OVERVIEW OF ASTRIUM EROSION / CONTAMINATION MODELLING TOOL AND VALIDATION ON ONERA EXPERIMENTAL RESULTS

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Despite their numerous advantages, electric propulsion devices may raise several issues such as erosion and contamination of sensitive surfaces. Therefore, to assist the design of the spacecrafts embarking electric propulsion, Astrium has developed its own modelling tool: CIONIC. The development of this tool has underlined the need for accurate data on the erosion and contamination of space-specific materials. Astrium has thus been involved in the erosion / contamination test campaign carried out at ONERA / DESP in Toulouse. During this campaign, erosion tests allowed to characterise the sputter yields of space materials (glasses, paints), whereas contamination tests allowed to correlate the sputter yield measurements, as well as obtain data on the thermo-optical degradation due to contamination. Those test results have then been applied to improve CIONIC accuracy, which now enables Astrium to reduce the margins in the design of spacecrafts embarking electric propulsion.

1. INTRODUCTION

Due to their high specific impulse providing interesting savings in propellant, electric thrusters are currently being used for station keeping on telecommunication satellites, and shall be considered for orbit raising or interplanetary missions. Yet, the interactions between the thruster plume composed of highly energetic ions and the surrounding spacecraft surfaces may raise several new issues. Indeed, the energetic ions colliding with the surface atoms create a collision cascade resulting in a physical sputtering process: atoms or molecules get extracted from the surface and may eventually re-deposit on adjacent surfaces, possibly leading to the contamination of sensitive surfaces. Such interactions may have several detrimental consequences at system level: erosion may lead to a mechanical weakening of thin surfaces, or to a modification of their thermo-optical properties; contamination may lead to a deterioration of surface transparency to visible or radio-frequency electromagnetic waves.

Therefore, to assist the design of the satellites embarking electric propulsion devices, Astrium has developed its own modelling tool for ionic erosion and contamination: CIONIC (standing for Contamination-IONIC). The purpose of this software, whose architecture is presented in §2, is to assess the effect of erosion and contamination at system level. Such a software relies on several analytical laws that have to be carefully validated by experimental data. Yet, despite the numerous literature data on sputtering processes and metals sputter yields, Astrium has been confronted with a lack of data on topics such as: sputtering of space-specific materials, distribution of sputtered products, erosion and contamination induced effect for those materials, etc. Therefore, to provide Astrium with such information, a dedicated test campaign has been carried out at ONERA / DESP in Toulouse. This campaign, co-funded by CNES and Astrium, has allowed to characterise several materials (glasses, paints, Kapton, carbon fibres, etc.) both in terms of erosion and contamination. The test set-up and results are presented in §3. Finally, those test results have been applied to improve the accuracy of Astrium erosion / contamination modelling tool (refer to §4). The erosion test campaign allowed Astrium to build an exhaustive sputter database, and the contamination test campaign gave the possibility to validate the computer tool by comparing experimental results and simulated results.

2. OVERVIEW OF ASTRIUM EROSION / CONTAMINATION MODELLING TOOL: CIONIC

2.1. Software architecture

The purpose of CIONIC is to assess the electric propulsion induced erosion and contamination of a spacecraft. This module is part of SYSTEMA framework, which allows to use several tools (3D modelling tool, display tools, etc.) common to all SYSTEMA modules.

The general architecture of CIONIC is presented in Fig. 1

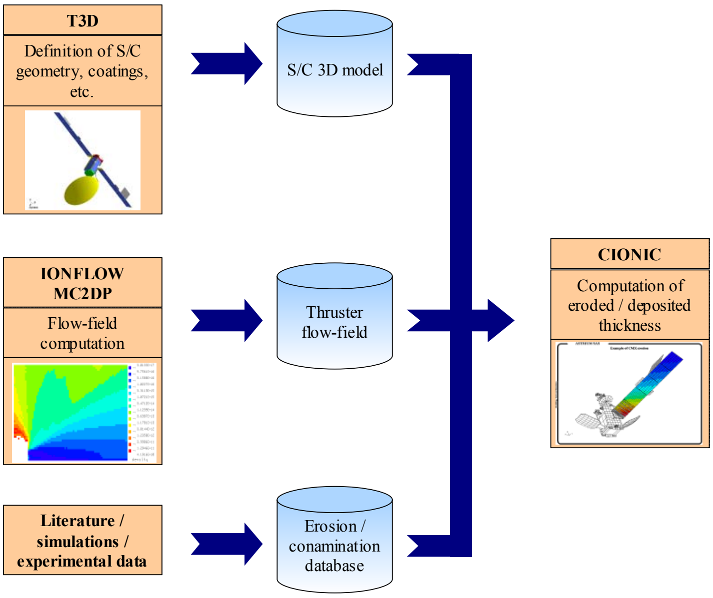

Fig. 1 – Software architecture of CIONIC

- ✓ The external model of the spacecraft is provided by a 3D modeller. The external coatings (glass, paint, etc.) are defined, as well as other surface parameters (e.g. surface potential).
- ✓ The computation of the thruster flow-field is carried out by another module (either by means of analytical fitting laws in IONFLOW, or with PIC-DSMC modelling of the flow in MC2DP)*. The distribution of ions current and energy can then be computed on every surface of the spacecraft.
- ✓ Thanks to a sputtering and contamination database, the sputter yields are computed (depending on the surface material, the energy and incidence of ions). This part of the software relies on several analytical laws giving, for each material, the energy and incidence angle dependence of sputter yields.
- ✓ The eroded thickness are computed from the knowledge of the materials sputter yields, and the total ion flux (ion current multiplied by firing duration).
- ✓ The computation of contaminant deposition on adjacent surfaces relies on an efficient ray-tracing method, including the possibility to account for complex re-emission lobes.
- ✓ Among the other possibilities provided by CIONIC are the account for kinematics (e.g. the rotation of solar panels) and the computation of direct contamination (contamination induced by the sputtering of the thruster itself, e.g. ceramic sputtered from the discharge chamber insulator).

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* The precise determination of the thruster flow-field in space conditions is another well-studied topic of PPS interactions modelling. In CIONIC, the flow-field determination and the computation of eroded / deposited thickness are decorrelated, i.e. the flow-field is assumed not to be disturbed by the spacecraft geometry.

2.2. Models implemented in the software

The accuracy of CIONIC computations relies on the following models: sputter yield energy and incidence angle dependence, re-emission laws, and erosion / contamination surface effect laws.

Sputter yields

The sputter yield of a material characterises the quantity of eroded material for a given quantity of incoming ions. For a given couple (type of ion, type of material), the sputter yield depends on both energy and incidence of ions. In CIONIC, well-known analytical laws have been implemented to evaluate the evolution of the sputter yield as a function of energy and incidence.

- ✓ The evolution of the sputter yield under normal incidence (as a function of ions energy) is described by Bohdansky analytical formula[3]. The evolution of the sputter yield Y is determined by two parameters, the slope K and the threshold energy E_{th}:

Bohdansky-2 formula:
$$Y_0(E)=\begin{cases}0 & \text{if } E\le E_{th}\\ K.E.\left(1-\left(\frac{E_{th}}{E}\right)^{2/3}\right).\left(1-\frac{E_{th}}{E}\right)^2 & \text{if } E>E_{th}\end{cases}$$

- ✓ At a given energy, the sputter yield is dependent on the incidence of impacting ions: the sputter yield reaches a maximum Y_{MAX} at a specified angle of incidence φ_{MAX}. The angular evolution is given by Oechsner analytical formula[4]:

Oechsner formula:
$$\underbrace{\frac{Y(E,\varphi)}{Y_0(E)}}_{\text{weighted sputtering yield}}=1+\left(\frac{Y(E,\varphi_{max})}{Y_0(E)}-1\right)\times\underbrace{1.284\left(\frac{\varphi}{\varphi_{max}}\right)^2 e^{-0.25\left(\frac{\varphi}{\varphi_{max}}\right)^8}}_{\text{angular evolution based on Oechsner model}}$$

The typical evolution of sputter yields as a function of energy (left) and incidence (right) is given in Fig. 2.

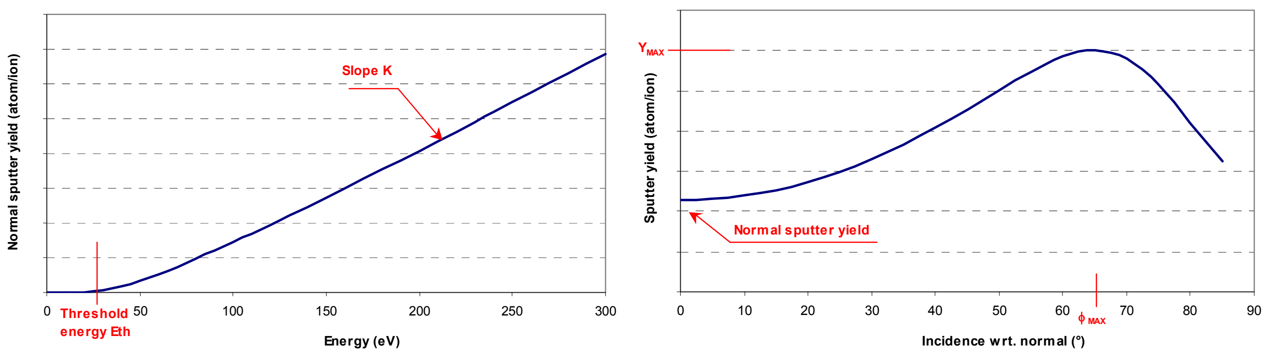

Fig. 2 – Energy and incidence dependence of sputter yields

Several information can be used to come up with the above parameters:

- ✓ Literature data are numerous as far as sputtering of metals is concerned[2].
- ✓ Computer tools (TRIM, MARLOWE, SIB[*]) can also simulate the collision processes and therefore compute the sputter yields of materials with a simple atomic structure.

Yet, very few data are available concerning space-specific materials such as a glasses or paints. The constitution of a sputter database for space materials is thus the first purpose of ONERA test campaign.

[*] SIB (Sputtering by Ion Bombardment) is a TRIM or MARLOWE-like software developed by Astrium

Re-emission laws

The products sputtered from spacecraft surfaces may re-deposit elsewhere on the spacecraft, according to their re-emission profiles. The levels of contamination are highly dependent on the re-emission law followed by the sputtered particles. CIONIC allows to account for two different re-emission profiles:

- ✓ Diffuse re-emission: the probability of re-emission in the direction θ wrt. the normal to the sputtered surface, is proportional to $\cos\theta$.
- ✓ Pseudo-specular re-emission: the prevailing direction of re-emission is approximately in the specular direction wrt. the incident ion flux. A set of computer simulations carried out with SIB software allowed to get an estimate of such re-emission lobes. Those lobes have then been fitted by an analytical law.

Both re-emission laws are represented on the following figure. On the represented lobes, the probability of re-emission in a direction θ wrt. the normal to the surface is proportional to the radius of the point on the lobe (r).

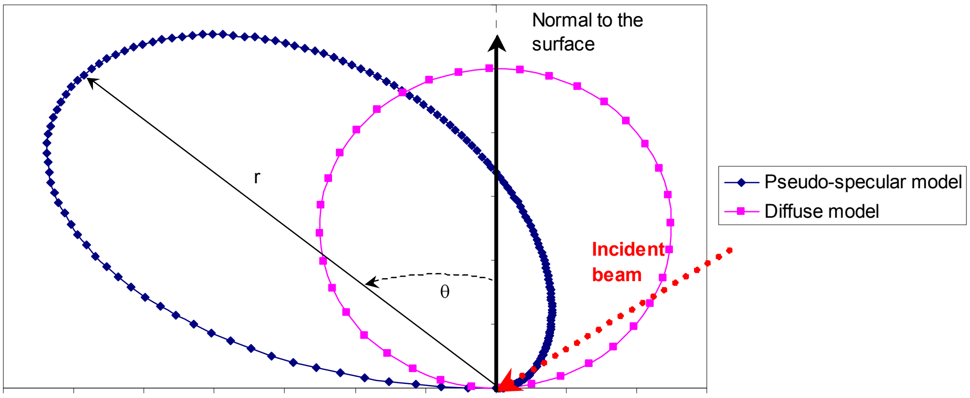

Fig. 3 – Diffuse and pseudo-specular re-emission lobes

In most spacecraft configurations, the diffuse assumption is worst-case wrt. the pseudo-specular assumption, and may therefore lead to an over-estimation of contamination. The investigation of the accuracy of re-emission laws is one of the purposes of ONERA contamination test campaign.

Surface effect laws

Since CIONIC purpose is to compute the erosion / contamination impact at spacecraft level, it has to include laws giving the effect of erosion and contamination. Therefore, the ONERA test campaign shall provide information such as: absorptivity and emissivity variation of eroded thermal coatings, loss of transmittivity of cover glasses, as well as absorptivity increase of contaminated thermal coatings (e.g. OSR radiators).

After reviewing the models involved in CIONIC, it turns out that uncertainties remain on topics such as: sputter yields of space-specific materials, re-emission profiles of sputtered products, and impact (mostly thermo-optical) of erosion and contamination.

3. ONERA EROSION / CONTAMINATION TEST CAMPAIGN

An erosion / contamination test campaign has been carried at ONERA / DESP in Toulouse. Two types of tests have been performed: erosion tests to characterise the sputter yields of space materials and evaluate the impact of erosion on materials properties, contamination tests to validate CIONIC chain of contamination modelling and evaluate the impact of contamination on materials properties.

This campaign was conducted in three phases: phase 1 (10/2000 to 03/2001) was funded by CNES and allowed to characterise the sputter yields of the main solar array materials[1], phase 2 (09/2001 to 10/2001) was funded by CNES and established the feasibility of contamination measurements, phase 3 (10/2001 to 02/2002) was funded by Astrium and allowed to characterise several additional solar array materials.

3.1. Erosion tests set-up

All experiments were performed in a cylindrical chamber, in which samples were placed within the flux of a xenon ion source (refer to Fig. 4). During erosion tests, eight small samples (15x20 mm^2) of different materials were placed at eight different incidences (from almost normal 5° to almost grazing 75°). The xenon ion source was used at given energy values (100 eV, 200 eV, 300 eV: typical values of SPT100 ion energies) and the ion current was measured at samples level before erosion tests.

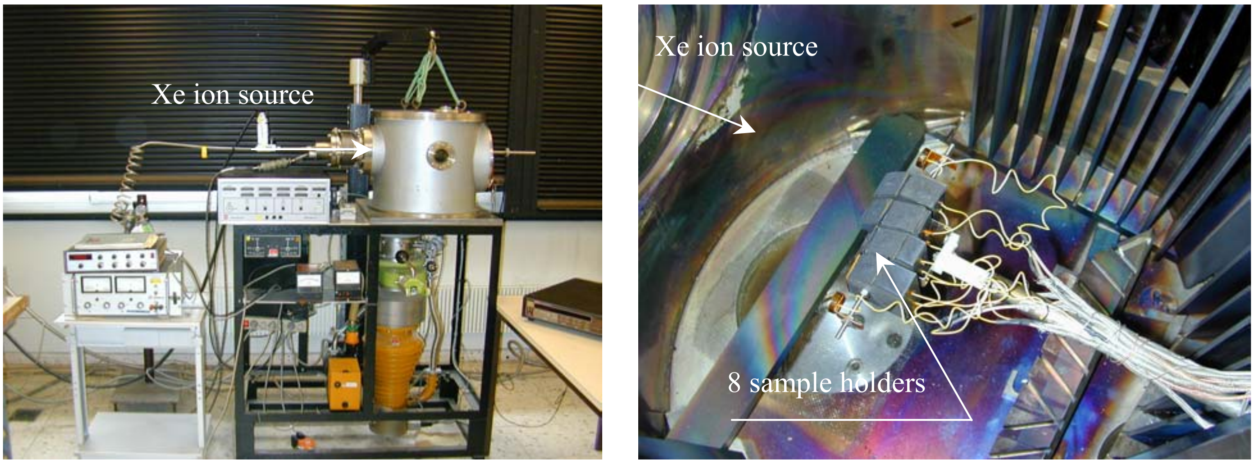

Fig. 4 – ONERA erosion test set-up

The mass loss of eroded samples was measured, and the sputter yield for every sample was then given by:

$$\textit{Sputter yield formula:} \quad \gamma = \frac{\Delta m}{J.S.t} \ (\mathrm{mg/C})^{*}$$

Where Δm (mg): mass loss, J (A/cm^2): current collected by the sample, S (cm^2): surface of the sample, t (s): duration of sample exposure to ion flux.

Those measurements allowed to get tabulated data for sputter yields as a function of incidence and for several ion energies. Furthermore, the thermo-optical properties of samples were characterised before and after erosion, which allowed to determine the degradation due to sputtering for different eroded masses.

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[*] The sputter yield expressed in mg/C characterises the materials in terms of eroded mass. If the sputtered product has the same mass density as the initial substrate, the sputter yield can be converted into mm^3/C, which then characterises the material in terms of eroded thickness.

3.2. Example of sputter yield measurement

Several space-specific materials have been tested: glasses (bare CMX, CMX + Anti Reflective coating), paints (white SG120, black PU1), Kapton (standard and carbon-loaded), carbon fibres (CFRP). More common materials have also been tested (silver, aluminium) to compare with other sputter yield measurements.

An example of sputter yield results for aluminium is given in Fig. 5.

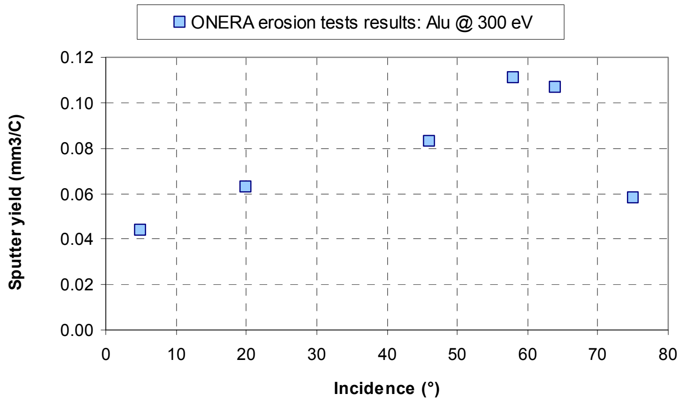

Fig. 5 – Example of aluminium sputter yields at 300 eV*

Similar curves have been obtained for the other materials. Sputter yields of silver and aluminium have been compared to other experimental results (e.g. Rosenberg and Wehner measurements[2] can be compared to the sputter yields obtained at near-normal incidence) and show very good agreement. The uncertainty of ONERA measured sputter yields has been evaluated to 30 % (including uncertainties on current and mass measurements) – this 30 % value has been verified on a reference CMX sample placed at 52° during all tests.

3.3. Thermo-optical characterisations of eroded samples

The thermo-optical properties (absorptivity, emissivity, transmittivity) have been characterised before and after erosion for each sample. Most materials used for thermal control showed almost no degradation with erosion (e.g. Kapton). Other eroded samples showed a very slight degradation, whose dependence on the outer coating eroded thickness could be inferred from the measurements.

* In this experiment, two incidences are missing: one sample placed at 52° was a CMX reference sample common to all erosion tests, whereas the 40° sample had fallen from the holder, and was thus not eroded.

3.4. Contamination test set-up

The contamination test campaign was carried out with the same chamber and ion source as during erosion tests. In this case, a bigger target is placed in the direct view of the ion source yielding 300 eV ions, and placed under incidence so as to be highly eroded. The re-deposition of the products sputtered from that target is evaluated thanks to three QCM (Quartz-Controlled Microbalances) located at three different positions in front of the target:

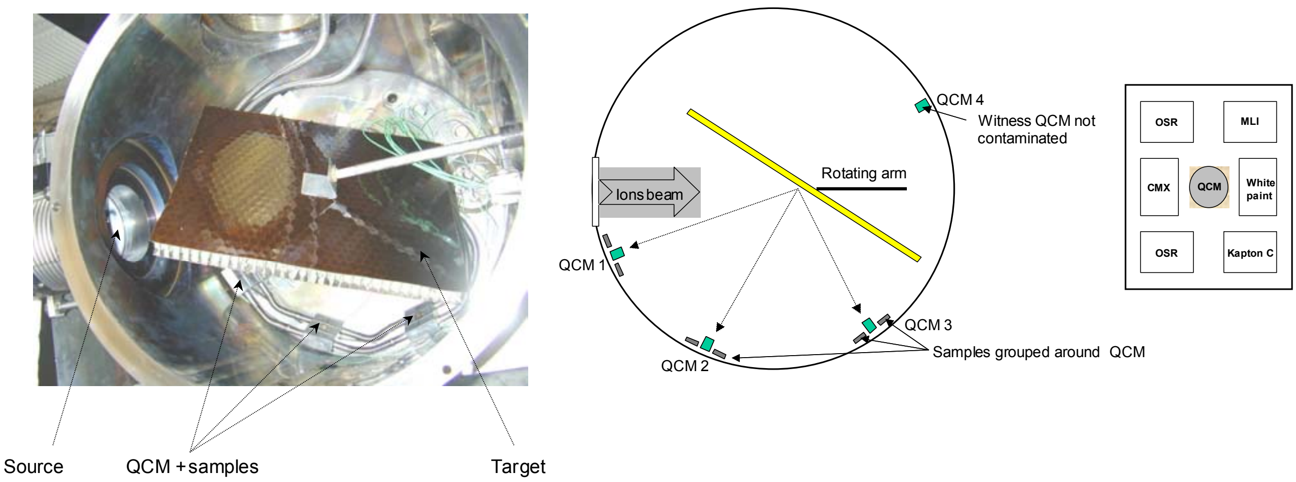

Fig. 6 – ONERA contamination test set-up

The target is sputtered during several hours, and the QCM mass measurements are recorded during this time. Furthermore, six samples are located near each QCM (potentially contaminated materials such as CMX, OSR, MLI, paints, etc.). The three positions of the QCM have been chosen in order to scan various angles: the first group of samples is directed towards the anti-specular direction wrt. the target normal; the second group towards the normal and the third towards the specular direction. The thermo-optical degradation of those contaminated samples (whose contamination thickness is given by the measurement of their surrounding QCM) is then characterised.

3.5. Example of QCM measurements

Five targets have been tested: Kapton, white paint, carbon-loaded Kapton, solar array front face and solar array rear face. The following figure gives an example of QCM measurements as a function of time, in the case of the Kapton 300 eV contamination test:

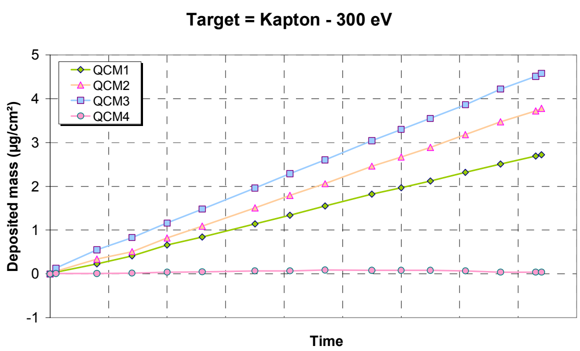

Fig. 7 – QCM measurements during Kapton-300 eV contamination test

3.6. Thermo-optical characterisations of contaminated samples

The characterisations carried out before and after contamination of the samples showed little effect in terms of emissivity, but on the contrary an important increase in absorptivity (e.g. for low absorptivity devices such as OSR). Since QCM measurements may give three different deposited thickness on the samples, a law: $\Delta\alpha = f(x)$, where α is the absorptivity, and x the deposited thickness, can be inferred from those measurements.

4. APPLICATION OF ONERA TEST RESULTS TO CIONIC IMPROVEMENT

4.1. Update of Astrium sputter database

Erosion test results gave tabulated data of sputter yields as a function of incidence, and for various energies. Therefore, the parameters K, E_{th}, Y_{MAX}, φ_{MAX} described in §2.2, have been fitted according to ONERA sputter measurements. A sputter database has thus been built with accurate data for the main materials likely to be sputtered on a telecommunication satellite. Tabulated data in energies and incidences allow to extrapolate the sputter yields measured during ONERA tests to exact spacecraft configurations.

As an example, aluminium sputter yield measurements at 300 eV give: Y_0 (300 eV) = 0.04 mm^3/C, φ_{MAX} = 60°, and Y_{MAX} = 0.11 mm^3/C:

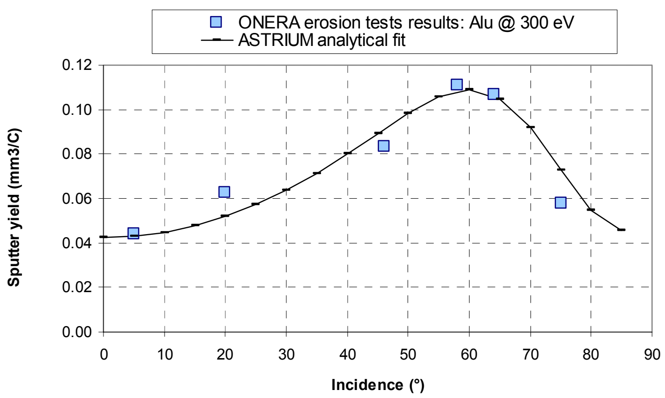

Fig. 8 – Analytical fit carried out on aluminium measurements

4.2. Validation of CIONIC end-to-end modelling

All materials tested during contamination tests (Kapton, white paint, carbon-loaded Kapton, solar array front face and solar array rear face) have been previously characterised during erosion tests. Their sputter rate being known, it is possible to use CIONIC to predict contamination results in ONERA tests conditions.

According to the architecture exposed in Fig. 1, ONERA ion source current and energy flow-field has been modelled, thanks to the current calibrations carried out during erosion tests. Then the geometrical configuration of contamination tests has been modelled (relative positions of ion source, target and QCM, and exact geometry of the different targets).

The sputter database obtained after erosion tests has been applied to compute the deposited thickness on QCM. As far as re-emission is concerned, both assumptions have been simulated: diffuse and pseudo-specular re-emission. The following figure gives an example of CIONIC computation results in the case of the Kapton 300 eV contamination test.

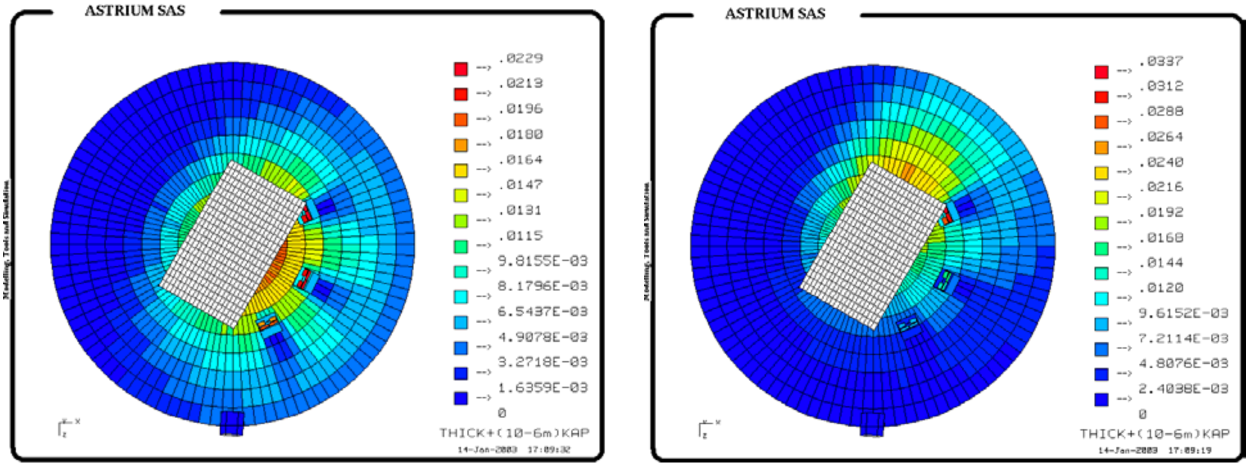

Fig. 9 – Example of predicted contamination in the case of Kapton 300 eV test:
Deposited thickness are expressed in µm, 1st figure accounts for diffuse re-emission, 2nd for pseudo-specular

The computed thickness on the QCM can then be compared to the experimental results given in Fig. 7:

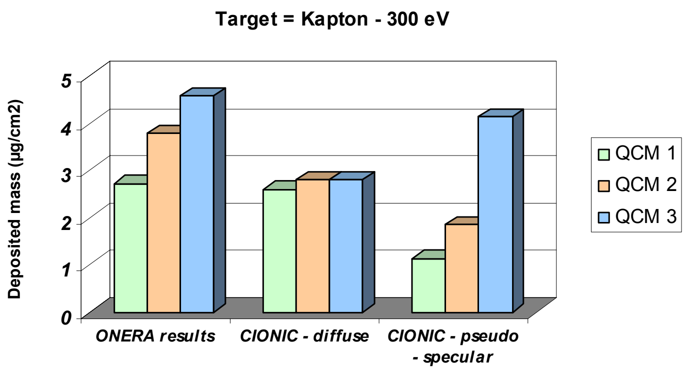

Fig. 10 – Comparison between ONERA QCM measurements, and Astrium predictions with both re-emission laws

In this case, the general agreement between predictions and test results is good. Kapton re-emission profile is rather specular but Astrium pseudo-specular model should be tuned to get more accurate results. For other targets, the correlation between predictions and experimental results remains good, and close to the intrinsic uncertainty of the modelling (mostly uncertainty due to ion source current modelling).

The comparison between predictions and measurements allows to validate CIONIC end-to-end modelling, from current model, to sputter yield and re-emission models. It underlines the fact that some materials have a re-emission rather specular than diffuse, which infers updated re-emission profiles for the sputter database.

4.3. Improvement of the sputter database with surface effect laws

The contamination tests give values of absorptivity degradation for three different deposited thickness of five different target materials. In most cases, the deposited thickness are of the same order of magnitude of what can be obtained in flight: the absorptivity variation can be directly applied. If the thickness obtained during tests are higher than in-flight values, ONERA results can be extrapolated with a typical atomic contamination law such as:

$$\Delta\alpha(x) = \left(1 - e^{-F.x}\right)\left(1 - \alpha_0\right)$$

Where: $\Delta\alpha$ is the absorptivity increase of the contaminated sample due to thickness x of contaminant, α_0 is the absorptivity before contamination, and F is the absorption factor. ONERA contamination test results allow to infer F absorption factors for the specific contamination due to space materials.

5. CONCLUSIONS

The erosion / contamination test campaign carried out at ONERA has yielded very interesting results in several areas: constitution of a sputter yield database for the scarcely characterised space materials such as glasses and paints, information on the impact of erosion and contamination on the thermo-optical properties of materials. Furthermore, the comparison of predicted and test contamination results confirmed the accuracy of CIONIC modelling, and allowed to investigate the trade-off between diffuse and pseudo-specular re-emission. The main consequence of this test campaign will thus be a reduction of the margins needed to design a spacecraft embarking electric propulsion devices. Furthermore, the success of the test set-up established with ONERA allows to consider further tests with other materials, geometries, or energy levels.

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