On the origin of the regularities observed in the dissolution of solid in plasma

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1. Introduction

In a paper, presented two years ago at this Conference [1], concerning the "dissolution" of solid Hydrogen projectiles in plasma, it appeared that the empirical average "speed of dissolution" of solid Hydrogen projectile, since 1975, varied "regularly" between a fraction of m/s to a few units of m/s. Moreover the ratio between the "outgoing" molecular flux and the "incoming" electron random flux at the projectile surface was never less than 1 and seldom less than 100. These two "regularities" may still be considered not very relevant in plasma-solid interaction phenomenology if, in the experiments observed, only solid Hydrogen projectiles were used. In this paper it is point out that if we considered all experiments on plasma–projectiles interaction to date, including those which use solid projectiles of different substances, it would appear that the regularities, first observed for solid hydrogen, persist for non-cryogenic solids which have very different thermal properties [2] [3] [4]. Consequently we may infer that when the solid interacting with the plasma, changes into fluid phase the phase transition would not depend on the thermal properties of the solid substances, but in the "dielectric" properties of the "solid state". Indeed as any dielectric substance would resist "disruption" of its insulating power if the electric external action has not reached some "critical" intensity, similarly the solid structure may also undergo disruption by a similar electric action when some critical intensity is attained. In low temperature electrical discharges, in stationary state, the latent heat released at the plasma-solid boundary, where plasma corpuscles may recombine [8], does not cause phase transition and so it slowly diffuse outward and manifest itself as "sensible" heat. But, in the case of high temperature (and high random flux) plasmas, in which solid projectiles undergo change of phase, the "empirical" elapse of time for the phase transition of a single "plasma-solid interaction layer" is so short (nanoseconds) that the change of phase cannot be due to slow molecular thermal diffusion, but rather to fast "convection" of "corpuscular" plasma energy directly into molecular mechanical energy, within the "plasma-solid interaction layer". This hypothesis may be proved indirectly by observing the luminous atmosphere surrounding the projectile. Indeed it has been observed that all molecules, which leave the solid Hydrogen when it change phase, have the same speed [5] and, as it is shown in the Table, its magnitude spans between 1 or 2.5 cm/microsecond for different solid substances [2] [4] [5] [6] [7].

2. Critical electric Displacement in the "Plasma-solid interaction layer"

According to the observations of Langmuir [8], the plasma boundary acts as a "current generator" which charges the bordering solid negatively leaving itself positively charged. However the plasma-corpuscles do not "stick" to an infinitesimal thin geometric surface of the boundary but fill the whole volume in which the plasma-corpuscles penetrate. The thickness of such a layer of solid dielectric is indeed very small (not smaller than a nano-layer anyway) but since is always finite the plasma-corpuscles can store their electric charge and energy. If we now assume that the plasma-solid interaction layer acts as an imperfect dielectric [10], the current of swift plasma-corpuscles (electrons) which first penetrate the dielectric solid splits into two parts, the conduction current and the induction (or Displacement) current. The power associated with the latter, stores electrostatic energy within the negative solid layer and is much larger than that associated with the conduction current. In 1979 [1] in the attempt to evaluate the dissolution speed of solid Hydrogen for the purpose of refilling the discharge chambers it was assumed that in high flux plasma the "dissolution speed" U should be very close to the speed of the (evanescent) wave **u** generated by the "electric impulse" exerted by the "current generator"within the "plasma-solid interaction layer". Since the imperfect dielectric is endowed of both specific resistance and inductive capacity a current wave should propagate with speed be defined as **u** = L*/t*, where L* = $1/n_0\,\sigma_L$ is the Lenard empirical characteristic length [8] and t* = $D_\infty / e\Gamma_{e0}$ the Maxwell characteristic time for charging and discharging of imperfect dielectrics [10] ($\Gamma_{e0} = n_e\overline{c_e}/4$, n_e and e the electron density and charge, $\overline{c_e}$ the random speed of electrons, σ_L is the Lenard cross section [9] and n_0 the solid number density). If the plasma corpuscular random flux is so low that the solid layer does not change phase the current wave damps out within the solid layer, heats it and eventually attains the stationary negative "floating" potential consistent with the vanishing current in the Langmuir's I-V characteristics [8]. Since D_∞ is not an "observable", and cannot be measured experimentally, the wave speed **u** could not be calculated but, on the contrary, D_∞ can be obtained if the "average dissolution speed" $<U>$ can be measured experimentally. Indeed when the charge and the energy transferred to the solid layer are high enough, so that the solid structure may collapse under an electric stress, the solid-fluid boundary is displaced and the resulting speed, defined as $<U> = \Delta R/\tau_P$, can be measured (ΔR is the observable total thickness of the dissolved shell of the projectile and τ_P the observable total plasma-solid interaction time). If we

define the empirical "counter-fluxes ratio" $\beta = n_0 < U > / n_e \bar{c}_e$ and we recall that for negative exponential distributions of characteristic time t^*, $D(t^*) \cong 2D_\infty / 3$ we can also calculate the "critical" Displacement field in the dielectric, $D^* \equiv D(\tau^*)$, which is attained when the solid structure collapses. Indeed if u $\cong$ $<U>$ and $\Delta R / \tau_P$ = L*/ τ^*, then $t^* \cong \tau^*$ and the critical field is given by $D^* \ (<U>) = e / 6\sigma_L \beta$. (1)

3. Critical stress in the solid phase and speed of expansion of the fluid phase

We have other two observables at our disposal besides $<U>$, namely, the expansion speed V of the atmosphere surrounding the dissolving projectile and the deviation η of the trajectory of the latter, to be able to confirm that the order of magnitude of the critical electric Displacement field D^*, in the negative dielectric layer, is just that given by (1). The derivation of the critical Displacement as a function of η cannot be done in a short paper like this one but that, given as a function of V, can be done using simple back of envelope calculations. Indeed let us now consider the relationship between the Maxwell electric tension σ_M [10] and the displacement field D, in the dielectric layer, that is, $D^2 / 2\varepsilon = \sigma_M$, where σ_M is the "electric tension" and ε the dielectric constant. If we assume that the change of phase occurs when the stressed solid layer "gives way" at the "critical" value $\sigma_C = \sigma_M{}^*$, then we can expect that the speed V acquired by the molecules which leave the collapsing solid structure has its magnitude dependent on the solid substance but independent of the type of plasma. Indeed the visible atmosphere in any experiment is observed to expand toward the plasma with a speed V which varies only between 1 and 2.5 cm/microsecond (see the Table), though the dissolution speed varies within one order of magnitude. By equating the electric tension to the flux of momentum of the molecules across the solid-fluid boundary, we get $\sigma_C = \rho_A V^2 / 2$, where ρ_A and V are the density and the empirical speed of expansion of the visible atmosphere. If we now use mass conservation across the plasma fluid boundary $\rho_A = \rho_0 < U > / V$ where ρ_0 is the mass density of the solid and if we define the critical Displacement from the critical tension $\sigma_C = D^{*2} / 2\varepsilon$ we eventually get $D^*(<U>, V) = \sqrt{\varepsilon \rho_0 < U > V}$ (2)

Conclusions

The fact that the same order of magnitude of the critical electric displacement D^*, can be derived from the observables $<U>$ & V displayed in the table using either (1) or (2), confirms the hypothesis that the phenomenon of the dissolution speed of solids in plasma has its root in

the disruptive action of the plasma on the structure of the bordering solid dielectric. The magnitude of D^* can also be found, in agreement with that given by (1) and (2), if the deflections of the projectile due to external fields are also considered. Therefore if we equate (1) and (2), D^* would of course not appear any more and the relationship between the two observables $<U>$ & V obtained may enable to "counter-check" the hypothesis formulated in this paper on the origin of the regularities displayed in the Table below (and in ref.[1]).

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Table [this table implements the table in ref. [1] (2012) so both should be looked at together]

Plasma Experiment	Solid Substance	V $cm/\mu s$	ε	n_o 10^{22} cm^{-3}	$<U>$ m/s	n_{13} $(10^{13}\ cm^{-3})$	T_e KeV	$\overline{c_9}$ $(10^9\ cm/s)$	σ_L $(10^{-16} cm^2)$	β
Puffatron Rotating plasma (1977)	*H*	*1 H plas* / *2 He plas*	*1.2*	*5.18*	*29*	*40*	*0.025*	*0.32*	*3.5*	*23*
Pulsator (1977)	*D*	*2.5*	*1.2*	*6*	*0.5*	*3*	*0.01*	*0.21*	*5.8*	*130*
ISX-A (1978)	*H*	*2*	*1.2*	*5.18*	*1,0*	*2.5*	*0.43*	*1.3*	*0,80*	*186*
ISX-B (1979)	*H*	*2*	*1.2*	*5.18*	*2.3*	*4*	*0.69*	*1.65*	*0.52*	*207*
ϑ pinch (1977)	C_8H_8	*1.3*	*2.5*	*0.6*	*6.0*	*1000*	*0.1*	*0.66*	*27.2*	*~1*
TFTR (1992)	*Li*	*1.4*	*1*	*4.6*	*1.0*	*3.5*	*6.6*	*5.3*	*0.28*	*25*
T-10 (1992)	*C*	*?*	*16.5*	*11.3*	*0.17*	*3.3*	*0.4*	*1.5*	*0.85*	*40*