic fuel retention and release. Continuously replenished liquid surfaces and a continuously operating fusion reactor are expected to have relatively good purity control such that the surfaces are, at present, expected to be dominantly composed of lithium. Experiments on contaminated surfaces, therefore, present difficulty extrapolating to future devices with different surface conditions.

Previous efforts at maintaining clean surface conditions have been successful with effort. The Red Star Capillary-Porous System (CPS) devices implement a reservoir of lithium in contact with a wicking mesh on a limiter structure[8]. The reservoir can be heated when desired and discharge cleaned to remove gettered impurities prior to operation as the limiter in a tokamak discharge. The method of discharge cleaning was also used in the PISCES-B linear plasma device experiments in an attempt to limit the impact of these impurities on experimental results[9]. The CPS devices utilize a removable sealing surface that is removed and retracted once adequate vacuum conditions are achieved.

Prior efforts of liquid divertor targets have been conducted on the NSTX device[5]. These experiments featured large-area, porous divertor targets that were filled using the NSTX lithium evaporation system. These same experiments, however, exhibited contamination from oxygen and carbon compounds in the vessel. Further, the details of the technical implementation prevented the usage of discharge cleaning similar to that used in the PISCES-B device. As a result, the experiments in NSTX indicated little relative change from experiments conducted on graphite surfaces vs. the metallic LLD.

The NSTX-U program has devised a program for the development and testing of liquid metal PFCs[10]. The program would culminate in the implementation of fully-flowing, recirculating liquid metal divertor components and enable exploration of novel plasma regimes such as vapor-shielded targets[1]. An interim step to this final goal is the implementation of pre-filled liquid metal targets for the NSTX-U divertor[10, 11]. Essential to successful testing of such targets is the development of a strategy to minimize or mitigate contamination of the lithium in the target. This proceeding describes a novel method for mitigating contamination of lithium targets and initial experiments for demonstrating the technical feasibility of implementing such pre-filled targets.

## 2 Conceptual Basis

The NSTX-U experimental device is a spherical-tokamak with major radius  $R \simeq 1$  m and aspect ratio  $A < 2$ [12]. The NSTX-U PFCs are composed of ATJ-graphite at present and a multi-year program for conversion to metallic components is described in ref. [10]. Due to the large quantity of graphite ( $> 1000$  kg), an extensive bake-out is required to reduce

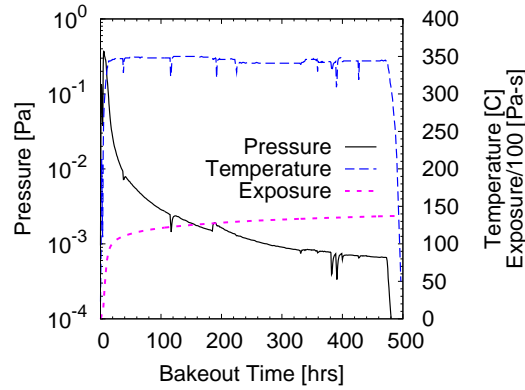


FIG. 1: Temperature and pressure telemetry from the 2010 NSTX bakeout. The exposure quantity (pressure-time integral) is shown as a function of time for this bakeout is also shown.

the amount of water vapor in the vacuum vessel. The bake-out procedure essentially consists of raising the temperature of the in-vessel components to approximately 350°C and maintaining this temperature until the vessel pressure reaches an acceptable limit. A representative bake-out was held in the year 2010 and is shown in figure 1. Surface-science experiments have demonstrated that conversion of materials exposed to gases is well characterized by the pressure-time integral or “exposure” [4]. Figure 1 also computes the exposure for this bake-out.

As can be seen in the figure, the NSTX and, by extension, NSTX-U presents a challenging environment for lithium work. Bake-out typically lasts approximately 500 hrs with temperatures of 350 °C for the entire period. This temperature is well above the lithium melting point of 180°C. In addition, surface-science experiments have shown nearly complete conversion of the first few nanometers of lithium into an oxide with approximately  $2.7 \times 10^{-3}$  Pa – s of exposure. The integrated exposure for the 2010 NSTX bake-out was  $1.5 \times 10^4$  Pa – s or nearly *seven orders of magnitude* more exposure than needed to convert the surface layers to the oxide. It should be noted, as well, that the surface experiments were conducted only at room temperature.

The method of Red Star will not serve in the general application of a component in the divertor of a confinement device. In the CPS devices, the macroscopic metal foil is released from the limiter and then mechanically retracted through the port that introduces the limiter. In general, one will not be able to locate all surfaces of a divertor near such ports without complex paths through the machine. In addition, retraction below or behind the PFC suggests the inclusion of a void region that can serve to store the surface metal layer. This requirement is often at odds with the need to tightly couple PFCs to a thermal reservoir and further structural components.

Filling of a PFC after bake-out procedures is likely difficult to achieve in a controlled manner. In this concept, experiments on a liquid lithium surface might be attempted by baking out the vacuum vessel and then filling a liquid PFC target after the fact. This

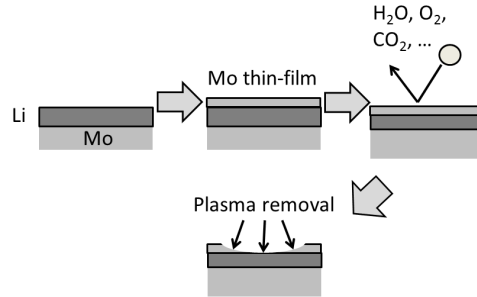


FIG. 2: Diagram of present scheme for mitigating contamination of a prefilled lithium component. First, lithium is loaded onto a metallic substrate, in this case composed of molybdenum. A thin film of molybdenum is deposited on top of the lithium. This thin film serves to avoid contamination of the surface from incident oxygen, water, or other molecules. Finally, when ready to proceed with experiments, the protective thin-film of molybdenum is removed by plasma etching leaving the original lithium layer.

particular method was recently tested on the Magnum-PSI linear plasma device in the testing of the LiMIT trench concept[13]. Successful loading was achieved after heating the sample to 475°C as well as agitating the surface of the liquid. With the presence of a manipulator for loading the target, agitation may be feasible also, but in general, a complex mechanical system will be required to reach remote locations inside of a toroidal confinement device. This approach, too, would seem sub-optimal due to the complex support hardware as well as the port-space allocation to support the activities.

In this work, therefore, we consider an alternative approach illustrated in figure 2. In a glove-box, or other controlled, inert atmosphere environment, the PFC sample will be loaded with lithium and solidified. Next, while maintaining the inert atmosphere, a metallic thin-film is applied on top of the lithium layer. This thin-film will prevent reaction between atmospheric gases such as those found in ordinary handling and during plasma bake-out. After bake-out, the thin-film is removed by plasma etching. This final step exposes the lithium layer and allows further experiments to proceed.

The essential advantages of this scheme are as follows. First, the eroding thin-film approach eliminates the need for storing a macroscopic film as utilized by the CPS method. Second, glow-discharge cleaning systems are a common and easily deployed method for generating a plasma in the vessel. Erosion of the thin-film can be enhanced by making the PFC target bias-able as considered in recent design studies[11]. Finally, by utilizing the identical metal as the substrate, the introduction of new materials into the tokamak can be avoided, thereby providing for cleaner experimental conditions. In the case of NSTX-U, molybdenum is currently the lead material for future upgrades and can be conveniently applied via physical vapor deposition techniques such as magnetron sputtering.

If, however, one considers the use of other materials for the layer, some basic re-

TABLE I: COMPARISON OF HELIUM AND DEUTERIUM SPUTTER YIELDS IN ATOMS PER INCIDENT ION.

Energy (eV)	Deuterium Yield	Helium Yield
100	$4.11 \times 10^{-6}$	$3.01 \times 10^{-3}$
200	$8.98 \times 10^{-4}$	$1.16 \times 10^{-2}$

quirements can be described. First, since the thin-film must remain intact during the bake-out process, it must be compatible with the liquid metal beneath it. Dissolution into the liquid partially through the bake-out constitutes failure. Second, the thin-film must be deposited to sufficient thickness that it remains intact during thermal cycling and the melt-thaw cycle. Third, the thin-film must be thin enough that excessive plasma etching is not required as extreme amounts of time might be required for very thick, difficult-to-erode materials. Fourth, the thin-film should not liquefy nor evaporate for the temperature-range under consideration.

In the case of the present program, we consider the use of molybdenum substrate and as the sacrificial thin-film material. Molybdenum erosion as a function of incident-particle energy can be calculated with the use of the Bohdansky formula and constants available in the literature[14]. Table I shows a comparison of sputter yields calculated using these values. Higher erosion rates can be obtained with the use of heavier gases such as neon and argon, however these gases can exhibit long residence times in the vacuum vessel and prove difficult to remove in a timely fashion. Deuterium and helium, on the other hand, are often used in glow discharge cleaning processes and present little additional difficulties.

The rate of removal of the material,  $\Gamma_{layer}$  is related to the yield,  $Y$  and incident flux,  $\Gamma_{inc}$  in the following way:

$$\Gamma_{layer} = Y\Gamma_{inc} = Y\Gamma_{\parallel} \sin(\alpha) \quad (1)$$

where  $\Gamma_{\parallel} = N_e c_s$  is the parallel flux density in the plasma and  $\alpha$  is the angle of incidence. In the case where the electron density is  $1 \times 10^{19} \text{ m}^{-3}$  and the electron temperature is 10 eV with an angle of incidence  $\alpha = 5^\circ$ , one calculates that 1s of exposure with 200 V bias will erode  $2.5 \times 10^{21} \text{ \#}/\text{m}^2$ . With the use of the number density of molybdenum, this can be converted to a material thickness of  $\approx 40 \text{ nm}$ .

### 3 Apparatus and Approach

Optimization of the PFC can be effected through the selection and engineering of the porous layer[1, 11]. In addition to examining previous flame-sprayed surfaces[5], novel materials have also been considered. In particular, a porosity-enhanced flame-sprayed material has also been evaluated as has a wire-EDM, micro-machined material. Initial evaluation is with the use of surrogate fluids such as isopropanol or water. Wicking

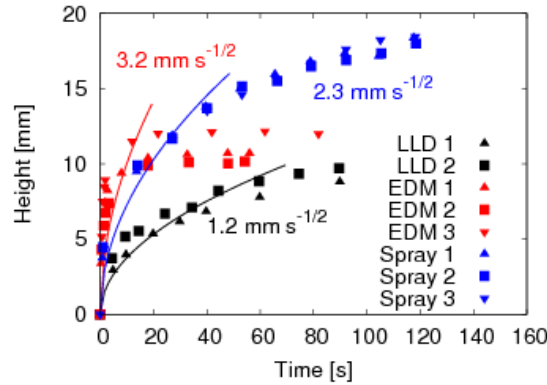


FIG. 3: Wicking height experimental results with three different candidate materials. A square-root time dependence function is fit to the early-time data for each material to estimate the sorptivity. Two types of flame-sprayed molybdenum (“LLD” and “Spray”) and a micro-textured, molybdenum surface (“EDM”). Numbers for each label indicate repeated tests. Wicking height as a function of time indicates a speed where faster wicking indicates improved performance. Experiments are conducted with surrogate fluid for these tests.

height results are compared in figure 3. Information on the porous sorptivity as a metric of performance can be found in the literature[10].

The porosity-enhanced flame-spray is achieved with the use of a pseudo-lost-wax process involving NaCl. The NaCl crystals are co-deposited with the molybdenum metal and then dissolved with water. The layers were applied by the Falmer Thermal Spray company. Figure 4 shows images before and after the removal of the sacrificial salt material. As can be seen in the figures, though, the flame-spray process does not leave a large quantity of salt behind. The quantity of salt has been evaluated by mass measurements and conductivity of the dissolving fluid. Initial estimates indicate a 25 mm square layer of  $\approx 0.1$  mm nominal thickness only contains about 1.7g of NaCl.

The sorptivity results indicate that early-time behavior of the layers favors the use of the EDM micro-machined surfaces. However, the departures from  $\sqrt{t}$  dependence indicate additional physical phenomena are present and a more comprehensive model is required to explain the data available.

Initial experiments have been conducted with the use of the “MCATS” and “TUFCON” experimental devices at the University of Illinois at Urbana-Champaign. These experiments are together able to apply lithium layers, deposit molybdenum layers as well as simulate an NSTX bake-out through an accelerated pressure-time test at 350°C. The accelerated pressure-time test is accomplished through the use of a novel water-carbon dioxide bubbler apparatus. Once the accelerated time test is completed, the surface is exposed to an etching plasma with plasma composition monitored by optical emission spectroscopy. Success is evaluated through the Li-I and O-I emission relative to background He emission in the plasma. The initial feasibility has been assessed and will be

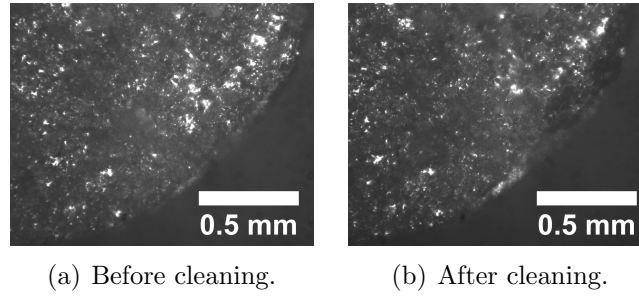


FIG. 4: Visible image of porous sample (a) before and (b) after salt removal. Scale bar is approximate. Careful comparison of the two images can identify specific salt crystals that were removed during the cleaning procedure.

reported in the full journal manuscript.

## 4 Conclusions

Continued development of liquid metal PFCs for use in diverted confinement devices has created the need for novel methods of introducing lithium to the machine. A novel method for enabling the use of pre-filled lithium targets has been proposed. The method provides several advantages over other demonstrated methods such as removable macroscopic metal foils or *in situ* loading after bake-out. Further development of the porous material has also been conducted with indications that the EDM micro-machined surface provides the most rapid wicking rate at early times. The simple sorptivity model is not, however, sufficient to explain all data available and work continues to develop a more comprehensive model. The evaluation of the eroding thin-film method has been conducted and will be reported in the full journal manuscript.

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