

IMPLEMENTATION OF A SURFACE DEGRADATION MODEL INTO ESA MASTER

Sebastian Stabroth⁽¹⁾, Peter Wegener⁽²⁾, Michael Oswald⁽¹⁾, Carsten Wiedemann⁽¹⁾, Heiner Klinkrad⁽³⁾, and Peter Vörsmann⁽¹⁾

⁽¹⁾*Institute of Aerospace Systems, Technische Universität Braunschweig, 38108 Braunschweig, Germany*

⁽²⁾*Wegener Aerospace Consult, 38108 Braunschweig, Germany*

⁽³⁾*ESA/ESOC, 64293 Darmstadt, Germany*

ABSTRACT

Since the first chemical investigation of residuals in Space Shuttle window impact craters in 1985, surface degradation particles are known to significantly contribute to the LEO small debris object environment. Later, this was confirmed by the LDEF Chemistry of Micrometeoroids Experiment, which could attribute the majority of the confirmed orbital debris impacts to paint. The driving factors for the surface degradation particle generation are atomic oxygen, thermal cycling, and ultraviolet radiation. However, there are a number of difficulties in modelling the particle release, since the knowledge of the processes leading to the generation of such objects is very poor. Thus, it is very difficult to formulate a closed form description of the surface degradation. This paper describes the approach to the problem that is used in ESA's MASTER model to account for surface degradation particles (paint flakes). The validation of the assumed size distribution against impact measurements is presented along with the implemented modelling approach and parameters for the release rate. The model runs in a time loop using annual snapshots from the Launch and Mission Related Objects population. This way, it is possible to account for aging effects on the particle release rate, and to consider newly added satellites and upper stages. The paper closes with a description of the orbital distribution of the resulting paint flake population in orbit.

Key words: space debris; surface degradation; paint flakes; size distribution; release rate; orbital distribution.

1. INTRODUCTION

The driving factors for the generation of surface degradation particles are atomic oxygen, thermal cycling, and ultraviolet radiation. Atomic oxygen, which only occurs in the LEO region, reacts with the surface of spacecraft. In case of some materials, the formed oxide layer is brittle, may crack and eventually spall off. If atomic oxygen is trapped between a coating and a substrate, an erosion of the sub-

strate underneath an atomic oxygen resistant coating can occur, causing a growth of cavities. This undercutting leads to a later delamination of larger coating flakes. At the same time, the large temperature fluctuations during eclipse entry/exit of spacecraft cause thermal expansion of coatings and substrates at different rates. In addition, ultraviolet radiation exposure embrittles surface materials, mainly polymers, such as Kapton and paint coatings. The combination of the processes leads to a shedding of debris in the μm size range, commonly referred to as paint flakes. The model for surface degradation used in the implementation in ESA's MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model has been derived by Bendisch and is based on deliberations of Maclay and McKnight (Bendisch et al., 2002; Maclay et al., 1996). In the frame of the MASTER²⁰⁰¹ validation process, the model was revised in terms of size distribution and parameters used for the release rate of the generated particles.

2. MODELLING APPROACH

2.1. Size Distribution

The quality of the diameter distribution is handled separately from the release rate in the MASTER implementation of the surface degradation model. Since there are nearly no clues for the size distribution of the surface degradation particles generated under space conditions, a power law approach is assumed in a diameter range between 2 and 200 μm . The gradient of the power law calls for a reduction by a factor of 2 within a 0.2 decade diameter interval. As it turned out from the validation review of MASTER²⁰⁰¹, the quality of the modelled flux distribution agrees with the slope observed in the Chemistry of Micrometeoroids Experiment (CME) measurement data, see Fig. 1. Thus, the modelled distribution is well suited to describe the paint flake population for large parts of the diameter spectrum. However, a reduced correction factor for objects larger than 90 μm could be postulated as an outcome of the validation process. This points to a stronger levelling-off of the size distribution in

that range. The distribution implemented in MAS-

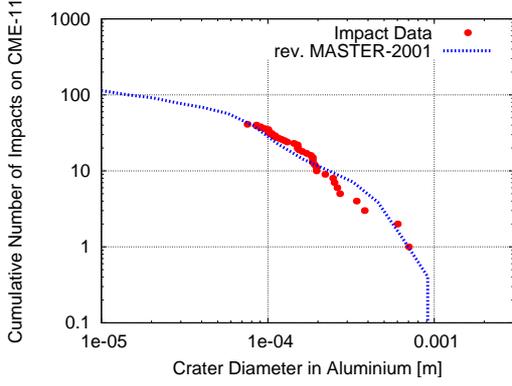


Figure 1. Comparison of revised MASTER²⁰⁰¹ model results with LDEF CME impact data (Wegener, 2004)

TER²⁰⁰⁵ therefore follows a cumulative description according to

$$\hat{N}(d) = \begin{cases} 10^{a \lg \frac{d}{d_{lw}}} & \forall d_{lw} \leq d \leq d^\circ \\ 10^{ra \lg(\frac{d}{d_x})} & \forall d^\circ < d \leq d_{up} \end{cases} \quad (1)$$

$$\hat{N} = \frac{N}{N_p} \quad a = \frac{\lg \frac{1}{f}}{w_{cl}^*} \quad d_x = \frac{d^\circ}{\left(\frac{d_{lw}^\circ}{d_{lw}^\circ}\right)^{1/r}}$$

$$d_{lw} = 2 \mu\text{m} \quad d_{up} = 200 \mu\text{m} \quad w_{cl}^* = 0.2 \\ f = 2 \quad r = 2$$

\hat{N} = normalised total number of objects $> d$

N = total number of objects $> d$

N_p = total number of generated particles

d = particle diameter

d_{lw} = lower diameter boundary of the model

d_{up} = upper diameter boundary of the model

w_{cl}^* = log. diameter class reference width

f = reduction factor within w_{cl}^*

a = standard gradient

r = gradient increase factor for tail-off.

The total debris volume generated per object by this approach can be determined by numerical integration to

$$\bar{V}_p = 4.2 \cdot 10^{-9} \text{ cm}^3.$$

2.2. Release Rate

A first outline for a possible modelling of the release rate for surface degradation particles has been published by Maclay and McKnight (Maclay et al., 1996). Based on their deliberations, the following

formulation can be derived:

$$\dot{N}_p = \dot{N}_{pO} + \dot{N}_{pC} \quad (2)$$

$$\dot{N}_{pO} = \frac{y(t_{\text{age}})}{\bar{V}_p} F_O A_O \quad \dot{N}_{pC} = x(t_{\text{age}}) r_C A_C$$

\dot{N}_p = particle no. released per time unit [1/a]

\dot{N}_{pO} = particle no. caused by atomic oxygen [1/a]

\dot{N}_{pC} = particle no. caused by thermal cycling [1/a]

y = yield due to atomic oxygen [cm^3/atom]

t_{age} = age of parent object [a]

\bar{V}_p = avg. volume per generated object [cm^3]

F_O = atomic oxygen flux [$1/\text{m}^2/\text{a}$]

A_O = surface area subject to atomic oxygen [m^2]

x = yield due to thermal cycling [$1/\text{m}^2/\text{cycle}$]

r_C = thermal cycling rate [cycles/a]

A_C = surface area subject to thermal cycling [m^2]

with the atomic oxygen flux being given by

$$F_O = f_O c_O v_{\text{orb}} p_{\text{res}} \quad (3)$$

$$f_O = \text{unit conversion} = 3.15569 \cdot 10^{16} \frac{\text{cm}^3 \text{ s}}{\text{km m}^2 \text{ a}}$$

c_O = no. density of atomic oxygen [cm^{-3}]

v_{orb} = orbital velocity of parent object [km/s]

p_{res} = residence probability at relevant altitude.

The surface degradation model implemented in MASTER assumes different parent surface areas for both generation mechanisms. Due to the dependence on relative velocity, the atomic oxygen flux is confined to the ram direction. Hence, the relevant parent surface area can be equated to its cross sectional area, while the area subject to thermal cycling is based on the assumption of an equivalent sphere of parent object size.

The age of the parent object is a significant parameter concerning the particle release rate (Maclay et al., 1996). Therefore, the erosion yield associated with atomic oxygen and that related to thermal cycling depend on the parent object age. In addition, the atomic oxygen number density strongly depends on the altitude and solar activity. Thus, the residence time in the lower LEO region is essential for the atomic oxygen erosion effects. The number density of atomic oxygen in the model is assumed to be zero above 2000 km altitude.

For the reactivity due to atomic oxygen, the ap-

proach

$$y(t_{\text{age}}) = y_0 \left(\frac{t_{\text{age}}}{1 \text{ a}} \right)^\alpha \quad (4)$$

y_0 = initial reactivity [cm^3/atom]
 α = time dependency parameter

has been chosen. The reactivity data of some materials with respect to atomic oxygen are listed in Tab. 1. As can be seen, especially paints with organic binders (polyurethane) are susceptible to atomic oxygen erosion as compared to those using inorganic binders like silicate.

Table 1. Examples for material reactivity wrt. atomic oxygen (Maclay et al., 1996; Stark et al., 1997)

Material	Reactivity [cm^3/atom]	Binder
Silver	$1.1 \cdot 10^{-23}$	n.a.
Kapton-H	$2.2 \cdot 10^{-24}$	n.a.
Chemglaze Z306 black	$6.0 \cdot 10^{-25}$	polyurethane
Chemglaze A276 white	$1.8 \cdot 10^{-25}$	polyurethane
IITRI YB-71 white	$6.0 \cdot 10^{-26}$	silicate
IITRI Z93 white	$3.6 \cdot 10^{-26}$	silicate
Borosilicate glass	$1.0 \cdot 10^{-26}$	n.a.
IITRI MH21-I black	$6.0 \cdot 10^{-27}$	silicate
IITRI MH21-S/LO black	$4.2 \cdot 10^{-29}$	silicate

Since the thermal cycling rate r_C is directly related to the orbital period, it can be derived via

$$r_C = \frac{f_C}{t_{\text{orb}}} \quad (5)$$

$$f_C = \text{unit conversion} = 3.15569 \cdot 10^7 \frac{\text{s}}{\text{a}}$$

t_{orb} = orbital period [s].

The erosion yield due to thermal cycling can then be given as

$$x(t_{\text{age}}) = c_C \left(\frac{\Delta T}{1 \text{ K}} \right) \left(\frac{t_{\text{age}}}{1 \text{ a}} \right)^\alpha \quad (6)$$

c_C = material constant [$1/\text{m}^2/\text{cycle}$]

ΔT = mean temperature variation during cycle [K]

α = time dependency parameter.

3. SIMULATION PARAMETERS

3.1. Preliminary Release Rate Parameters

The surface degradation model has been implemented into the MASTER environment. The release rate parameters for the atomic oxygen and thermal

cycling dependent degradation effects have been set to

$$y_0 = 6 \cdot 10^{-25} \frac{\text{cm}^3}{\text{atom}} \quad \alpha = 2$$

$$c_C = 0.1 \frac{1}{\text{m}^2 \text{ a}} \quad \Delta T = 200 \text{ K}$$

for the production of preliminary MASTER²⁰⁰⁵ paint flake populations. The degradation particles are assumed to have a spherical shape with a mean density of $4700 \text{ kg}/\text{m}^3$.

3.2. Comparison with LDEF Data

The model can be tested on its ability to reproduce the mass release rates that were observed with painted surfaces on the Long Duration Exposure Facility (LDEF) satellite. Fig. 2 shows the simulated mass release rates for a reference surface in LDEF's mean orbital altitude of 475 km, pointed into the ram direction. For this plot, only the degradation due to atomic oxygen is considered. The release rate due to thermal cycling is assumed to be orders of magnitude lower. If one considers typical paint materials like Chemglaze A276 and Z306 (see Tab. 1), their material reactivities result in a release rate in the order of 1 to $100 \text{ g}/\text{m}^2$ per year, depending on the solar activity ($c_O = 10^7 \dots 10^8 \text{ cm}^{-3}$ assumed for this altitude). This is in agreement with painted surfaces on LDEF, which were pointed 38° off the ram direction and lost between 10 and $70 \text{ g}/\text{m}^2$ of paint each year (Kessler et al., 1999).

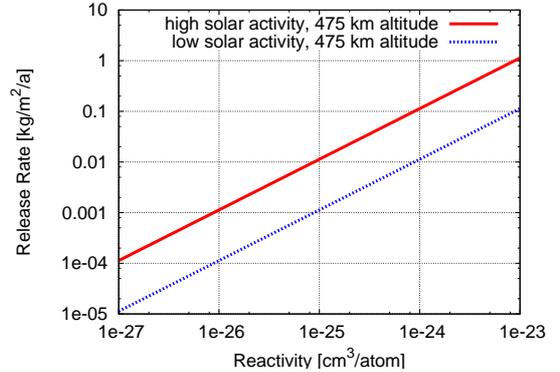


Figure 2. Simulated paint flake mass release rate due to atomic oxygen vs. material reactivity for low and high solar activity; circular orbit in 475 km altitude assumed

4. SIMULATION RESULTS

The implemented surface degradation model runs in a time loop using annual snapshots from the MASTER Launch and Mission Related Objects (LMRO)

population. This way, it is possible to reflect the actual on-orbit parent population, to account for newly added satellites and upper stages, and to re-calculate the age of the remaining population. In addition, the changing atomic oxygen flux environment due to the variation of solar activity with time can be considered.

The simulation results reveal an increase of the paint flake population from 10^{10} to 10^{12} particles in orbit in the time frame from 1970 to 2000.

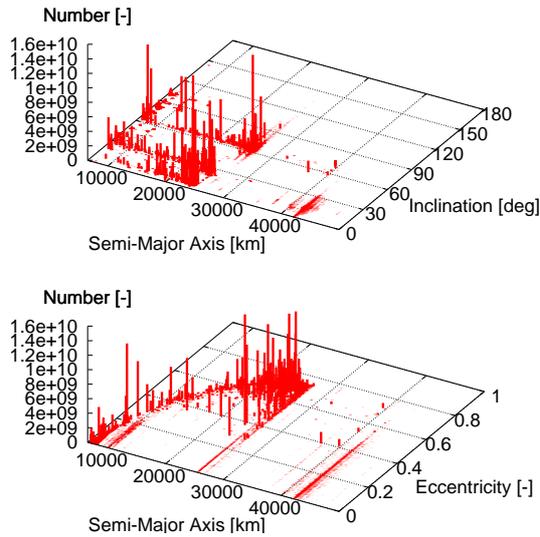


Figure 3. Inclination and eccentricity distribution vs. semi-major axis of the paint flake population in the year 2000

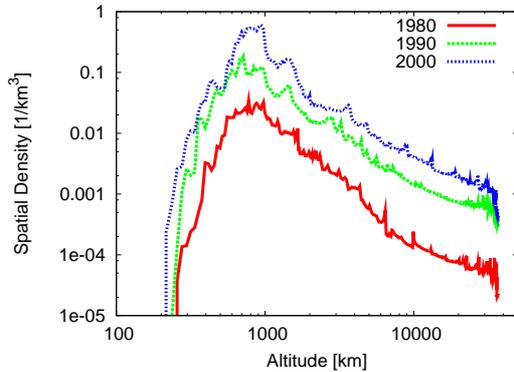


Figure 4. Spatial density evolution of the paint flake population $> 1\mu\text{m}$ with time

The release from the parent surface occurs without significant additional energy. Thus, the velocity difference of the degradation particles is nearly zero. The resulting paint flake population is therefore concentrated in orbital regimes of the parent satellites, see Fig. 3. However, the very small objects with large area-to-mass ratios of up to $100\text{ m}^2/\text{kg}$ are subject to large orbital perturbations caused by the solar

radiation pressure. According to the simulation, the objects in higher altitudes experience a periodic inclination and eccentricity variation.

The evolution of the paint flake population with time is given in Fig. 4 in terms of spatial density. Due to the highly dynamic development, the resulting debris fluxes should vary significantly with time.

5. CONCLUSION

In this paper, a description is given to quantify the generation of orbital debris resulting from degradation mechanisms of spacecraft surfaces. The model shows that atomic oxygen related surface degradation produces comparable particle release rates as observed on LDEF. The on-orbit area and orbital distribution of the LMRO population further quantifies the release rates. Due to the high area-to-mass ratios obtained by the degradation particles, the very small objects are subject to large orbital perturbations caused by solar radiation pressure.

ACKNOWLEDGMENTS

The work described in this paper was done under ESA contract no. 18014/03/D/HK(SC). The responsibility for the contents resides in the authors who prepared it.

REFERENCES

- Bendisch J., Bunte K.D., Krag H., Sdunnus H., Wegener P., Walker R., Wiedemann C., 2002, Upgrade of ESA's MASTER Model – Final Report, ESA Contract No. 14710/00/D/HK
- Kessler D., Johnson N., Stansbery E., Reynolds R., Siebold K., Matney M., Jackson A., 1999, The Importance of the Non-Fragmentation Sources of Debris to the Environment, *Advances in Space Research*, ISSN 0273-1177, Vol. 23, No. 1, pp. 149–159
- Maclay T.D., McKnight D.S., 1996, The Contribution of Debris Wakes from Resident Space Objects to the Orbital Debris Environment, *Proceedings of the 45th IAF, Space Safety and Rescue, Science and Technology Series*, Vol. 88, Gloria W. Heath Editor, pp. 215–228
- Stark J., Nombro A., Walker R., Crowther R., 1997, A Model for the Generation of Micro-Debris Resulting from Atomic Oxygen Impact, *Proceedings of the Second European Conference on Space Debris*, ESA SP-393, pp. 285–288
- Wegener P., 2004, Modelling and Validation of the Space Debris Flux onto Satellites, ZLR Forschungsbericht 2004-02, Center of Aerospace Technology, Braunschweig, Shaker Verlag Aachen