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SPATIAL DISTRIBUTION OF AL_2O_3-PARTICLES IN THE NEAR EARTH ENVIRONMENT

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ABSTRACT

During all transfer manoeuvres carried out with solid rocket motors, which contain an aluminium-supplement, aluminiumoxid-particles are ejected.

In my work geostationary satellite injections are examined, because -owing to their large number- they are the most important producers of aluminiumoxid-pollution.

The investigations focus on the initial populations, the orbit-evolutions and the lifetime of the particles dependent on the geographical latitude of the launch site and the date of GEO-injection. Additionally a comparison between the artificial aluminiumoxid-flux and the natural, constant flux of meteoroids is carried out.

At least the number of aluminiumoxid-particles, which collide with LDEF is computed, based on two ejection-models.

1. LAUNCH SYSTEMS

The first step in analysing the aluminiumoxid-particle ejection during GEO-injection, must be an examination of the launch systems.

Altogether from April 1965 until December 1990 the large number of 392 satellites was injected in GEO with 334 rocket launches. This number increases continuously with time (with the exception of the decrease in 1986, when 3 US carrier systems failed).

Fig. 1 shows the distribution of all launches to the different carrier systems. This distribution is important for my research, because only rockets, which use upper stages (perigee motors) with solid propellant, produce aluminiumoxid-particles during burning.

Most of the launches (altogether 222) are carried out with the US systems: Delta (77 launches; upper stage: solid), Space-Shuttle (32 launches; upper stage: solid (25), liquid (7)), Titan (36 launches; upper stage: solid (5), liquid (31)) and Atlas (39 launches; upper stage: liquid). The 90 Russian satellites accomplish the transfers LEO-GTO and GTO-GEO with the "escape-stage" of the "D-1-e", which uses liquid propellants without any aluminium-supplement. Therefore they are not relevant for my considerations. The "Ariane" of ESA is responsible for 58 satellite injections and uses an upper stage with liquid propellant. At least the Chinese (CZ-3; upper stage: liquid; 6 launches) and Japanese (N-1, N-2, H-1; upper stage: solid; 16 launches) systems contribute with 22 injections.

Altogether 130 (38.9 %) of the 334 transfers LEO-GTO are accomplished with solid rocket motors of American and Japanese upper stages, which produce aluminiumoxid-particles.

For the apogee-motors used to inject satellites in GEO,

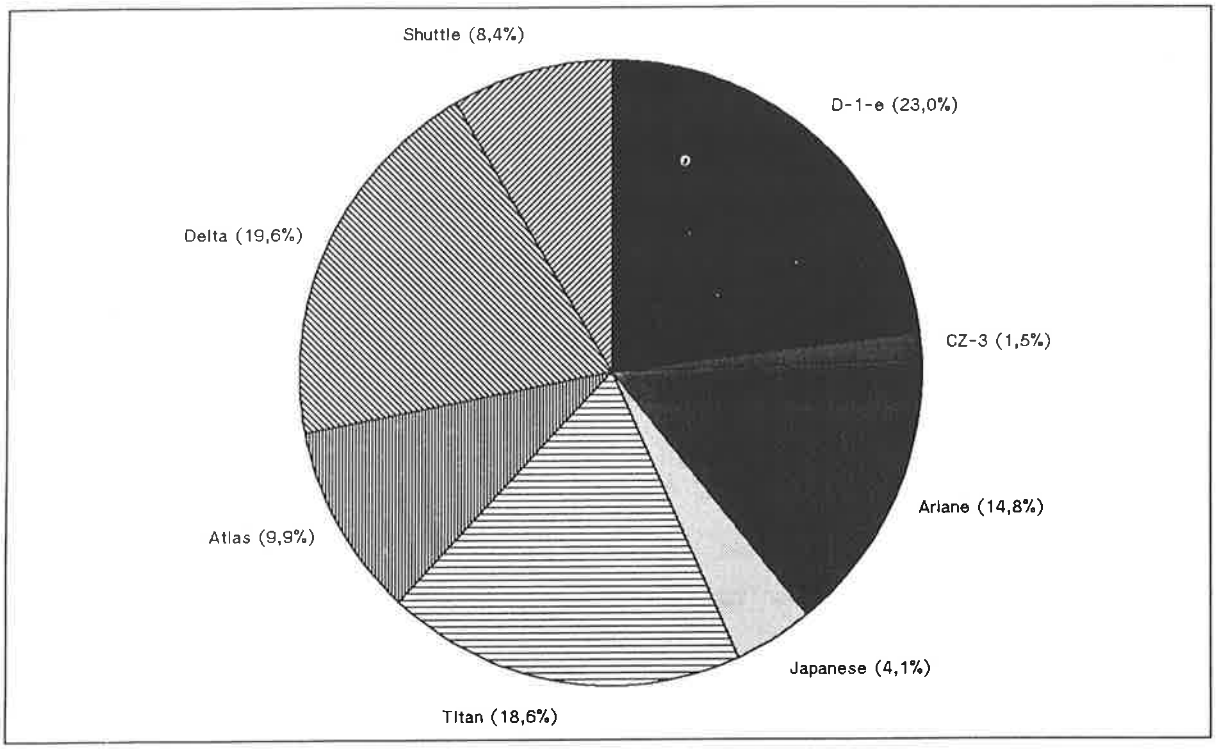


Figure 1. Carrier systems used for GEO-injection.

the situation is more complicated. Here the type of the apogee-motor is dependent on the manufacturer of the satellite and -with a few exceptions- independent from the carrier system.

Pleasantly Mr. J. McDowell placed a list of all apogee-motors used since January 1980 at my disposal. The utilization of this list and the fact, that before 1980 - without few exceptions- all satellites used solid apogee-motors, yield to the results displayed in the table (Fig. 2).

Satellites (in GEO)	Number of Apogee-Motors			
	Total	Solid	Liquid	Unknown
392	354	219 (61.9%)	130 (36.7%)	5 (1.4%)

Figure 2. Propellant used by apogee-motors.

Altogether 349 transfers must be examined (130 transfers LEO-GTO (American and Japanese systems) and 219 transfers GTO-GEO (American, Japanese, Chinese and European systems)). Because of the large number it is impossible to accomplish a separate examination of each transfer manoeuvre, rather the transfer manoeuvres must be classified in a few, characteristic cases.

2. EJECTION-MODELS

Aluminiumoxid-particles ejected from solid rocket motors have a diameter of some μm.

Unfortunately there exist two totally different ejection-models concerning the size-distribution of the particles. The first one is by a Japanese group of scientists led by Akiba (Ref. 1). According to their model, which is based on firing- and flight-tests with the stages of the Japanese Mu-rocket, $9.271 * 10^{12}$ particles with a diameter between 0 and 39 μm are ejected, if 1 kilogram of solid propellant is burned.

The second model is by Kessler (Ref. 2). In contrast to the Japanese model, it tends towards smaller particles with diameters between 0 and 10 μm. Hence, a much larger number of $4.794 * 10^{16}$ particles is produced per kilogram of burned propellant. The model of Kessler is based on a theoretical study of Burnes.

Fig. 3 displays the size-distribution of the aluminiumoxid-particles for both models.

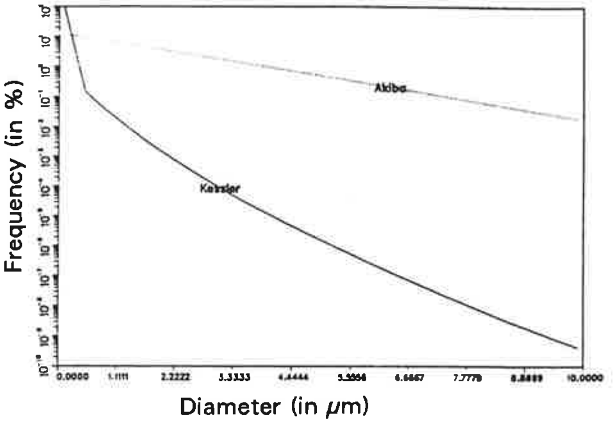


Figure 3. Size-distribution.

Additionally Fig. 4 and Fig. 5 show the ejection-velocity of the particles and the maximum angle of the ejection-cone as a function of particle-diameter (the values for both figures are out of Ref. 2).

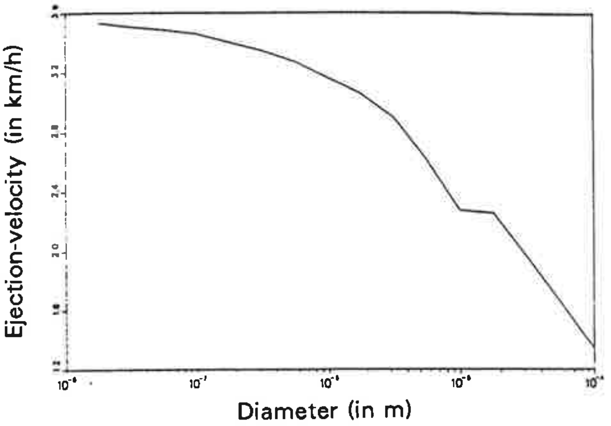


Figure 4. Ejection-velocity as a function of particle-size.

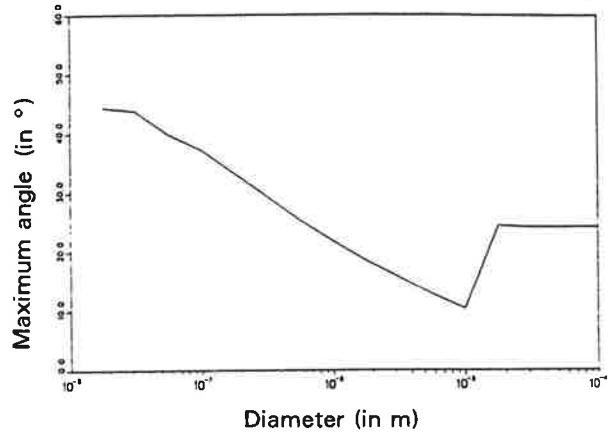


Figure 5. Maximum angle of the ejection-cone as a function of particle-size.

The velocities range from 3.6 km/h for very small particles (diameter: 0.01 μm) to 2.2 km/h for large particles (diameter: 10 μm).

The maximum angle of the ejection-cone decreases with increasing size of the particles for diameters from 0 to 10 μm. At a diameter of 10 μm the angle increases rapid and is nearly constant for larger particles. Unfortunately Ref. 2 gives no explanation for this extraordinary behaviour.

3. GEOGRAPHIC LATITUDE OF LAUNCH SITES

Launch Site	Nation/ Organization	Geographic Latitude	Geographic Longitude
Xichang	China	28.1° N	102.3° E
Cape Canaveral	USA	28.5° N	81.0° W
Tanegashima	Japan	30.4° N	131.0° E
Tyuratam	Russia	45.6° N	63.4° E
Kourou	ESA	5.2° N	52.8° W

Figure 6. Launch sites for GEO-injections.

In Fig. 6 all geostationary launch sites are summarized.

All nations and organizations use near-equatorial sites for their GEO-launches, which lead to a small inclination of GTO (geographic latitude of the launch site = inclination of the GTO) and to a low consumption of energy for injection in GEO ($i = 0°$).

A close look at the table (Fig. 6) reveals, that the Japanese (30.4°N), the American (28.5°N) and the Chinese (28.1°N) launch sites have nearly the same geographical latitude. Therefore all satellites launched from one of these sites have almost equal geostationary transfer orbits. Hence, also the transfers LEO-GTO and GTO-GEO are similar and the satellite transfers for these three launch sites could be examined in one group.

If it is taken into account, that for Russian transfers LEO-GTO and GTO-GEO and for European transfers LEO-GTO only liquid propellants were used and no aluminiumoxid-particles were produced, there remain only the following three characteristic cases of aluminiumoxid-ejection:

1.) GTO-GEO transfer of European satellites
2.) LEO-GTO transfer of Japanese and American satellites
3.) GTO-GEO transfer of Japanese, Chinese and American satellites

4. INITIAL DISTRIBUTIONS

During a normal transfer GTO-GEO (propellant mass: 600kg) the enormous number of $5.6*10^{15}$ (Model of Akiba) respectively $2.9*10^{19}$ (Model of Kessler) particles is ejected. For a transfer LEO-GTO this number is even larger, because of the larger amount of burned propellant.

To realize a useful examination of the initial distribution and the temporal evolution of the particle-orbits, this enormous number is reduced to a relative small number (some hundreds) of characteristic particles. Each of these characteristic particles represents all particles ejected in a specific part of the ejection-cone and a specific period of time during the burning process.

An examination of the initial distribution of the characteristic particles for the 3 characteristic transfer manoeuvres leads to the results in Fig. 7.

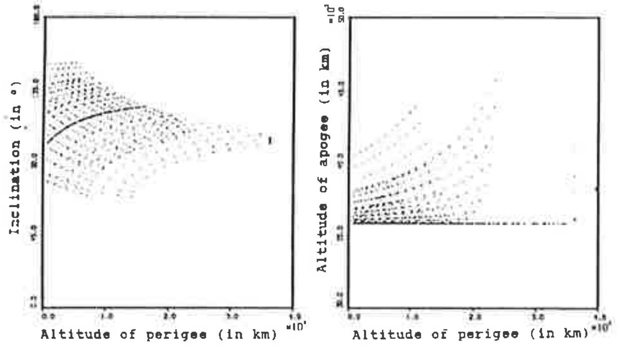
	Percentage of particles decayed immediately on earth			
Transfer	Diameter (in µm) : 1.00	3.18	10.00	31.80
GTO-GEO Europe	90.62 %	99.57 %	100.00 %	99.97 %
LEO-GTO USA, Japan	27.34 %	34.62 %	68.97 %	73.74 %
GTO-GEO USA, Japan, China	100.00 %	100.00 %	97.56 %	87.86 %

Figure 7. Comparison of the 3 characteristic transfers.

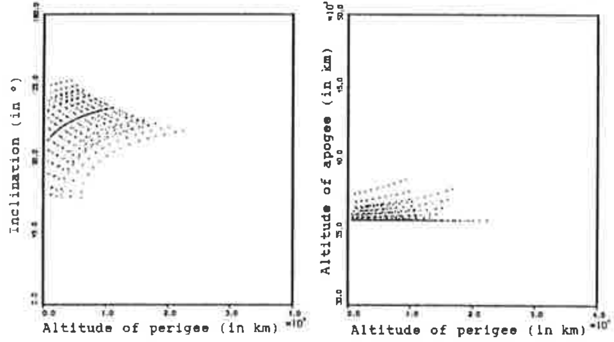
The table (Fig. 7) displays the percentage of aluminiumoxid-particles, which decay directly on Earth. Only for the transfer GTO-GEO (USA, Japan, China) large amounts of particles of all sizes remain in orbit. On the contrary, for the transfer GTO-GEO (Europe) and the transfer LEO-GTO (USA, Japan) only few particles do not decay immediately. An examination shows, that the lifetime of this remaining particles is only a few days.

Hence, my research is focused on the transfer GTO-

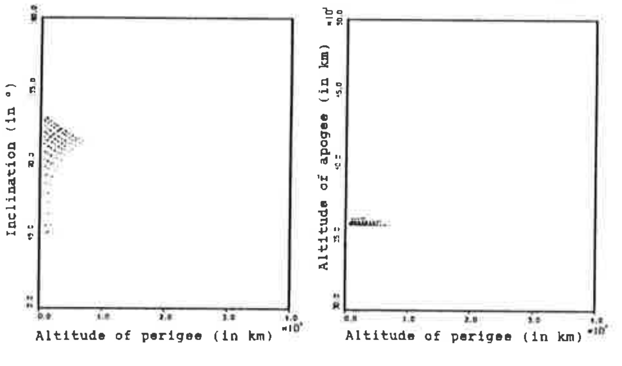
Diameter: 1 µm



Diameter: 3.18 µm



Diameter: 10 µm



Diameter: 31.8 µm

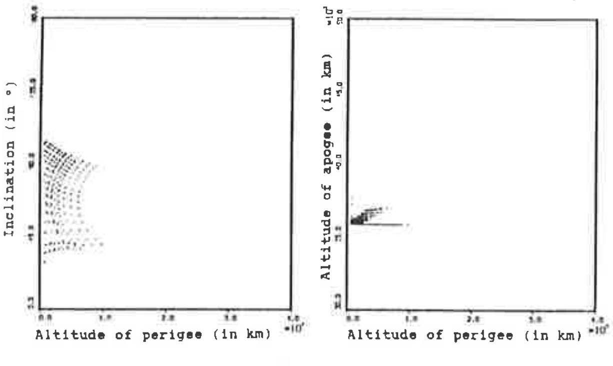


Figure 8-11. Inclination and apogee altitude of the characteristic particles as a function of the perigee altitude.

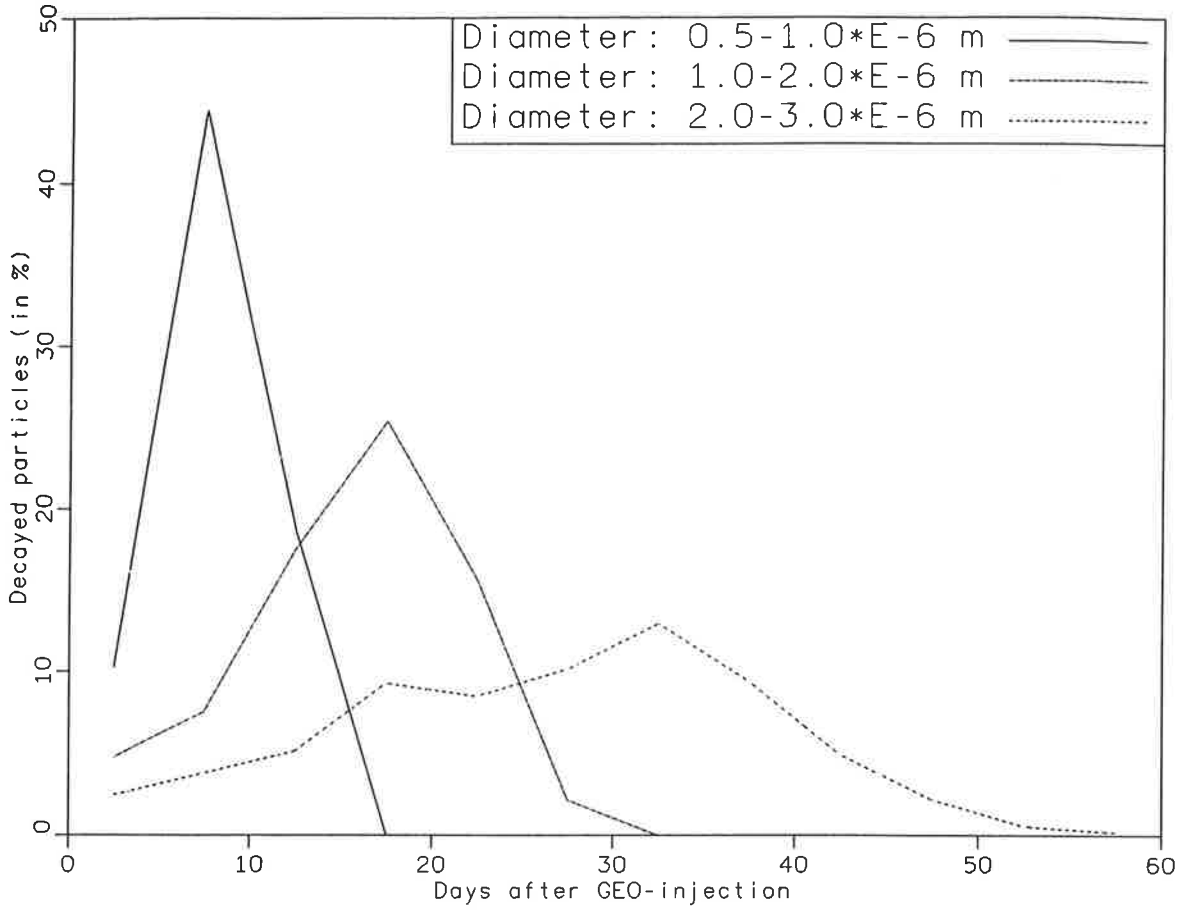


Figure 12. Mean decay of particles (Diameter: 0.5-1 μm, 1-2 μm, 2-3 μm).

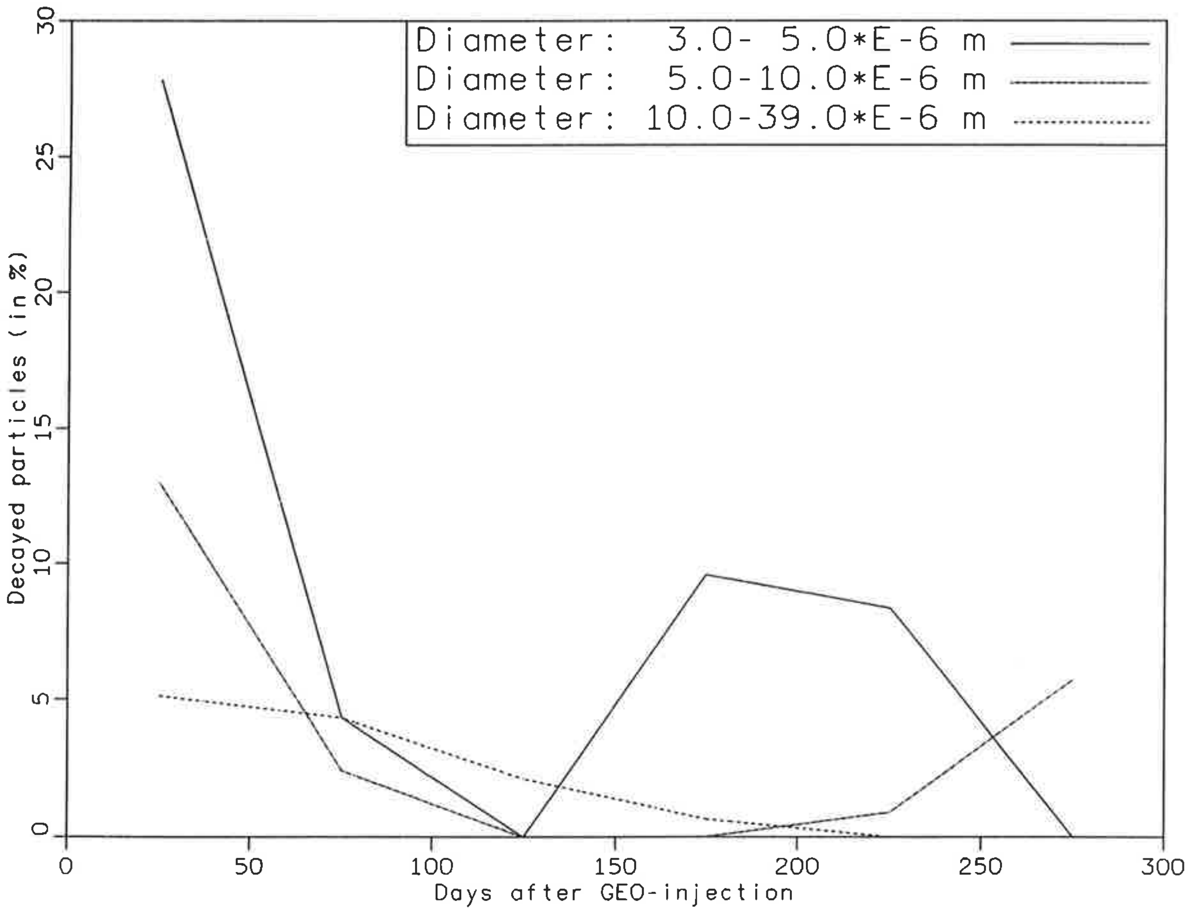


Figure 13. Mean decay of paıticles (Diameter: 3-5 μm, 5-10 μm, 10-39 μm).

GEO (USA, Japan, China).

5. TRANSFER GTO-GEO (USA, JAPAN, CHINA)

To examine the dependence of the initial distribution of characteristic particles from the particle size, distributions are produced for diameters of 1 μm, 3.18 μm, 10 μm and 31.8 μm (transfer GTO-GEO (USA, Japan, China)). Therefore the ejection-cone and the burning process are divided in angle bins as mentioned in section 4.

In the diagrams (Fig. 8-11) the inclination and the altitude of apogee of the particle-orbits is displayed as a function of the perigee altitude for the different diameters.

An exact view of the diagrams reveals the following features:

1.) The number of particles, which decay immediately, increases with increasing particle-diameter.
2.) The inclinations of most particles are near 90°, whereby for small particles inclinations increase and for large particles inclinations decrease.
3.) The large particles have orbits similar to GTO. With decreasing particle-diameter quasi geostationary orbits and orbits between GTO and GEO become more frequent.

6. TEMPORAL ORBIT EVOLUTION

To realize a temporal orbit evolution the particle-diameter is partitioned in bins from 0.5-1μm, 1-2 μm, 2-3 μm, 3-5 μm, 5-10 μm and 10-39 μm (10-39 μm-bin: only for the Akiba-model).

Then for each of the diameter bins an initial distribution of characteristic particles is produced and an orbit-evolution over one year is carried out. Additionally for all diameter bins the number of particles produced is evaluated.

During the orbit-evolution the forces caused by the air drag, the radiation pressure of the sun, the gravity of moon and sun and the oblateness of the Earth are taken into account. Particles with a diameter less than 0.5 μm are ignored, because problems in determining the radiation pressure force occur and the effect of such small particles is neglectable.

Fig. 12 and Fig. 13 display the mean decay of aluminiumoxid-particles (averaged over four different dates of GEO-injection: 21.3.91, 21.6.91, 21.9.91, 21.12.91) for all diameter bins as a function of the time after injection in GEO.

The diagrams (Fig.12 and Fig.13) show an increasing lifetime for particles with increasing size, because the forces caused by air drag and radiation pressure of the sun decrease with the area-to-mass ratio (A/m) of the particles.

For large particles (diameter > 3 μm) a considerable percentage of particles remain in orbit longer than one year.

For all particles with a diameter less than 3 μm (which experience an enormous force by the solar radiation pressure) another regularity could be found. Such particles have an average lifetime, if GEO-injection takes place at the beginning of spring and autumn, whereas for an injection at beginning of summer the lifetime is shorter and for an injection at beginning of winter is longer than the mean value.

7. COMPARISON BETWEEN METEOROID- AND ALUMINIUMOXID-FLUX

On the orbit around the sun the Earth is permanently exposed to a flux of extra-terrestrial particles, the meteoroids. (Annotation: Meteoroids with a diameter less than some μm are called cosmic dust.)

Most of the meteoroids originate from the solar system and probably are fragments of comets and planetoids. They move through the solar system on unregulated, single orbits and in streams. In my examinations only the constant flux of single meteoroids is regarded and the effects of meteoroid-streams is ignored.

The distribution function for the meteoroid-flux in the Earth environment is derived from Cour-Palais (Ref. 3). The aluminiumoxid-flux is evaluated with a program, that calculates the mean densities in spherical shells around the Earth (latitude: - 30°-30°; altitude: 200-600 km; width of one spherical shell: 50 km), and with the velocity in a circular orbit of the appropriate altitude.

In Fig. 14 the constant meteoroid-flux in the Earth environment is compared with the average aluminiumoxid-flux at an altitude of 400 km, based on the ejection-models of Akiba and Kessler.

It is remarkable, that for small and middle particle-diameters (Akiba: Diameter < 7 μm; Kessler: Diameter < 3 μm) the artificial aluminiumoxid-flux caused by GEO-injection of satellites exceeds the natural meteoroid-flux in the average over one year.

8. PARTICLE IMPACTS ON LDEF

LDEF was placed in LEO in April 1984 and operated until it was recovered and brought back to Earth by the Space-Shuttle flight STS-32 in January 1990. During this time the altitude of its nearly circular orbit changed from 477 km at the beginning to 335 km before recovery.

The mission of LDEF was to get more information about the space debris in its operational altitude.

Diameter (in μm)	Number of particles collided with LDEF Model of Kessler	Model of Akiba
0.5- 1.0	1 847 205	52 129
1.0- 2.0	748 293	128 585
2.0- 3.0	40 350	173 172
3.0- 5.0	20 314	229 678
5.0-10.0	299	80 208
10.0-39.0	---------	628

Figure 15. Impacts on LDEF (evaluation).

Taking the average surface of LDEF and an average velocity between aluminiumoxid-particles and LDEF as a basis and using the density-model mentioned in

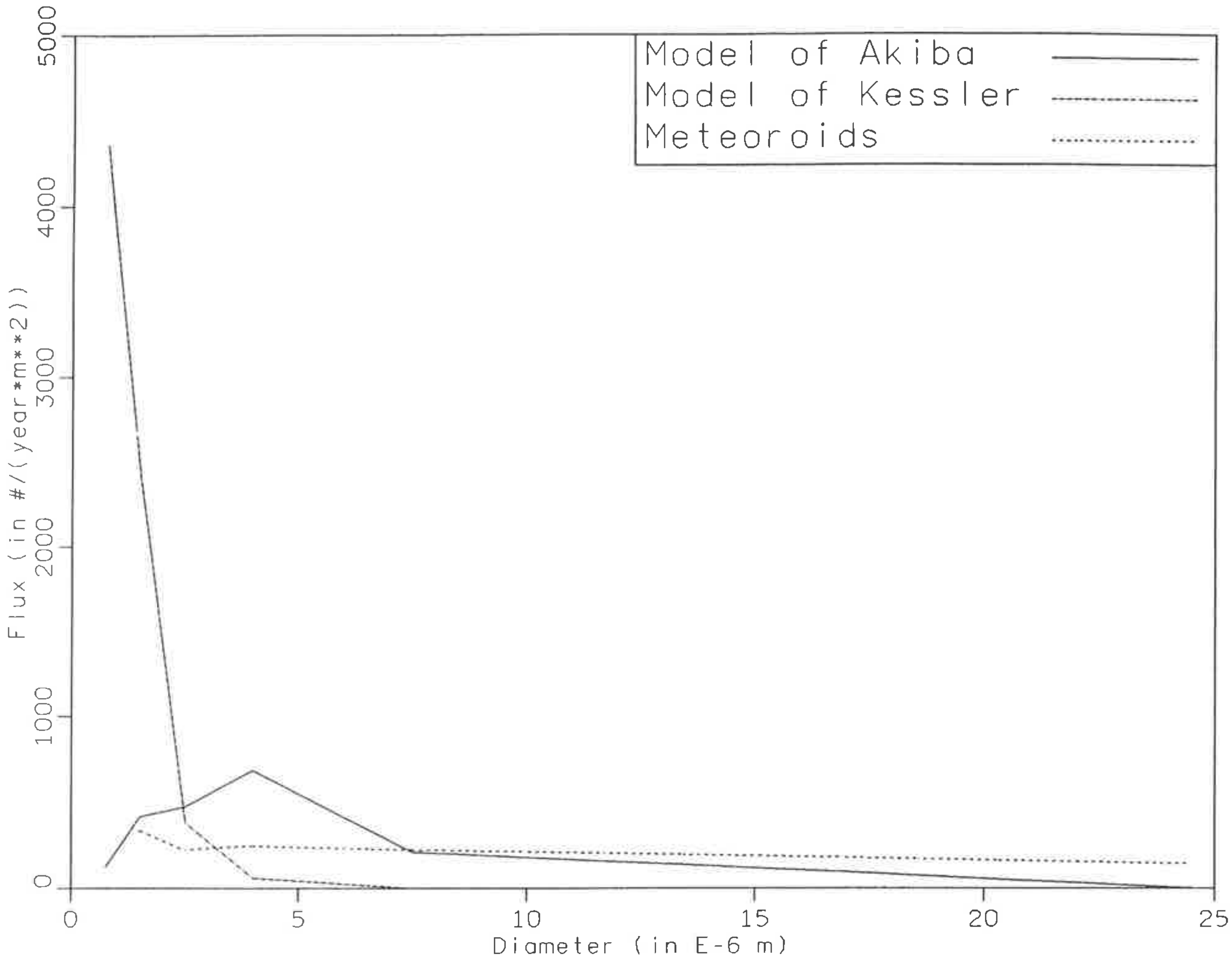


Figure 14. Comparison between meteoroid- and aluminiumoxid-flux.

section 7 and the datas about the GEO-injection of satellites in the relevant period of time, a mean number of particle impacts on LDEF could be evaluated for both ejection-models (Akiba, Kessler).

This number is shown in the table (Fig. 15) for the different diameter bins.

For both models a large total number of impacts is evaluated, whereby for the Kessler-model the total number of impacts is four times higher than for the model of Akiba. But for the Kessler-model only 0.75 % of the colliding particles are larger than 3 μm in comparison to 46.74 % for the model of Akiba.

9. CONCLUSIONS

If all possible transfer manoeuvres during GEO-injection are regarded, only for the transfer GTO-GEO of American and Japanese systems there remain greater amounts of particles of all sizes in orbit.

Examinations show that the lifetimes of the particles ejected during these transfer manoeuvres are strongly dependent on the particle size. While small particles up to 3 μm decay within two month, some of the larger particles remain in orbit for more than two years. Additionally the lifetime is shortened for small particles, if GEO-injection takes place in summer.

The aluminiumoxid-flux estimated in 400 km exceeds the meteoroid-flux for small particles, independent from the ejection-model the examination is based on.

At least there is computed a large number of particles which impact on LDEF, wherby for the Kessler-model the number of impacts is larger and the particles themselves are smaller than for the model of Akiba.

10. REFERENCES

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3. Battelle-Institut e.V. Frankfurt/Main; Work package 150: Review of meteoroid models; p. 50-58