THE EFFECTS OF ORBITAL DISTRIBUTION FROM SOLID ROCKET MOTOR SLAG

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ABSTRACT

Solid rocket motor (SRM) firings are an important source of space debris environment. The resulting by-products are generally divided into two categories: slag and dust. Dust will re-entry sharply and do not pose a significant hazard. Slag debris can achieve centimeter level, these particles have a serious effect on risk assessment and defend structural design of spacecraft. It is important to understand the size distribution and orbital behavior of slag in order to predict the hazard posed both currently and in the future. Utilizing previous researches on SRM slag and 8-year launch cycle, we have analyzed the orbital distribution of SRM slag. The results indicate that SRM slag is a crucial component of the space debris environment. In order to sustainable utilization outer space, human should forbid the use of SRM in the future, especially for the medium Earth orbit (MEO) and geosynchronous Earth orbit (GEO) regions.

1 INTRODUCTION

Aluminium is used as an additive in the solid rocket motor (SRM) propellant in order to increase the performance and to dampen burn instabilities. The mass fraction of aluminium powder is normally about 18% of the motor propellant mass. During the combustion process most of this aluminium is transformed into Al_2O_3 and partly ejected into the space environment. The primarily resulting by-product is dust particles. The size of dust is mostly micron scale, and the exhaust velocity will be 3km/s which mean these particles will re-entry sharply and do not pose a significant hazard for spacecrafts [1]. But dust is not the only residue, much larger slag objects which can achieve several centimetres in diameter had been observed ejecting from the rocket nozzles [2,3]. 5mm debris can penetrate the International Space Station (ISS) in sensitive locations, and 0.1mm object can penetrate astronaut's space suit [4]. Using an 8-year launch cycle, this paper provides the slag orbital distribution, and analyses the effects on space debris environment both currently and in the future.

2 SRM SLAG SIZE DISTRIBUTION

Only few investigations had been made concerning the ejection of slag from solid rocket motors, particularly after burnout. The first SRM slag deterministic model was introduced by Meyer, but the output of this model turned out to be very sensitive to variation of crucial motor structural parameters (e.g. nozzle throat diameter, offload factor) or spin [5,6]. However, the input could not be reliably provided in such detail due to a lack of this type of data for most of the historical launch missions. More universal approach had to be developed.

The three main commonly used models described in literature were the National Aeronautics and Space Administration (NASA) model, Michigan institute of Technology / Lincoln Laboratory (MIT/LL) model and Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) slag model. NASA model was based on optical observations of statically fired SRM [2], the latest version was described by Horstman and Mulrooney [7]. MIT/LL model was derived from the observation of ascending sub-orbital launch vehicles using ground-based radar devices and infrared telescopes [3]. MASTER slag model, which is the most common approach, is a combination of both NASA model and MIT/LL law. In general, the MASTER model mainly comprises size distribution, area-to-mass distribution and eject velocity distribution [8].

2.1 Slag Size Distribution

The MASTER slag approach for the size distribution is:

$$N_{sl}(d)=\begin{cases}\dfrac{m_{prop}}{m^*_{prop}}N^*_{sl}\left(\dfrac{d_p^3+d^{*3}}{d_p^3+d^3}\right) & \forall d\le d^* \\ \dfrac{m_{prop}}{m^*_{prop}}\left[(N^*_{sl}+\Delta N)(\dfrac{d^*}{d})^3-\Delta N\right] & \forall d>d^*\end{cases} \quad (1)$$

$$d_p^3=\frac{N^*_{sl}d^{*3}-N_{osl}d_{lw}^3}{N_{osl}-N^*_{sl}}\ ,\ \Delta N=\frac{N^*_{sl}}{(\frac{d_{up}}{d^*})^3-1}$$

$$N_{osl}=\frac{m_{prop}}{m^*_{prop}}N^*_{osl}\ ,\ d_{up}=f_{th}\times d_{th}\ ,\quad f_{th}=1/3$$

Where d is slag object diameter, $N_{sl}(d)$ is cumulative number of slag and liner objects greater

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than d , $d_{lw} = 10\mu m$ is lower diameter limit, d_{up} is upper diameter limit, d_p is virtual pole diameter, $d^* = 5mm$ is reference diameter, d_{th} is the nozzle diameter, m_{prop} is propellant mass, m^*_{prop}=700kg is propellant mass of reference motor, $N^*_{osl} = 3\times10^8$ is total number of objects generated for reference motor, N_{osl} is total number of generated objects, $N^*_{sl} = 1800$ is number of observed slag and liner objects larger than d .

The remaining problem with the slag size distribution approach is that the nozzle throat diameter d_{th} as the scaling parameter for the upper diameter limit is not known for many common space engines. Assuming burn rate is a constant, this means d_{th} for a given motor can be derived from propellant m_{prop} and the burn time. But the burn time is not known for most motors, Stabrath [9] proposed another fit for the propellant mass alone to compute the nozzle throat diameter (see Eq. 2). Based on this correlation it is possible to derive the nozzle throat diameter d_{th} only from the knowledge of its propellant mass m_{prop} .

$$d_{th} = 4.142\times10^{-3} m_{prop}^{0.436} \quad (2)$$

2.2 Area-to-Mass and Velocity Distribution

The MIT/LL radar measurements could distinguish the slag number, but could not identify the material of the observed objects. The only reliable slag data source is the NASA ground tests, because the recovered particles could be chemically analyzed. As a simplification, all generated slag objects are assumed to be of spherical shape. 50% of the particles are assumed to exhibit Al_2O_3 characteristics with an average density of 3500kg/m^3, while the remaining 50% are treated as liner material residuals with an 1800kg/m^3 average consistency.

Based on NASA approach, the ejection velocity of the generated slag objects is mass independently set to a constant value of 75m/s. Like the ejection velocity, the ejection angle plays only a minor role within the model, because of the low resulting radial velocities. The ejection angles are assumed to distribute over a 20^o exit cone relative to the motor axis.

3 LAUNCH EXAMPLES

Examples of low Earth orbit (LEO), geosynchronous transfer orbit (GTO) and geosynchronous Earth orbit (GEO) SRM firings were examined using MASTER slag model. An Orion 38 solid rocket motor was used for LEO case, and a Star 48B was used in both GTO and GEO case. The orbital evolution of slag includes zonal harmonics J_2, atmospheric drag, solar radiation pressure and third body luni-solar perturbations.

The LEO launch used an Orion 38 to achieve a final 840km×850km orbit, this motor contains 770kg of propellant. Fig. 1 depicts the slag shortly after launch and a 10-year projection to illustrate the residual particles. For GTO example, a Star 48B which has a 2010 kg fuel mass was used to propel the payload into a 300km×36000km orbit. Fig. 2 shows how the environment is affected by both the 1 January 2003 launch and the residual slag one year later. Fig. 3 illustrates the GEO case, which also used a Star 48B motor. This motor was used to transmit the payload into a 36000km×36000km orbit in GEO, which is the most long-lived orbit. No slag particles decay from this orbit in the 10-year projection studied.

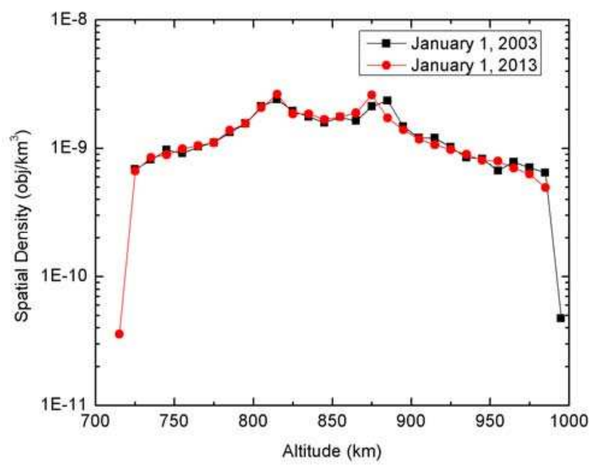

Figure 1. Spatial density of slag from a single LEO SRM (d > 1cm)

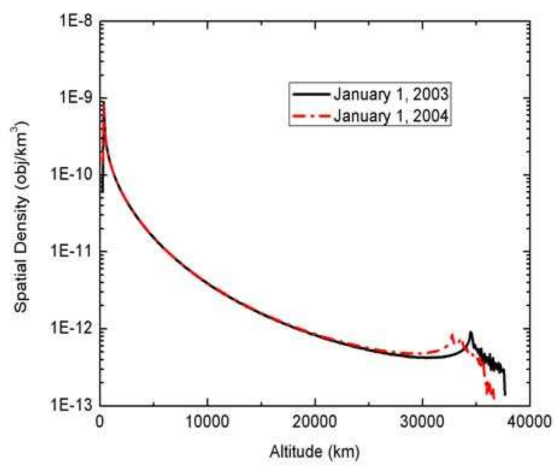

Figure 2. Spatial density of slag from a single GTO SRM (d > 1cm)

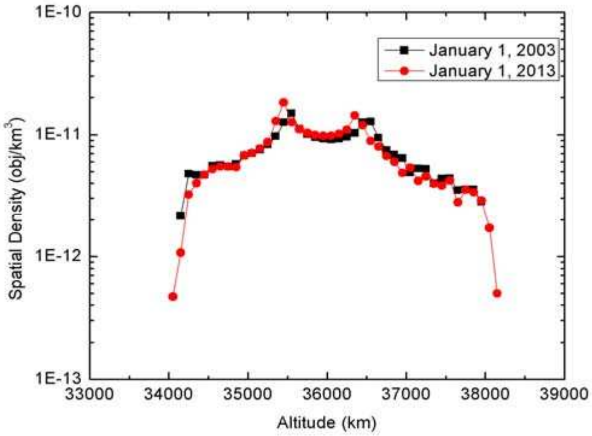

Figure 3. Spatial density of slag from a single GEO SRM (d > 1cm)

4 HISTORICAL SRM LAUNCHES AND FUTURE SLAG ENVIRONMENT

The number of solid rocket motor firings between 1957 and May 2005 was 1076, with a mean rate of approximately 22.5 per year [10]. It has since declined sharply to about six launches per year and this rate is expected to continue. Despite the decline, slag amount injected into the orbital environment every year is still huge. Fig. 4 shows the launch traffic over an 8-year period from 1 January 2003 to 1 January 2011. In modelling the future slag environment, this population was repeated every 8 years for five cycles.

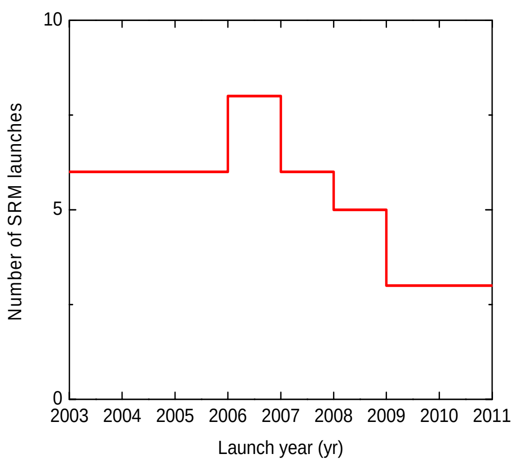

Figure 4. Reference SRM launch number for the first cycle (2003-2010)

The spatial density from LEO to GEO in 1 January 2011 and 2051 for slag diameter larger than 1cm is shown in Fig. 9. SRM slag particles are generated during the post-burn phase of the engines and ejected with low additional velocities. This means the orbits of slag are very close to the source motors. Since a large share of SRM missions is dedicated to the circularization of transfer orbits into GEO and the semi-synchronous orbit at about 20000km altitude. There are strong peaks for semi-synchronous orbit at about 20000km altitude and GEO region (Fig. 5). The dominance of such characteristic is also proved by the large share of near-circular slag orbits visible in the eccentricity spectrum (Fig. 6). Fig. 8 shows the distribution by object diameter, the maximum peak is about 100µm. Fig. 7 reflects the spectrum for inclination, which indicates GEO range and inclination of 28° (US (United Nation) GTO transfer orbits), 55° (US Navstar), 65° (GPS (Global Positioning System) apogee kicks) and 98° (SSO (Sun Synchronous Orbit))have the most slag residues.

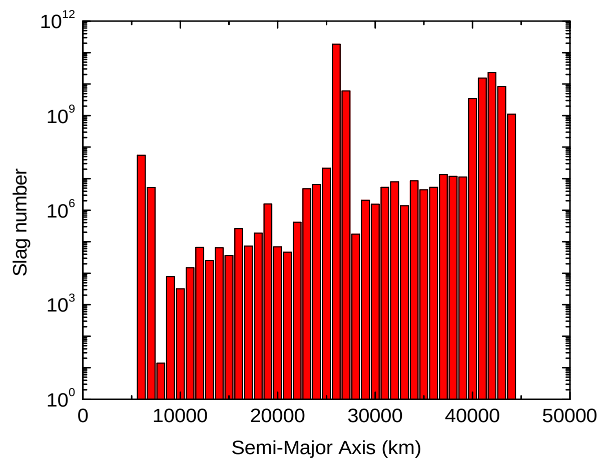

Figure 5. Semi-major axis distribution for SRM slag with Δa = 1000km

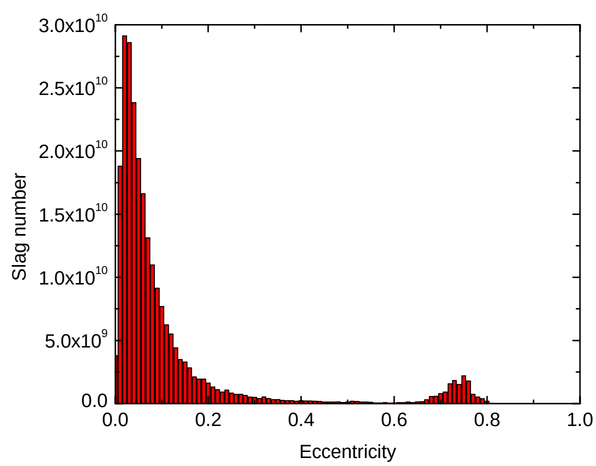

Figure 6. Eccentricity distribution for SRM slag with Δe = 0.01

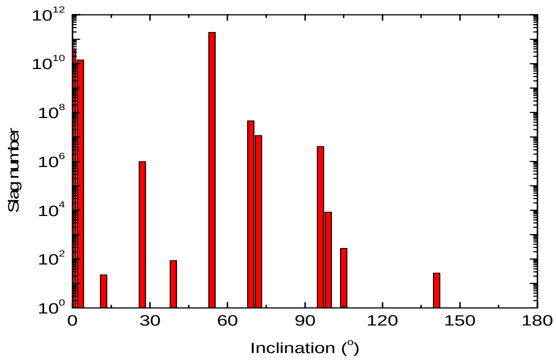

Figure 7. Inclination distribution for SRM slag ΔI = 3°

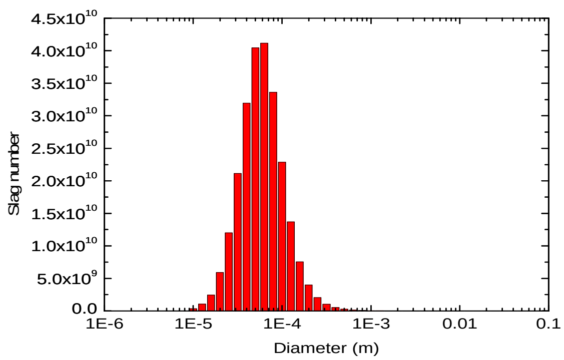

Figure 8. Diameter distribution for SRM slag with Δ(log d = 0.1)

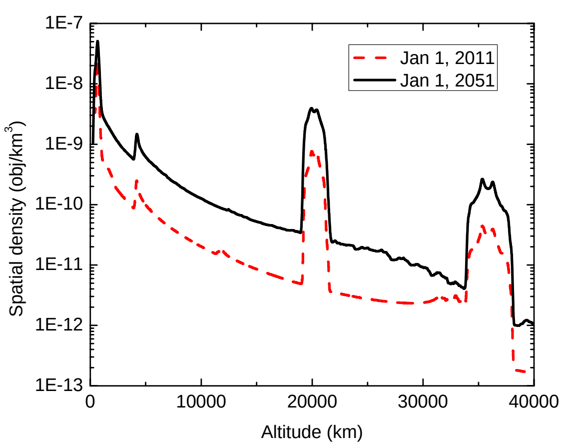

Figure 9. Spatial density for 8-year launch cycle and the cumulative population after 5 total cycles with d > 1cm

5 CONCLUSION

Solid rocket motors slag are an important source of space debris, although the use of solid rocket motors has steadily decreased, past slag particles will continue to effect the environment persistently, as will the few remaining annual solid rocket motor launches. Using MASTER slag model and an 8-year cycle, we analyzed orbital distribution and long-term effects of slag from solid rocket motor ejection. The result shows that slag is a crucial component of space debris environment, especially for semi-synchronous orbit at about 20000km altitude and GEO region. Going forward, we intend to add additional historical launches and combine slag into the overall debris model.

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