EXPERIMENTAL MODELS OF EFFECTS SIMULATION

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ABSTRACT

Testing to space environment is a difficult process in which test representativity is always a question. Every time a new experimental array is set up, a trade-off has to be performed to produce an acceptable blend of physical accuracy, versatility, growth capability, and cost efficiency.

Coatings are tested to resist UV, electron and proton irradiations and also oxat, in test bed where vacuum is held all along the test.

Electronic parts are tested to total doses in far more simple arrays, using Co60 sources.

Sporadic effects such as SEE due to cosmic rays and fast protons and also such as ESD depends strongly on the instantaneous values of space environment affected by solar activity. SEE tests are performed on a few big accelerators. ESD experimental arrays are presently undergoing a great complexity due to the necessity to take into account the whole spectral of energies from ionospheric plasma (or propulsion plasma) to MeV radiation belt particles.

For all the examples quoted, the environment thus simulated depends strongly on the sun activity. Implementation of space weather could contribute to the best definition according three points : -a better definition of worst cases (magnitude, frequency of occurrence…); -a better understanding of mean cases; - a better analysis of in-flight measurements.

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1. INTRODUCTION

Two main classes of effects due to the space environment are to be taken into considerations for prevention :

*cumulative effects in which the degradation observed is the result of an increasing exposure to the environment, with such example as aging of thermal coating, drift of electrical properties of EEE parts, erosion of materials under atox, micrometeoroids and debris...

*sporadic effects in which an event occurs due to present conditions of environment - or at least accumulation over a short lapse of time of a few hours or days - such as noises of any kinds, ESD effects, SEE, impacts of meteoroids and debris… with or without creating permanent damages.

Of course, one cannot fully ignore that in some cases sporadic effects are affected by previous exposure to cumulative stress.

When dealing with experimental simulation, the main concerns are not exactly the same for both set of experiments. For cumulative effects tests, the problems underlying are "Acceleration laws ?", "Completeness of the test ?", "Mean values of the environment ?". For sporadic effects tests, these problems are now "Worst case for the environment ?", "Completeness of the test ?" and often problems relative to an higher level than the sample tested that can be symbolized by "System implication ?".

The question hereunder addressed is "will Space Weather have consequences on how tests to space environment are performed ?"

2. CUMULATIVE EFFECTS : THERMAL COATINGS

Thermal coatings are a good example of how the questions concerning acceleration laws and completeness of test can affect the conception of the facilities and the cost of their operation. Spacecraft materials are directly submitted to the various components of the space environment (vacuum and residual atmospheric species, contamination, thermal cycling, ultraviolet radiation, electron and proton fluxes, micrometeoroids and debris). Due to ever growing life time (twelve years for current missions, twenty years as a specification of near future telecom satellites, up to thirty years for the future Space Station), it is mandatory to predict the long term performance of materials to be used on board during a specific mission. The physics of the interaction forbid to wholly uncouple the various tests.

2.1. Effects of space environment constituents (Ref 1)

a) Vacuum

The presence of oxygen molecules strongly modifies the effects of radiation in organic materials. Many free radicals remain trapped in the bulk of a material irradiated under vacuum. When re-exposed to air they undergo oxidative reactions with products differing in abundance from the products of irradiation in air, but similar in kind, i.e. ketones and alcohols.

An instantaneous bleaching of the radiation-induced coloration is also observed quite often when vacuum-irradiated white paints are exposed to air. This bleaching is due to the reabsorption of oxygen at the pigment interface (during vacuum irradiation, oxygen is removed by photodesorption, leaving oxygen vacancies in which electrons can be trapped, providing optical absorption). An example of the air recovery of a paint is given in Fig.1.

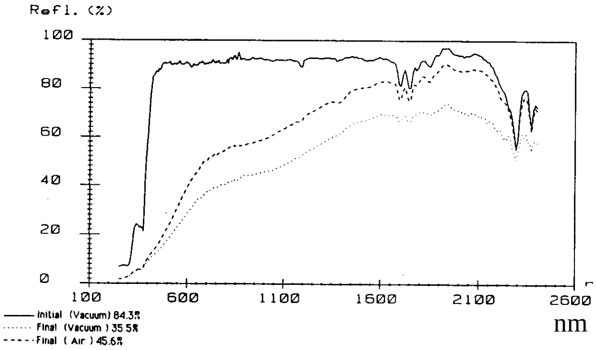

Figure 1. *Air recovery of the SG11 FD white paint irradiated in vacuum with electrons , protons and UV. The irradiation conditions were equivalent to 7 years in GEO.*

In vacuo irradiations as well as in situ measurements are thus compulsory when space simulation irradiations are made.

b) Synergy of UV and particle irradiations

The species which play a role during radiolysis and photolysis are qualitatively different. Photolysis only gives rise to a few of a general chemical mechanisms which can be contemplated for the high-energy radiations. Furthermore a monochromatic source of light can provoke a unique and well defined excited state. Also, the defect spurs (specially those densely packed along the proton tracks), which are created by particle radiations, are not produced under UV radiation leading to defects widely spread and uniformly distributed in the planes perpendicular to the light beam.

Different effects from radiolysis and photolysis, even for comparable doses are thus expected. Moreover, simultaneous ultraviolet and ionizing radiations (as expected in space environment) can give different results than those obtained during an irradiation using only one type of irradiation, or two types of irradiations sequentially carried out. In simultaneous conditions, the additivity of the effects is not ever observed. Such phenomena may be specially important at low temperature where trapped species are more stable.

Such synergetic effect has been observed in combined irradiations performed at ONERA/DESP : for various white paints and polymers[1], a partial damage recovery is observed when an ultraviolet irradiation step follows either a particle irradiation step or a simultaneous particle/UV step ; the solar reflectance increases in comparison with the value reached just after the particle irradiation (see Fig.2). This increase is noticed for at least 20 days under vacuum. Samples irradiated by particles and only exposed to vacuum do not exhibit reflectance changes as confirmed by a 15-day exposure to vacuum of all samples after the last particle irradiation step.

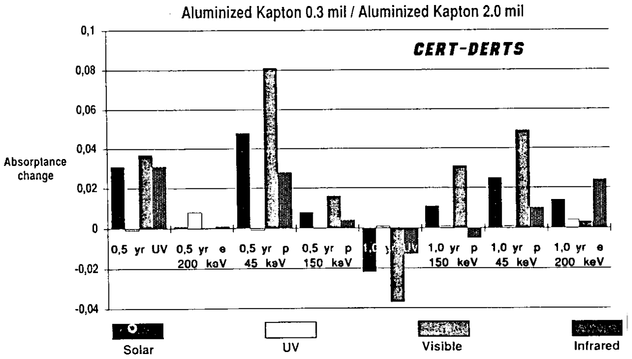

Figure 2. *Effects of sequential irradiations on the solar absorptance of an aluminized Kapton SSM; the irradiation conditions were those for the north and south faces of a GEO satellites. Solar stands for the whole spectra (black bars). The following sequence is applied: 0.5 yr UV, 0.5 yr 200 keV e^-, 0.5 yr 45 keV p^+, 0.5 yr 150 keV p^+, 1 yr UV, 1 yr 150 keV p^+, 1 yr 45 keV p^+ and 1 yr 200 keV e^-.*

When UV irradiations take a longer time than particle irradiations, it seems advisable to end the irradiations with a UV illumination step in order to avoid an overestimate of damage.

c) Dose rates

The prevailing idea is that the total dose equivalence (which implies that the effects are equivalent for a same dose whatever the dose rate) is valid as long as irradiations with electrons alone (or irradiations with protons alone) are carried out within a ratio of two orders of magnitude in the dose rates. This is substantiated by electron irradiations performed at DESP on a polyethyleneterephtalate film between $2x10^{10}$ and 10^{12} cm^{-2} s^{-1} at 600 keV for the same dose, and experiments at Boeing (Ref. 2) between $4x10^8$ and $1.7x10^{12}$ cm^{-2} s^{-1}, on aluminized Kapton, several white paints and surface coatings. This may be supported also (Ref. 3) by measurements on ZnO paints for protons between 10^{10} and 10^{12} cm^{-2} s^{-1}. A few anomalies which have been noticed can be explained by thermal effects when the cooling of the samples is not achieved adequately.

Such parasitic thermal effects are much more difficult to surmount in the case of UV irradiations using high intensities of light. If an appropriate filtering of the visible and infrared parts of the Xenon sources used for solar simulation is achieved, the equivalence seems validated for irradiations performed between one and four "UV-suns[2]". Some studies carried out at DESP on a few material types have shown that, in such experimental conditions, UV irradiations between 1.0 and 5.0 suns lead to similar thermal control coating degradation.

For many glasses, at temperatures for which the defects created by the irradiation (mainly colors centers and intersticials) are mobile, such a total dose equivalence cannot be relied upon.

d) Temperature

Temperature is also a parameters affecting the results of the test. For instance, for polymeric materials molecular chain motions are hindered for temperatures below the glass temperature transition T. Above T, radical and/or ion recombinations are possible ; they can modify the chemical reactions and therefore the degradation ultimately obtained.

The deterioration of a FEP film in an actual low temperature (ie +30°C) space environment will approximately occur at a rate 3-10 times that observed at high temperature (ie +50°C).

e) Atox

Non excited oxygen atoms coming from the atmosphere remain at orbital levels up to 3000 km altitude, where they are collected by the front face of satellites at a speed around 8 km s^{-1} equivalent to a temperature near 50000 K. Fluxes of about 10^{16} $e^-/cm^2/s$ are observed around 200 km and decrease exponentially with altitude, depending on the solar activity. Observations performed (Ref. 4) on Kapton, Mylar A and Mylar B show an erosion proportionnal to $(\cos \theta)^{1.5}$, θ being the incidence of impact. This means that the geometry is also a parameter to take into account.

f) Atox/VUV synergy

Exposition of materials such as Teflon FEP and Kapton to far UV enhances their sensitivity to oxat as exemplified on the satellite Solar Max after 50 months on a 500 km orbit, and

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[1] Polyamide KAPTON ; White paints S13G/LO, PSG120, Z93, PSZ 184

[2] One UV-sun corresponds to 11.8 mW cm-2 of the radiation emitted by the sun at wavelength shorter than 400 nm.

studied on polymers by B. Weils and M. Van Esbeeck (Ref. 5) with VUV ranging from 50 nm up to 250 nm.

g) Contamination

The strong effect of contamination layers from epoxy adhesives, pump oils… in enhancing the degradation of optical properties of surfaces exposed to UV and ionizing radiation is observed both in flight and during ground experiments. Contaminants also interfere with atox.

2.2 Experimental arrays

The brief description provided here above shows that three mains problems (quoted previously as "Acceleration" and "Completeness") are to be coped with in thermal coatings ground testing :

*necessity to reduce test duration by using higher intensities than in space.

*difficulty to reproduce some constituents such as VUV, high energy particles, oxat…

*synergetic effects almost always present, at least - but not only - with vacuum, and acting through sophisticated processes the physics of which is not usually well understood,

The consequences of that is that efficient test arrays are sophisticated and costly facilities. They are costly not only in their implementation but also in their operation. This arise another question, which is the right equilibrium between versatility (dedicated to physics understanding, necessary to define the conditions of qualification) and simplicity (aiming at reducing the cost of the qualifications).

The sketch of the SEMIRAMIS , (Système d'Essais et de Mesures In-situ de Revêtements pour l'Application de leur Modification sous Irradiations Spatiales), system in ONERA/DESP is presented in figure 3.

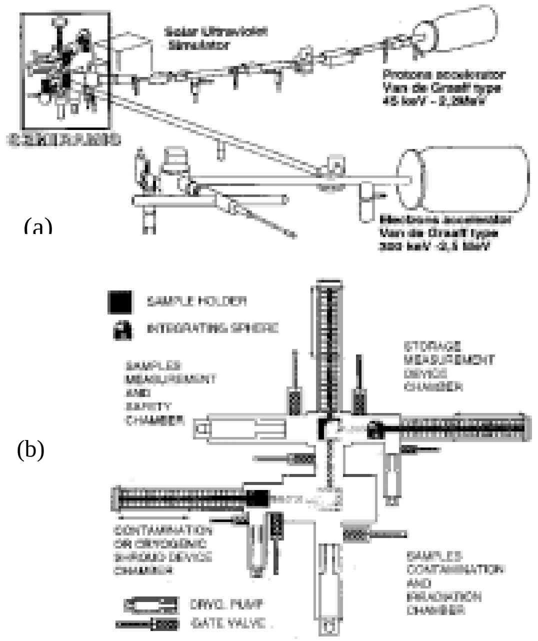


Figure 3. *Sketch of SEMIRAMIS facility and associated irradiation sources. (a) general implementation (solar UV : 200-380 nm, protons 40-350 keV, electrons 200-2500 keV). (b) vacuum chamber system*

UV radiation, electrons and protons are simultaneously directed onto the samples which are maintained under a high vacuum (less than 10^{-6} Torr) for all the irradiation time as well as during the measurement periods. The UV-irradiation is uninterrupted (except during the measurement periods) while the high energy particle irradiations are achieved by steps (with the UV-beam on). In situ measurement techniques are associated to the irradiation tests which are performed under vacuum.

The irradiation chamber is connected to two Van de Graaff accelerators ; one delivers protons with energies ranging from 40 keV to 2.5 MeV (the required upper limit for coatings being in fact 350 KeV), the second gives electrons of 600 keV to 2.5 MeV. The scattering of electrons through an uniform foil and an electrostatic rastering of the proton beam allow uniform irradiation of a 12 x 12 cm sample array. The samples receive ultraviolet radiation (in the spectral domain 200-380 nm) by the means of short arc Xenon sources, equipped with interferential filters eliminating the visible and infrared parts of their spectrum. UV-irradiations are carried out at 1-4 suns.

Typical laboratory conditions call for a 20-40 days exposure duration in order to simulate one year in space. As the operational life of spacecraft tends to become longer, the duration of tests is considerably extended with correlative requirements for the test facility reliability.

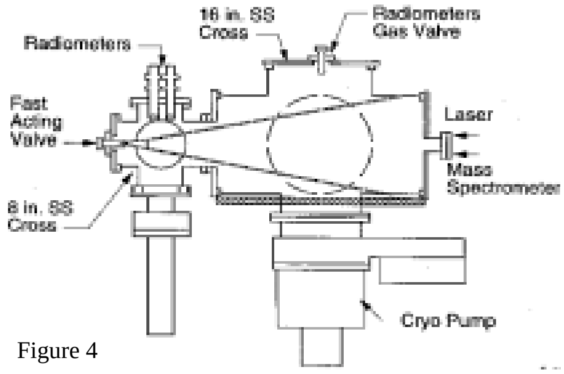
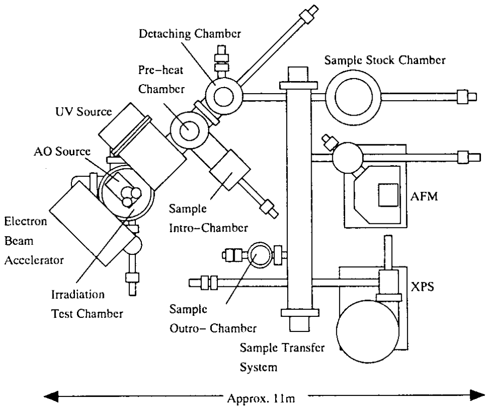


Figure 4

Figure 4 (Ref. 6) presents the schematic of the FAST-2 system developed by Dr Caledonia (PSI Hanscom US) and dedicated to atox exposure, , system which bases have been adopted on the atox facilities of ESTEC and DESP for the cleanliness (few ions) and the width of its beam.

Under ESTEC support an under vacuum transfer mechanism has been developed at DESP to allow consecutive exposures of samples to contamination, ionizing radiations (SEMIRAMIS Array) and ATOX (CASOAR Array). NASDA uses a combined oxat-radiations facilities (Fig. 5, Ref.7) allowing simultaneous exposures.

Figure 5



3 COTS

The satellites market becomes more and more competitive, driving the project teams to use at a large scale commercial electronic components (COTS). These devices are very reliable, of high performance level, and easily available, but their hardness level varies in a very broad range. So, the various experimental parameters influencing the components degradation must be studied to better define the design margins.

The experimental parameter being the most different between the laboratory and the actual environment is the dose rate: this parameter is well known to have a large impact on the CMOS devices hardness level. In 1991, an enhanced sensitivity of devices of bipolar technologies at low dose rates (LDRS for Low Dose Rate Sensitivity) has been demonstrated (Fig. 6). This rises problems of hardness assurance for space applications.

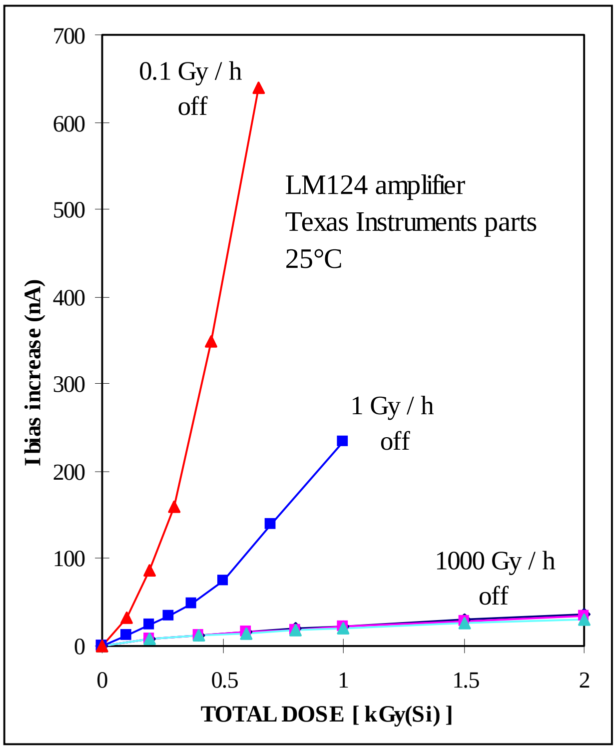


Figure 6.*Low dose rate sensitivity effect on bipolar amplifier*

Other experimental parameters like bias condition or irradiation temperature (Fig. 7) also have a strong effect on device behavior under total dose irradiation.

The practical laboratory response to these physical properties passes by the good choice of the irradiation facilities and procedures: large irradiation facility to carry out concurrent irradiations at moderate dose rates (~ 1 Gy(Si) per hour) to minimize cost testing, conservative bias condition and irradiation temperature. The same methodology must be applied for optoelectronic and III-V components, with possible other representative irradiation source (protons).

The singular event rate prediction in orbit for a device is calculated by combining its experimental sensitivity curve with the appropriate environment parameters (particle fluence versus LET or Energy). A test covering the full range of LET/E values will require a strong particle accelerator (critical parameters are threshold and saturation cross-section). In order to simulate energetic protons from radiation belts or solar flares, it is necessary to cover the 10-500 MeV range since the event mechanism depends on nuclear collisions (energy dependence) between the incident proton and the target's atoms. As a matter of fact, different attempt to develop a method to relate protons and heavy ions rates have been made. None of them giving presently full satisfaction, it is still necessary to actually measure the proton cross-section curve. For heavy ions, the particle accelerator will permit to simulate the deposited energy in the device. Laboratory facilities (laser, microbeams, ^{252}Cf fission fragments) remain useful in some cases (spatial and temporal information, error mode analysis), but the complexity of device technologies (increasing number of superficial layers, deep or vertical structure …) limits their ability to get complete and valid data.

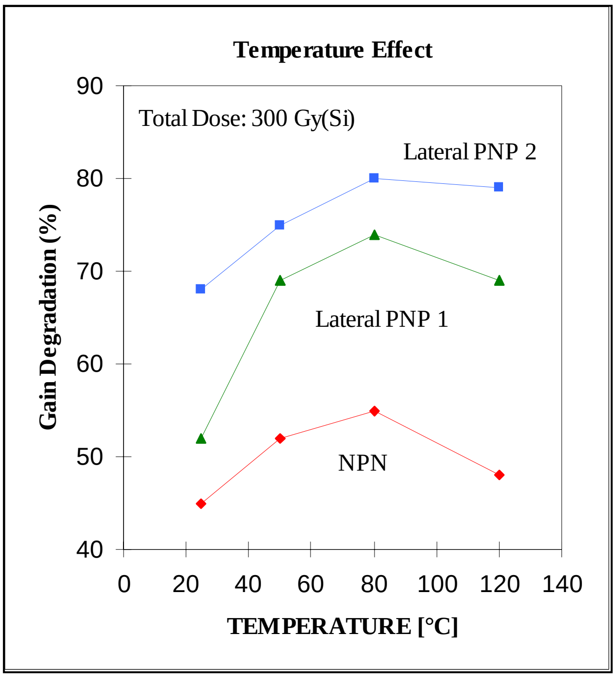


Figure 7. *Effect of the irradiation temperature on gain degradation (bipolar technologies)*

4 SPORADIC EFFECTS : CHARGING EFFECTS

When dealing with such effects the problem is now reproducing mean and extreme events that can be observed in space during a short term, typically from a few minutes up to a few days.

4-1 Electrostatic behavior (Ref. 8, 9, 10)

In geostationary orbit the various elements of a satellite reach voltage equilibrium controlled by :

$I_c + I_{esc} + I_{ise} + I_{bse} + I_{ph} = Ie + Ii$

meaning that the absorbed electronic and ionic currents Ie + Ii coming from the environment are equal to the outgoing current composed of :

I_c : resulting conduction towards and from the other part of the satellite

I_{ese} + Iise = electronic and ionic secondary emissions

I_{bse} : backscattered elections

I_{ph} : photoemission current
In fact, almost all of these terms depend either of the intensity or the energy of the ongoing radiation.

For instance the bulk conductivity of a material is produced through several mechanisms : "hopping", Poole Frenkel, Schottky and Fowler, Nordheim effects… In most of cases this conductivity cannot be described as a simple Ohm relation. Figure 8 (Ref. 11) presents the measurements obtained on Kapton 25 µm, Teflon 130 µm and Ce added glass. Furthermore this figure evidences the strong temperature dependence of the Teflon conductivity, representative of a similar behavior of other materials. Therefore, the logical approach of a qualification to ESD effects (in which some steps may be skipped if not needed) is schematized as follows :

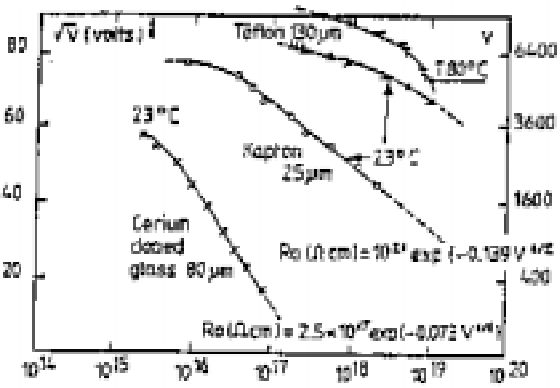


Figure 8.*Electric influence on the bulk resistivity (in shadow) of Kapton, Teflon and Ce doped glass.*

Measurements of materials	Bulk conductivity Surface conductivity Radiation induced conductivity Secondary emission /electron Secondary emission/protons Photoemission

↓

Modelisation of satellite or part of satellite (NASCAP…) giving the asymptotic voltage and electric field repartition for the reference environment

↓

On ground reproduction of environment measurement of voltage building discharge threshold and discharge characteristics

4.2 Experimental Simulation

Various experimental problems appears :
-measurement of electrical properties in dielectric materials,
-determination of environment worst case conditions,
-simultaneous application of all the relevant parts of this environment,
-reproduction of the conditions in which discharges are triggered
-reproduction of the system (i.e. the whole satellite) answer in a test performed on samples only.

The figure 9a presents the spectra used in the Sirene facility at DESP, compared with measurements issued from the SCATHA mission, and the higher energy spectra (Fig. 9b) in the GEODUR facility used for the study of deep charging effects. Both spectra are not applied simultaneously. A new facility is presently under study in order to combine these two environments.

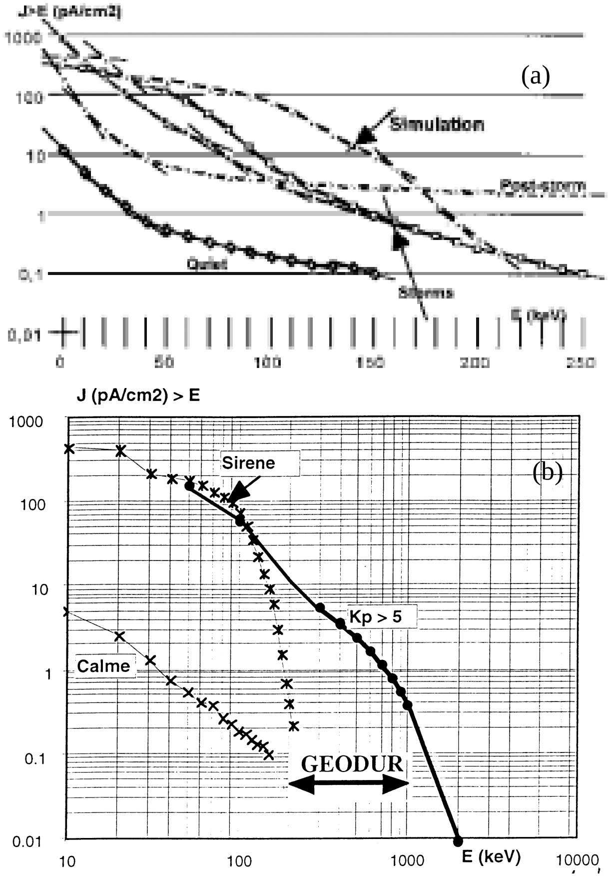


Figure 9. *Comparison of the electron energy spectra as observed by SCATHA and as produced by the facilities (a) SIRENE (< 220 keV) and (b) GEODUR (0.2-1 MeV)*

Happily in the field of plasma satellite interaction, combined environments concern only (presently ?) those addressing "surface" effect. The implementation of a 50 keV electron gun in a plasma chamber is not a major problem. The main concerns are due to the difficulty to get complete and good measurements in plasmas, the great dimensions of the chambers, and the difficulty to get a "clean enough" vacuum…

5 SPACE WEATHER AND TEST FACILITIES

The cases mentioned here above do not aim at a thorough description of all test facilities used in the prevention of space environment effects, but at highlighting on which directions will space weather influence the conception and operation of test facilities.

One of the main problems is the correct definition of the "worst case" taken into account. Space Weather will provided a considerable increase in knowledge in that topic. Under estimation (not only in magnitude but also in complexity) of such worst cases can lead to in orbit misfunctions. If accepted, that is risk management. If unforeseen, that is quality management failure. Over estimation of the worst cases has important technical and cost impacts on the experimental facilities, as seen above. With smaller uncertainties on the "fluxes" of all sort, one can either reduced test requirement (for instance duration), or at the contrary argue better for a difficult and costly implementation of facility.

In fact, in-orbit observation of unusual facts is the basis of the concern, and should be such before it turns into an anomaly. Space weather will help to correlate the observations on satellites with the environment conditions and even program such observations. For instance, charging effects in plasmas can be evidenced by fluctuations in an ionic spectrometer signal in a scientific mission, but will not help improving the knowledge on plasma satellite interaction unless a good description of the local environment is provided. Furthermore, a good insight of system behavior will result, leading to tighter system margins.

Last point, in orbit exposure experiments are part of the test facilities. Ground facilities are used to understand the physics of a problem by varying the parameter of the simulation, and thus define the right conditions of further qualifications. They are also used to perform the qualifications by applying the "worst case" required. In orbit experiments are used to verify if nothing -mainly synergetic effect- has been overlooked and identify new concern, although one cannot presently plan to met a suitable "worst case". Reliable in flight experiments – i.e. experiments including monitoring of the local environment - are presently very often sophisticated and expensive ones. By providing a good nowcasting and may be forecast of this environment, space weather will open new fields for in-orbit test facilities.

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