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ALPS – Advanced Limiter-divertor Plasma-facing Systems*

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Abstract

The Advanced Limiter-divertor Plasma-facing Systems (ALPS) program was initiated in order to evaluate the potential for improved performance and lifetime for plasma-facing systems. The main goal of the program is to demonstrate the advantages of advanced limiter/divertor systems over conventional systems in terms of power density capability, component lifetime, and power conversion efficiency, while providing for safe operation and minimizing impurity concerns for the plasma. Most of the work to date has been

applied to free surface liquids. A multi-disciplinary team from several institutions has been organized to address the key issues associated with these systems. The main performance goals for advanced limiters and divertors are a peak heat flux of >50 MW/m^2, elimination of a lifetime limit for erosion, and the ability to extract useful heat at high power conversion efficiency (~40%). The evaluation of various options is being conducted through a combination of laboratory experiments, modeling of key processes, and conceptual design studies. The current emphasis for the work is on the effects of free surface liquids on plasma edge performance.

1. Introduction

The Advanced Limiter-divertor Plasma-facing Systems (ALPS) program is evaluating the potential for improved performance and lifetime for plasma-facing systems. The ALPS team has worked together to address key issues through analysis and experimentation, to establish procedures for evaluation of different concepts, and to establish closer ties with the fusion plasma physics community as well as other areas of advanced technology development. The main goal of the program is to demonstrate the advantages of advanced limiter/divertor systems over conventional systems in terms of power density capability, component lifetime, and power conversion efficiency, while providing for safe operation and minimizing impurity concerns for the plasma. Systems being considered include both free surface liquids and advanced solid plasma facing systems, although most of the work to date has focussed on free surface liquid systems. The technical information given below is limited to free surface liquid systems.

The idea of using liquids for plasma facing components goes back over twenty years [1,2] and, since then, most of the effort to examine these systems has focused on divertors in tokamaks. The liquid options can be divided into two major classes - concepts with film flow over solid surfaces and concepts with droplets or waterfalls. Film flow concepts are further classified by the speed of flow and by the choice of liquid and backing materials. Droplet concepts are further classified by the droplet size, the method of droplet formation, and the choice of liquid and backing materials. The range of options to be considered is presented in Table 1, which shows the liquids, configurations, and confinement schemes under consideration.

One manifestation of the liquid surface concept is shown in Figure 1 where liquid jets are substituted in place of solid divertor collector plates. The jet velocity is ~10 m/s, and the length of the jet is 30-40 cm before entering the capture manifolds. In order to assess the potential for such liquid surface components, a number of issues must be resolved. The key issues identified are:

Effect of liquid surfaces on plasma edge and core performance

Effects of transient/disruption events

Achieving high power density

DT/He trapping and release from surfaces

The following sections summarize the progress to date on addressing these issues.

2. Effect on plasma edge and core performance

Interactions of the liquid surface with the plasma edge will affect the operating limits of free surface liquid systems. Areas being addressed include (1) surface temperature, plasma edge temperature, and heat flux limits on flowing liquid surface divertors, (2) sputtering and evaporation effects on scrape-off layer (SOL) and edge plasma, tritium codeposition, (3) surface transient response to overheating, (4) helium and D-T uptake in the plasma facing surfaces, and effects on core plasma and reactor performance, (5) compatibility between wall and divertor materials, and (6) critical data needs (e.g., self-sputtering yields).

2.1 Modeling Studies

Calculations were made to provide calculations of the two-dimensional edge-plasma profiles in the presence of liquid divertors and walls using the UEDGE transport code for the purpose of assessing impurity influx into the core plasma from evaporation and sputtering from liquid surfaces. The studies to date have been in a tokamak geometry. The use of a hydrogen-absorbing divertor material such as liquid lithium results in a low-recycling divertor plasma with high plate temperature, low density, and somewhat lower peak heat-flux than a high-recycling divertor. Physical sputtering of Li appears not to be a problem, but evaporation and self-sputtering needs to be further assessed.

The 2D UEDGE code was used to obtain profiles of hydrogen ion density, parallel ion velocity, and separate ion and electron temperatures. The base-case is an ITER-like tokamak where the transport simulation sets boundary conditions of power and density a small distance inside the magnetic separatrix and calculates the resulting scrape-off layer (SOL) profiles. Of particular interest has been the effect of low-recycling divertor plates such as those of liquid lithium. These calculations show that the peak heat flux actually drops in the low recycling regime because electron heat transfer is in the sheath-limited regime where there is only a small drop between the midplane and the divertor plate. Plate electron temperature is about 220 eV for the anomalous radial transport coefficient of 0.33 m**2/s for density and 0.5 m**2/s for electron and ion energy.

Redeposition of sputtered particles was analyzed for the low recycling divertor using the WBC code. For the WBC code lithium analysis, sputtered Li atoms were launched from the divertor surface into a spatially-unvarying near-surface plasma characterized by high electron temperature and low electron density. Particles are launched with a "cosine" type angular distribution, and random-collision-cascade energy distribution, and with a preliminary binding energy estimate. The 3-D particle trajectory is then computed with a full kinetic treatment, including Lorentz force motion and charge-changing and velocity-changing collisions with the plasma. A particle history terminates upon redeposition to the surface or leaving the ~20 cm near-surface region. Table 2 shows selected key redeposition parameters from this study for the case of an edge temperature of ~200 eV.

The following is observed: (1) very high near-surface lithium redeposition rate (~100%), (2) high redeposited average energy with highly oblique Li ion impingement. Result (1) is favorable showing low potential for plasma contamination by sputtered lithium. Result (2) gives rise to concerns about runaway self-sputtering although preliminary estimates show that this will probably not occur.

2.2 Experimental Studies

Experimental data on plasma materials interactions are being obtained from several institutions including Sandia National Laboratory, University of California (San Diego), the University of Illinois (Urbana-Champaign), and General Atomics.

The plasma-materials interactions of both solid and liquid lithium are being investigated in the PISCES-B device. The objective of these experiments is provide sufficient experimental measurements of lithium, while exposed to actual plasma environments, to allow benchmarking of the various modeling codes and thereby to increase the confidence of calculations when these codes are applied to plasma confinement devices. Lithium samples, in both solid and liquid states, have been exposed to deuterium and helium plasma bombardment. Spectroscopic measurements of the ionization rates of sputtered atomic neutral particles are in good agreement with calculated rates [3].

Doppler shift measurements of light emitted from neutral lithium atoms ejected from the surface confirm a surface binding energy of 1.7 eV for solid lithium samples. During liquid sample exposures the Doppler shift measurements see evidence of evaporation like loss from the surface. Finally, the comparison of weight loss data to spectroscopic measurements indicates the presence of a chemical erosion mechanism during deuterium plasma exposure, which does not appear during helium plasma exposure.

Plasma material interactions with gallium are also being investigated. The primary objectives are measuring the sputtering yield and deuterium retention in plasma exposed liquid gallium under different experimental conditions. Low temperature (330 K) liquid gallium sputtering experiments performed on PISCES agree well with the predictions calculated by Laszlo and Eckstein [4] as shown in Figure 2. The sputtering measurements were performed using both a weight loss measurement technique as well as a spectroscopic technique. Deuterium retention in plasma exposed liquid gallium showed a saturated level around 4.5×10^{17} D/cm^2 over a wide range of substrate temperatures (330 to 800 K) and ion fluences (10^{20} to 10^{21} D/cm^2).

The surface composition of liquid Li has been measured at Sandia National Laboratory (SNL). The surface composition of a liquid can differ from its bulk composition due to segregation of impurities or additives. For ALPS components with exposed liquids, it is important to know what constitutes the plasma-facing surface, since evaporation or sputtering of segregants would lead to plasma contamination and compositional changes in the liquid. Consequently, experimental measurements of liquid surface composition are needed to establish purity requirements and the feasibility of using multi-component liquids. The composition of a solid/liquid Li surface has been measured using low-energy ion scattering spectroscopy under ultra-high vacuum conditions in real time as a function of temperature in the range from 25 to 350 °C. For in-situ sputter-cleaned, high-purity Li samples, the surface coverage of oxygen increases upon melting. The predominant species observed at the liquid surface are lithium and oxygen. No evidence of higher-Z impurities at the liquid surface was found. An estimate of the composition at 350 °C gives about 10% oxygen coverage of the lithium surface, indicating that the surface to bulk segregation ratio is on the order of 10^2.

The absolute sputtering yields of D+, He+ and Li+ from D-saturated solid lithium have been measured at the University of Illinois to assist plasma edge/PMI modeling efforts in light of the lack of experimental data. Furthermore the VFTRIM-3D simulation is used along with the experimental results to gain further insight into the physical processes which occur in low energy sputtering events of D-saturated solid lithium. The first experimental campaign focused on the sputtering behavior of solid lithium while the second campaign will focus on liquid lithium. The absolute sputtering yields of D+, He+ and Li+ on D-saturated solid lithium have been successfully measured and modeled at low energies. The Ion-surface InterAction Experiment (IIAX) has been optimized to reliably measure the absolute sputtering yield of many ion-target combinations including D+ on Be [4]. Measurements demonstrate that previous computational results of D,Li sputtering of 100 a/o lithium overestimate the yields [5]. Careful measurements show that D saturation of solid lithium inhibits sputtering to some extent as shown in Figure 3. Furthermore, correlation of VFTRIM-3D simulations and IIAX experimental data imply that the effective heat of sublimation of solid lithium decreases from 1.68 eV to 1.12 eV, due to surface roughness effects.

In order to examine the interaction of a liquid surface with a divertor plasma, a 0.5mm thick lithium sample was recently exposed with the DiMES system on the DIII-D lower divertor. Three different plasma environments were recorded. (1) A sample was exposed to four plasma shots of ELMy H-mode with outer strike point on DiMES. Good data of neutral lithium and singly ionized lithium was collected and there was evidence of melting of the lithium surface. (2) The sample was exposed to private flux quiescent plasma and bright Li-I emission was recorded. Which may be showing effects from charged exchange neutrals. (3) The sample was exposed to a high power deposition MHD event and all Li-I and Li-II lines were recorded. Detailed plasma and spectroscopic data will be distributed to DiMES collaborators for analysis. The sample will also be shipped to SNL for material analysis.

3. Effects of transient/disruption events

Work is underway at Argonne National Laboratory to evaluate the effect of disruptions on liquid surfaces. During thermal quench phase of a tokamak plasma disruption sufficient part of a core plasma energy (more 50% of total thermal energy) is delivered from the tokamak core to the scrape-off layer (SOL) and then carried to the divertor plate by energetic plasma ion and electron fluxes. Therefore, the power load to surface is very high and reaches up to hundreds GW/m^2 and is capable of causing sufficient damage [6]. The liquid layer protecting the structure, if removed, can result in significant heating and damage of substrate. However, because of the developed vapor cloud at the early stages of a disruption above the divertor plate, this layer will shield the original surface from the incoming energy flux and significantly reduce the heat load onto the divertor plate surface. The dynamics of this shielding consists of the following. After the initial phase of direct heating of divertor plate surface a vapor cloud of the divertor surface material forms in front of the disrupting plasma and completely absorb incoming particles flux. As a result the vapor cloud is heated to temperatures of up to several tens of eV [7]. At such temperatures the vapor plasma radiation W_{rad} becomes comparable with incoming power W_d. Because of the absorption by more cold and correspondingly more optically thick vapor plasma nearby the divertor plate surface, radiation power to the divertor plate surface is significantly decreased. The HEIGHTS simulation magnetohydrodynamics (MHD) package calculations predict that radiation power onto the divertor plate surface is less than 10 percent of the original incident power because of the shielding effects [8]. The main feature of this vapor shielding layer is that W_s is defined by the 'temperature of ionization' T_{ion}, below which vapor media becomes optically thin. This T_{ion} depends on Z, radiation power to surface W_s varies from 10 MW/m^2 for heavy elements as the tungsten to about 50 MW/m^2 for light element as beryllium and carbon-based composites. The Lithium, as a candidate surface material, is the lightest condensed material and therefore special calculations were carried out using the package HEIGHTS. The conclusion from such detailed modeling of erosion of divertor plate as a result of plasma disruptions is summarized below. Due to the shielding by both the developed vapor and liquid droplets clouds, erosion losses do not seem to be very excessive and therefore, divertor erosion due the thermal quench phase of a tokamak plasma disruption may not be the main life-limiting issue for the divertor system. Of course, this conclusion is only valid when the vapor plasma is well confined by the oblique magnetic field. However, loss of vapor confinement can occur if the balloon mode of the MHD flute instability arises due to the distortion of the oblique magnetic field lines by the expanding vapor plasma. In this case arising turbulence results in vapor flow along the divertor plate surface. Due to this flow, first, the Kelvin-Helmholtz instability of unstable surface waves arises that results in splashing. Second, this flow blows away both vapor and droplets along target surface. This second phenomena results in lower vapor shielding efficiency due to vapor cloud removal and, in addition, lower efficiency of droplets shielding due to the decrease of droplets exposure time in the depleted vapor.

4. Achieving high power density

The evaluation of the heat removal capability is a very basic performance parameter for liquid surface (LS) concepts. Designing reasonable experiments to measure this capability is challenging and will require thoughtful development. The initial efforts in ALPS on heat transfer have focused on characterization of the issue through simple calculations and planning and simple experiments on liquid metal (LM) surfaces to get some experience with the challenges that we may face in diagnostics for future liquid surface PFC tests. Magneto-hydrodynamic (MHD) effects control the flow of liquid metals in a magnetic field and this in turn affects heat transport. The primary MHD effects are (1) the suppression of turbulence that would more rapidly distribute heat throughout the bulk of the flowing liquid in the absence of a magnetic field and (2) a large pressure drop. The maximum heat load that a liquid plasma facing surface can sustain for steady state applications is limited by the surface temperature at which the impurity influx into the plasma from vaporization is unacceptable. Sputtered atoms, molecules (Flibe) or ions (Li) may contribute to this influx; but the maximum temperature will likely be set by the vaporization. Figure 4 shows the evaporation rate for several candidate liquid metals. The surface temperature limits ultimately depend upon the source term and how effective the screening of impurities is at the plasma edge. However, these temperature limits will still fall within a fairly narrow range because of the steep slopes in the evaporation rate curves (which as a rough approximation increase exponentially with temperature).

An important aspect of heat removal of free surface liquid impurity control systems is the impact of MHD effects on free surface flow of conducting liquids. The present understanding of state-of-the-art of experiments and models of free surface flow have been reviewed as a first step in establishing a comprehensive plan for MHD modeling and testing [9]. The status of work for MHD flow on a plate, jets, and droplets is reviewed. There are several uncertainties that are potential "show-stoppers." These concern stability of the film, uniformity of film height owing to inertia, 3-D effects, inclination of the field, plasma wind, etc. Finite conductance of the sidewalls, combined with inclined field, may lead to very undesirable effects. Concerning velocity profiles, it seems that only if walls are electrically insulating velocity profiles are more or less insensitive to the field inclination. This leads to the necessity of insulating coatings. Another question arises then, whether wettability of the coatings by a LM can be guaranteed. If this is not the case, the LM film may turn into rivulets, and dry spots may appear. For LM jets the number of MHD-related problems is considerably lower. An initial experiment demonstrating stable jets and mirror-like, disturbance-free layer of LM on the receiving plate, is very convincing. Although the LM coatings in the supplying/draining systems are likely to be necessary due to pressure-drop considerations, they will not be in the critical region of a tokamak, and the requirements to such coatings could be not very strict. Major question remains as to how the jets will behave during plasma disruptions, but this question is as important for the films. Similar to jets, drop divertors have few MHD-related problems. The crucial question for drops is how to create them realistically in a tokamak. Also, due to their small size, they will be vulnerable to evaporation and plasma wind.

5. DT/He trapping and release from surfaces

The interaction of DT/He particles with liquid surfaces can potentially have a significant impact on plasma operation as well as fuelling and vacuum pumping systems. In the case of Li, which has a strong chemical affinity for DT particles, the particles hitting the surface will likely be trapped, and the plasma edge conditions will likely be high energy and low density due to the lack of recycling. Other liquids, like gallium or Flibe, which have low DT solubilities, may result in rapid recycling and little change in the edge conditions. The key issue to be addressed is the kinetics of the surface recycling process. If the effective residence time of the particle in the liquid surface is comparable or longer than the transit time of the liquid across the divertor plate, then the particles striking the surface a likely to be removed from the chamber.

A similar argument on particle recycling applies also to He particles. If the He particle has a sufficient residence time, it will be removed from the chamber by the moving liquid, and thus the liquid divertor plate can serve as a vacuum pump. At this time, there is very little information, either of an experimental or theoretical nature, on the kinetic interactions of He particles with liquid surfaces. A future modeling and experimental effort is planned to address this issue.

6. Future Studies

The work addressing the plasma edge and plasma materials interactions will continue. There will be an expanded effort in the area of achieving high power density with a combination of modeling and experiments in a magnetic field. The kinetics of surface particle interactions will also be addressed. In addition, installation and testing of liquid surface systems in tokamak devices is planned. Successful resolution of individual issues is expected to lead to a proof-of-principle experiment in a large tokamak approximately five years from now.

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Table 1. Possible Materials, Configuration, and Confinement Options

Liquid species	Li, Flibe, SnLi, Ga
Surface configuration	Fast film, droplets, waterfall, stagnant film, pool, backside impinging jet
Confinement Options	Tokamak, Advanced Tokamak, Spherical Torus, Field Reversed Configuration, Stellerator

Table 2. Lithium Redeposition analysis with WBC Code

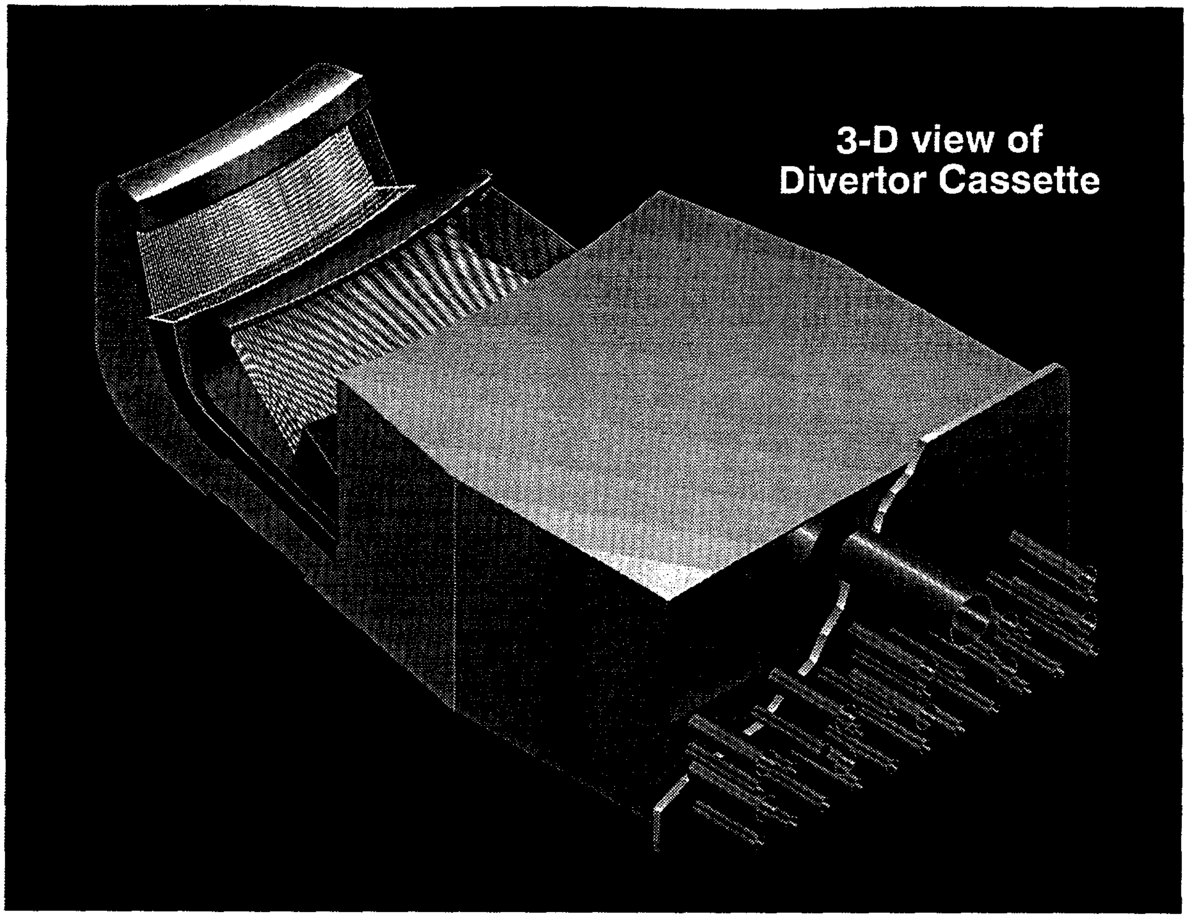
	T_e(eV)/N_e(10^{19}m^{-3})
Parameter	200/1.5
Mean free path for sputtered atom ionization (perpendicular to surface)	1.8 cm
Average charge state	1.8
Transit time (Average)	52μs
Elevation angle (Average)	59 Degrees
Energy (Average)	~1 KeV
Poloidal distance from launch point (Standard Deviation)	7 cm
Redeposition fraction (for 20 cm near –surface cutoff)	0.99

Figure 1. Example of an advanced liquid surface divertor module.

Figure 2. Sputtering coefficient of liquid gallium compared with model predictions.

Figure 3. Low energy sputtering coefficient for D^+ on solid D-saturated Li.

Figure 4. Vaporization rates for several candidate free surface liquids.



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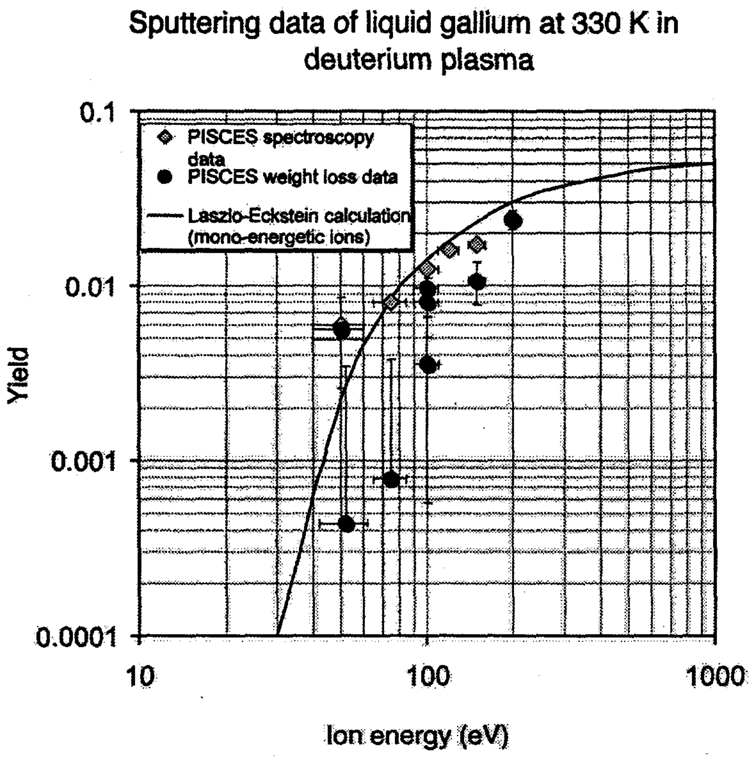

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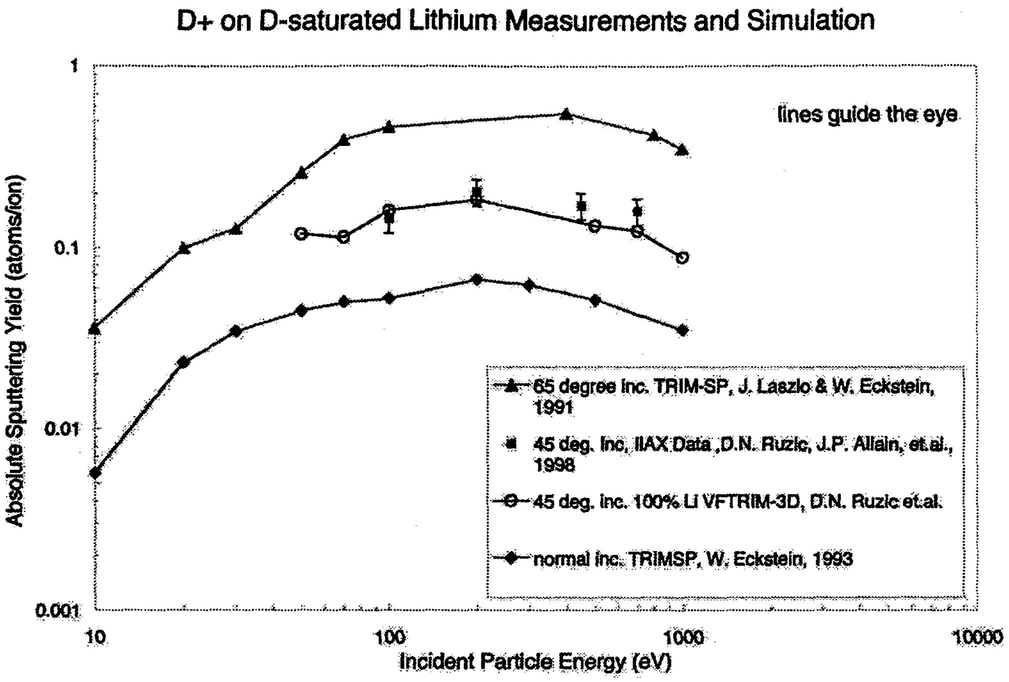
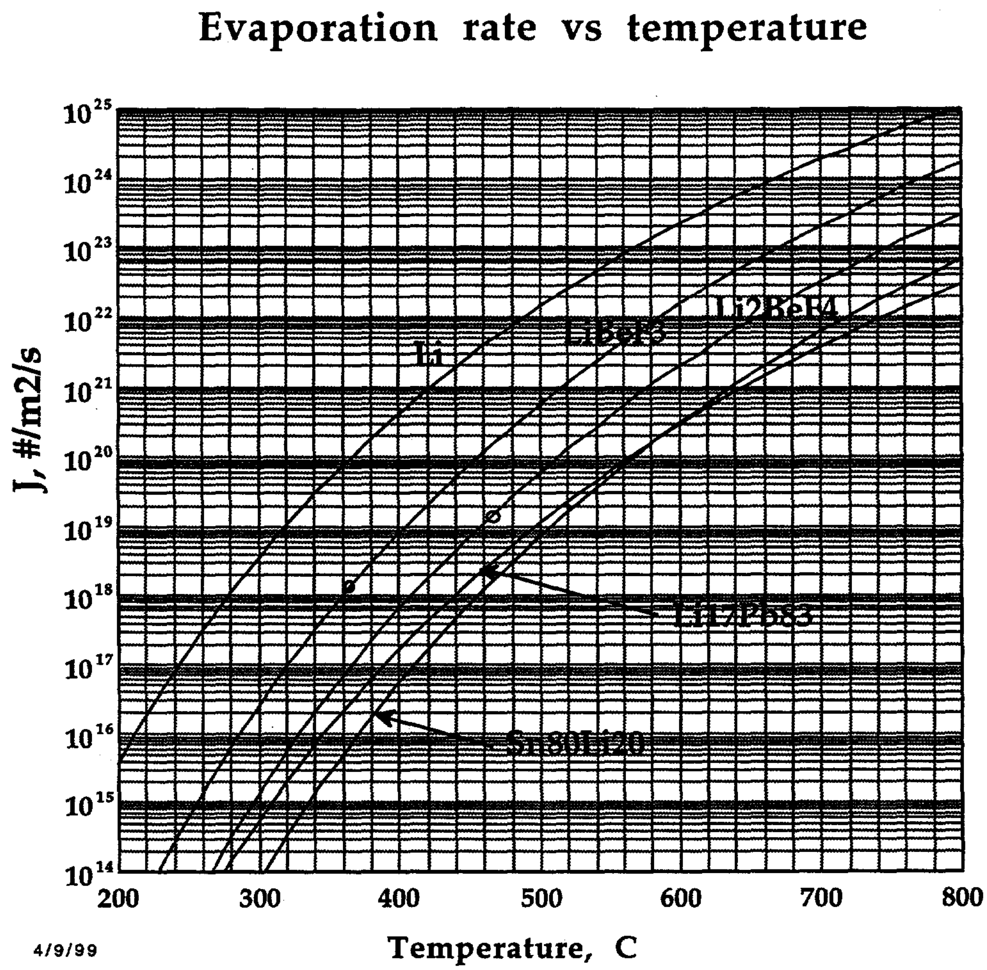


Figure 3. Low energy sputtering coefficient for D^+ on solid D-saturated Li.



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