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THE POSSIBLE LONG TERM OVERCROWDING OF LEO AND THE NECESSITY AND EFFECTIVENESS OF DEBRIS MITIGATION MEASURES

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ABSTRACT

Due to the continued leaving behind of useless space objects in long-lived orbits, an overcrowding of LEO has become a real threat. The fragments generated by collisions among objects in earth orbits can trigger again destructive collisions, leading to collisional cascading effects. In this paper, the necessity, the benefits and the costs of various debris mitigation measures to avoid cascading effects have been analyzed. To increase the reliability, the analysis has been conducted thrice, using absolutely different tools: a simple evaluation based on the kinetic theory of gases and more detailed simulations using the sophisticated computer programs POEM and CHAIN. The results are indicating that, besides the avoidance of explosions in orbit, also the de-orbit of R/B and P/L after completion of their missions is inevitable to avoid collisional cascading effects. In addition, subsequent active removal of large objects could become necessary.

1. INTRODUCTION

Earth orbiting satellites are increasingly endangered by collisions with orbital debris objects. The 3 collision avoidance manoeuvres recently performed by the SHUTTLE and the necessity of adding heavy shields to protect the planned Space Station from impacts are indicating this very clearly.

The evolution of the respective population in earth orbits is the result of a dynamic process of the generation of new objects and the removal of objects from orbit (re-entries), mainly due to atmospheric braking (see Fig. 1). The simulation of this process is the basic task of debris modeling. At present, the fragments originating from explosions of payloads and rocket upper stages in earth orbits are dominating the debris population, as can be seen from Fig. 2. This problem should be solvable on the short and mid term by appropriate countermeasures, e.g. by banning intentional explosions, venting of spent upper stages and the avoidance of battery caused fragmentations.

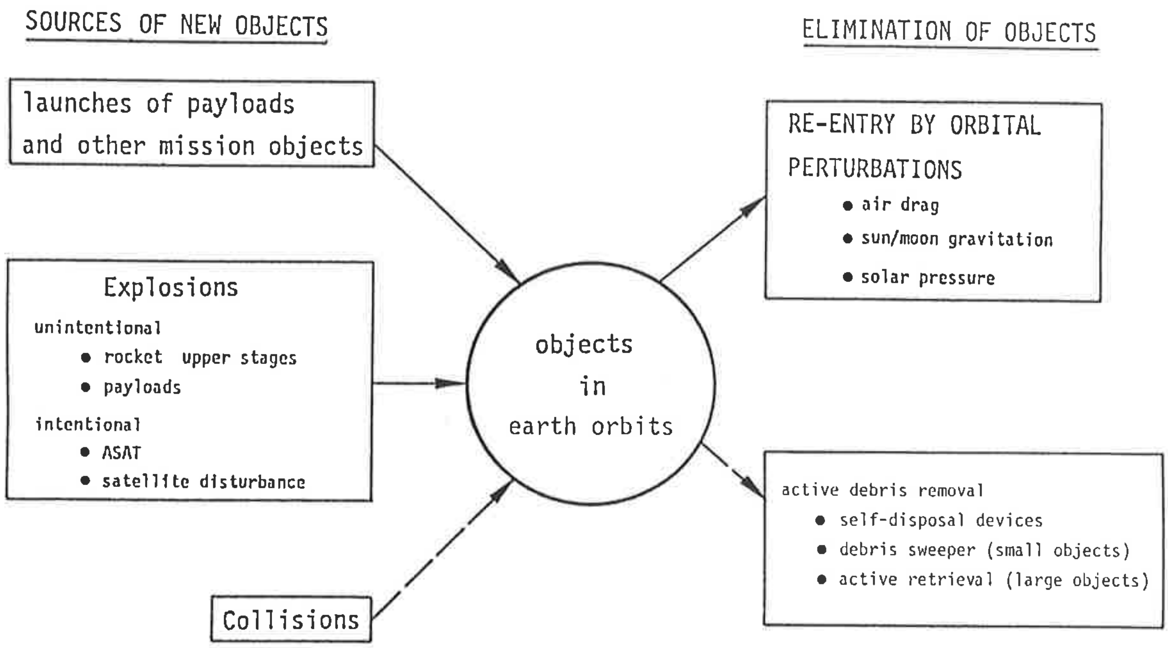

Figure 1. Debris population dynamics

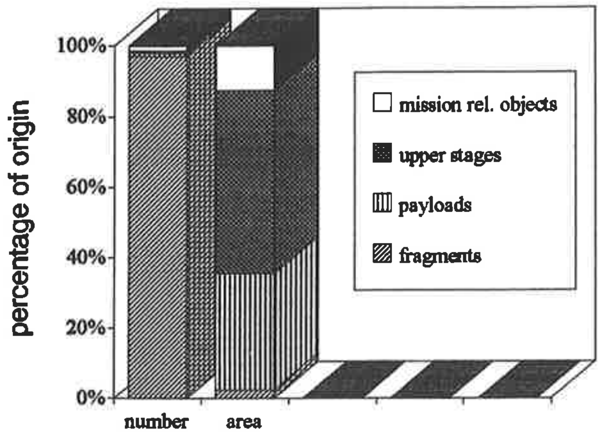

Figure 2. Percental distribution of objects in earth orbits (rough values)

But on the mid and long term, interactive collisions between larger objects in earth orbits will become the main source for the generation of fragments (Refs. 1-6, 12). A collision between two larger objects in earth orbits will generate up to several hundred larger, trackable objects (above 10 cm) and millions of millimeter and centimeter sized objects. Payloads and rocket bodies are of decisive importance in this concern, because - despite they are only representing about 3% of the population above 1 cm in earth orbits - they are containing more than 90% of the total mass and area of the earth orbiting population (Fig. 2). The risk of such kind of a destructive collision between any two objects in earth orbits is presently in the order of about 10% per year, and it will rise squared to the number of larger objects in earth orbits (Ref.1).

The larger fragments generated by a collision in earth orbit can trigger again destructive collisions, i.e. leading to a complete breakup of the target object. Such kind of a collisional cascading could successively lead to the formation of an artificial debris belt around the earth. The resulting avalanche of generated collision fragments could make spaceflight impossible in LEO for centuries.

A steady increase of the population within a limited space, as LEO is representing, will always lead to collisional cascading effects (Refs. 1-6, 12). Hence, assuming the continuation of the current way of performing spaceflight activities, the matter of uncertainty is not if, but only when such a process will start up. Thus, the necessity of effective countermeasures to limit the earth orbiting population is evident.

2. EVOLUTION OF THE POPULATION IN LEO

2.1 Reliability of the modeling results

The required changes in design and operation to reach a 'litter free space flight' will add restrictions and costs to future S/F missions. Therefore, the reliability of the modeling predictions and the risk analysis, which are the basis for these recommendations, is of paramount importance and has always been a point of discussion.

The idea of an impending cascading effect of interactive collisions in LEO starting up only a few decades from now may appear doubtful on the first sight, more Science Fiction than a real threat. Unfortunately, it is not possible to identify collisions in orbit or the possible setting in of a cascading effect directly at the moment, e.g. by measurements. Within the last years, several different research groups around the world - using totally different approaches and methods - were all independently resulting in the same basic tendency of collisional cascading effects (Refs. 1-6, 12). Nevertheless, the reliability of these results is not yet generally accepted. The simulation results indicating this threat are only the output of large, sophisticated computer programs, which are hard to duplicate for non-specialists in this field.

Hence, to increase the reliability of the modeling results, in this paper the problem of the impending overcrowding in LEO will be examined threefold

- a simple, easy to duplicate evaluation, if the population in LEO is critical concerning collisional cascading effects (see Chapter 2.2.1) and
- two independent, detailed analysis of the evolution of the population in LEO using sophisticated and proven computer programs based on totally different approaches: POEM and CHAIN (see Chapter 2.3)

2.2 Simplified statistical approach for the collision rate

Basically, the impact rate (or flux) on a given target object in earth orbit can be calculated by a simplified statistical approach using the kinetic theory of gases. This approach has been proven also by comparison with the results of precise deterministic analysis (Ref. 1). Accordingly, the impact rate **F** equals the volume of space swept out by the satellite times the existing spatial density

$$F = V \cdot \rho, \text{ where } V = v_r \cdot A_c \cdot \Delta_t \quad \textbf{(1)}$$
$$\Rightarrow F = v_r \cdot A_c \cdot \Delta_t \cdot \rho$$

where **V** volume of space swept out by the fragments during the considered time frame **Δt**

v_r adjusted average collision velocity (7.5 km/s)
A_c average collision cross section area [m^2]
ρ spatial density [km^3]

The overall collision rate **a** among all objects of a given population in earth orbit can be expressed as

$$a = \frac{N}{2} \cdot F \qquad (2)$$

where **N** total number of objects in the considered volume V_0
V_0 considered volume around the earth, in this case LEO

Inserting for the object density $\rho = N/V_0$ renders

$$a = \frac{1}{2 \cdot V_0} \cdot v_r \cdot A_c \cdot \Delta_t \cdot N^2 \qquad (3)$$

$$\Rightarrow a \sim N^2$$

and expressing the total cross sectional area in earth orbit as $A_{tot} = N \cdot A_c$

$$a \sim A_{tot} \cdot N \qquad (4)$$

Hence, it can be stated that
- the impact rate concerning one target object is proportional to the number of objects ⇒ domination of the fragments as projectiles (Fig. 2)
- the collision rate within a population is proportional to the square of the number of objects or to the number times the total area ⇒ as the area and the mass is concentrated in the larger objects, the R/B and P/L are dominating as the targets (Fig. 2)

Please note that Equ. 4 is a approximation, neglecting the differences between the individual physical cross section areas of objects and the mutual collision cross section area of 2 colliding objects. These differences have to be considered in case that the diameter of the projectile is not small compared to the target, as the collision cross section equals the sum of the cross sections of the colliding objects.

2.2.1 Simple Evaluation of the critical density

One important question to be answered by the analysis of the long term evolution is: do we have already reached or even exceeded the critical, unstable population level concerning interactive collisions in earth orbits?

The impending phenomenon of collisional cascading is basically depending on the number of larger fragments generated per collision, the lifetime of the fragments and the density of potential target objects. As collision events are likely to occur in higher altitudes around 800 to 1500 km, where the largest population density can be found, the lifetimes of the fragments may well exceed hundreds or even thousands of years. This could lead to an unstable situation, where the rate at which collisional debris is generated exceeds the rate at which fragments are eliminated by air drag. If, in the statistical average, the fragments of one collision will trigger again more than one new destructive collision within their lifetimes, this will result in an amplification of the process, i.e. in a self-reinforcing of collisions.

The question, wheather the current population level could already be unstable, will be answered with the help of a simple, easy to duplicate evaluation. Therefor, the total number of follow-up collisions triggered by the fragments of one collision will be calculated, i.e. the overall follow-up collision rate a_f within the lifetime of the fragments. Only destructive follow-up collisions are considered here, i.e. collisions leading again to the complete break-up of the target object. In case of

$a_f < 1$ ⇒ the consequences of the collision will be damped by the selfcleaning effect of the earth's atmosphere
$a_f > 1$ ⇒ the collision process will be amplified, the unstable, critical population density will lead to a collisional cascading effect.

Using the approach of the kinetic theory of gases (Equ. 1), the rate of follow-up collisions a_f can be expressed as

$$a_f = N_{fr} \cdot F = N_{fr} \cdot v_r \cdot A_c \cdot \Delta_t \cdot \rho \qquad (5)$$

where
$N_{fr} = 300 \pm 100$ number of larger, trackable fragments generated per collision
$v_r = 7.5$ km/s adjusted average collision velocity
$A_c = 10\ m^2$ average collision cross section area
$\Delta t = 400 \pm 200$ y average lifetime of the fragments (collision in 1000 km)
$\rho = 5 \cdot 10^{-9}\ km^{-3}$ current density of the potential target objects (P/L and R/B) in the most occupied region around 1000 and 1500 km altitude

The above mentioned values can be considered as absolutely reliable, because they refer to the tracked population, which is deterministically known by radar measurements (Ref.8). Insertion in Equ. 5 renders a current rate of follow-up collisions of a_f **= 1.42 (0.33 to 2) = 0.47 to 2.84**. Therefore, the current population level could be already critical. Assuming a further increase of the population at the current rate

(5% per year), the critical density will be exceeded by sure within the next 20 years: then the population density and hence the rate of follow-up collisions have been doubled, leading to a rate of $\mathbf{a_f = 2.84 \cdot (0.33\ to\ 2) = 0.95\ to\ 5.68}$. These results are consistent with investigations conducted by other research groups as e.g. NASA using totally different approaches (Refs. 1-6, 12).

2.3 Detailed Analysis of the problem

For the more detailed analysis of the evolution of the population in LEO, simulations using the sophisticated computer programs POEM and CHAIN are conducted over 50 years, that is up to the year 2042. This is thought to be an overseeable time span, in which the effects of various debris avoidance measures can be studied. To demonstrate the effectiveness and the benefits of the different degrees of mitigation measures, the following realistic scenarios have been calculated stepwise:

- **1992** current population level, only for means of comparison
- **1** 'no more launches', i.e. total, immediate stop of all S/F activities. unrealistic, only for means of comparison
- **2** 'business as usual', i.e. continuation of the current S/F activities (= about 5% linear increase per year)
- **3** easily achievable mitigation measures, i.e. reduction of explosion rate and Mission Related Objects (MRO) to the half from 1998
- **3a** in addition: total avoidance of R/B explosions from 1998
- **3b** in addition: total avoidance of P/L explosions from 1998
- **3c** in addition: de-orbiting of R/B from 2003 after mission
- **3d** in addition: de-orbiting of P/L from 2010 after mission

This paper is concentrated on the analysis of the necessity and the effectiveness of the various debris mitigation measures. For a detailed description of the technical procedures and the feasibility of the measures see e.g. Ref. 7 and 9. A brief analysis of the cost increases of space missions by these measures are given in chapter 3.

2.3.1 Detailed Analysis using POEM

The program POEM has been prepared by the Institute for Spaceflight Technology and Reactor Technology (IfRR) within a contract from ESA as part of the ESA Reference Model on Space Debris and Meteoroids. POEM is using a semi-deterministic approach, i.e. each object in earth orbits is treated individually with his specific, complete set of orbital parameters. Fig. 3 shows the scheme of the simulation process. A more detailed description of POEM can be found in Ref. 11.

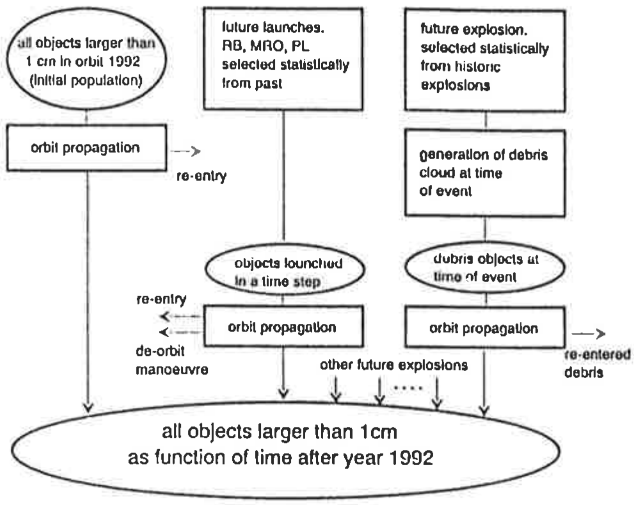

Figure 3. Scheme of modeling the evolution of the population, semi-deterministic approach (Program POEM)

As the fragment generation by interactive collisions is not included in the program, the results are underestimating the evolution, as can be seen also from a comparison with the results of CHAIN presented in the next chapter. Nevertheless, due to the precise semi-deterministic approach, already the results concerning the evolution of the population due to launches and explosions are valuable.

The most important results of the simulation of the evolution of the population in LEO using the program POEM are depicted in the Fig. 4 to 6. As can be seen from Fig. 4, the number of objects will increase steadily to about the threefold within 50 years, if S/F activities are continued unchanged (scenario 2). Each step in the curve is representing a statistically triggered explosion. Also the influence of the solar cycles can be observed, e.g. leading to a temporarily decrease of the population from 2000 to 2005.

Already the easily achievable mitigation measures are leading to an appreciable reduction effect (3), while with the help of explosion avoidance the population can be reduced to about the initial level (3a, 3b). The de-orbit of R/B and P/L, however, is having nearly no effect on the population (3c, 3d). This is due to the fact, that the number of objects is absolutely dominated by explosion fragments (Fig 5). The generation of fragments by collisions, which will become a major source in the future, is not yet included in the analysis (as in the results of CHAIN, see chapter 2.3.2). This

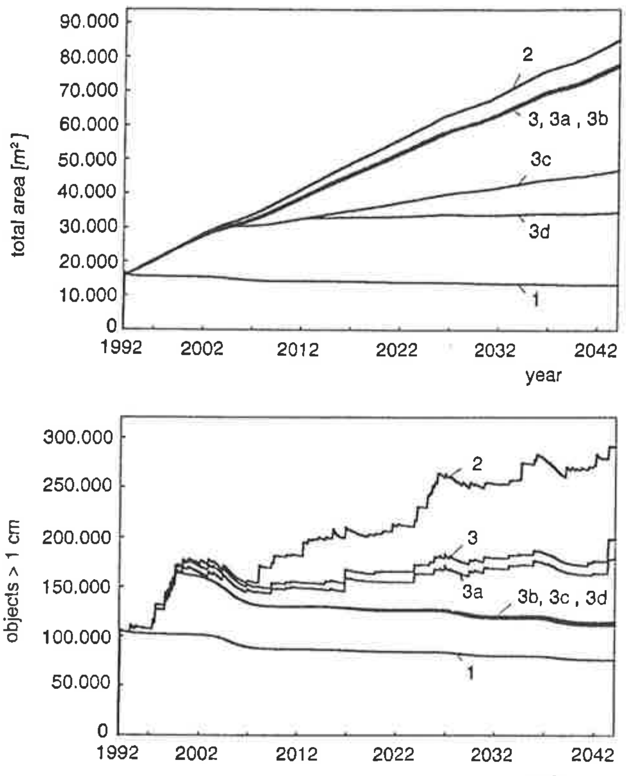

Figure 4. Evolution of the number and total area of the objects > 1 cm in LEO (POEM, w/o collisions)

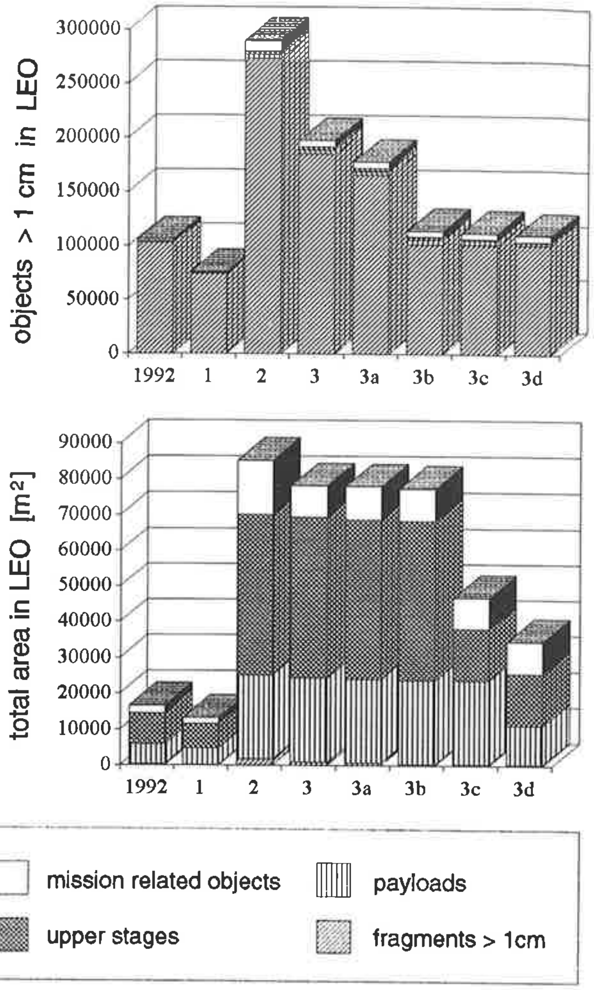

Figure 5. Composition of the number and total area of the objects > 1 cm in LEO in 2042 (POEM, w/o collisions)

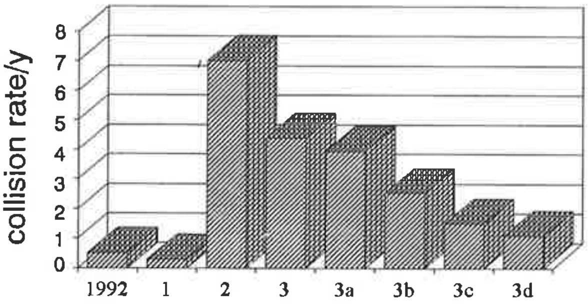

Figure 6. Evaluation of the collision rate among all objects > 1 cm in 2042 assuming different debris mitigation measures

could lead on the first sight to the wrong result that banning of explosion is sufficient to avoid an over-crowding of LEO and the de-orbiting is unnecessary. In fact, one should not only consider the number of objects, but also the total area and mass in orbit.

According to Equ. 4, the rate of interactive collisions is basically proportional to the total cross-sectional area A_{tot} in earth orbits. As A_{tot} is dominated by the P/L and R/B (Fig. 5), a reduction is possible only by de-orbit (Fig. 4). Using Equ. 4, also a simple evaluation of the collision rate among all objects > 1 cm in LEO is possible. Proceeding from a known value of about 0.5 per year in 1992, the collision rate will rise to about 7 in 2042 assuming the unchanged continuation of the S/F activities (Fig. 6).

The results are showing how necessary also the de-orbit of the large objects is to reduce the collision rate. But even assuming the realization of full preventive mitigation measures (scenario 3d), the collision rate will be doubled from 1992 to 2042. This is indicating, that subsequent removal of larger objects may become necessary in addition. The more detailed analysis using the program CHAIN, which considers the fragment generation by collisions, will collaborate these results (see next chapter).

2.3.2 Detailed Analysis using CHAIN

Due to the very high consumption of computer time for the determination of the rate of interactive collisions as well as for the orbit propagation, a semi-

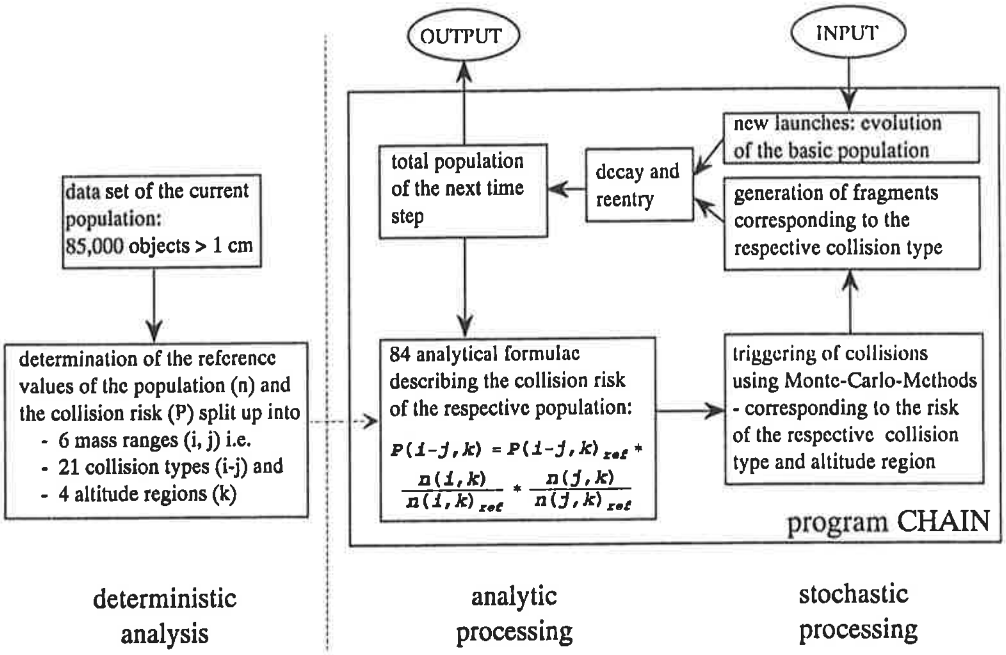

Figure 7. Logic flow of the program CHAIN

deterministic approach like POEM can be used only hardly for this kind of long term simulations including the fragment generation by collisions. Therefore, a computer program has been developed at the Institute for Space Technology and Reactor Technology (IfRR), which is a combination of a semi-deterministic analysis and a fast analytical and stochastical approach (Refs. 1, 3). Fig. 7 shows the logic flow of this program called CHAIN, which is described more detailed in Ref. 1.

The deterministic analysis of the current population has to be performed once to establish important input parameters: the reference values of the current population and the collision risk split up into 6 mass ranges, 21 collision types and 4 altitude regions.

The main program CHAIN consists of two parts, which are processed in a loop with a step size of 1 year:

- an analytic part, where the collision risk of the respective population will be calculated using analytical formulae. The reference values determined by the deterministic analysis are used for this formulae.

- a stochastic part, where the fragment generation is simulated by triggering collisions using a Monte-Carlo-Method corresponding to the respective collision risks.

The total population consists of the basic population, e.g. payloads, rocket upper stages, mission related objects and explosion fragments (comparable to the POEM results), and of the collision fragment population. The basic population can be changed from time step to time step to simulate the different scenarios of S/F activities. By calculating the orbital decay and the Re-Entry of both basic population and collision fragments, the respective total population of the next time step can be determined.

As can be seen from Fig. 8, the continuation of the current S/F activities will lead to an exponential increase of the collision fragment population, indicating the setting in of collisional cascading. The steps in the curve are resulting from collision events, triggered accidentally corresponding to the respective collision rates. The lower curve ('basic population') is comparable to the results of POEM. One can see clearly that the increasing number of collision fragments is more and more dominating the total population.

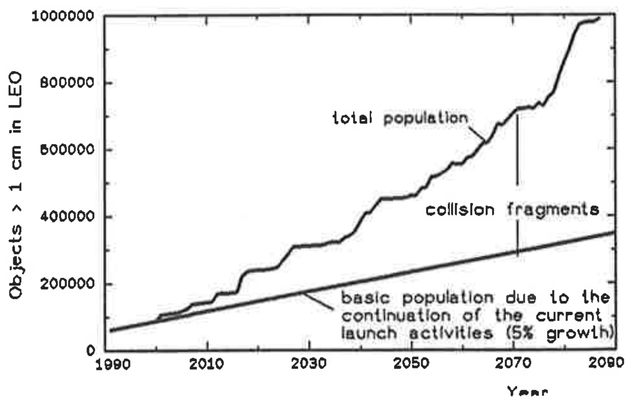

Figure 8. Exponential increase of the population due to interactive collisions

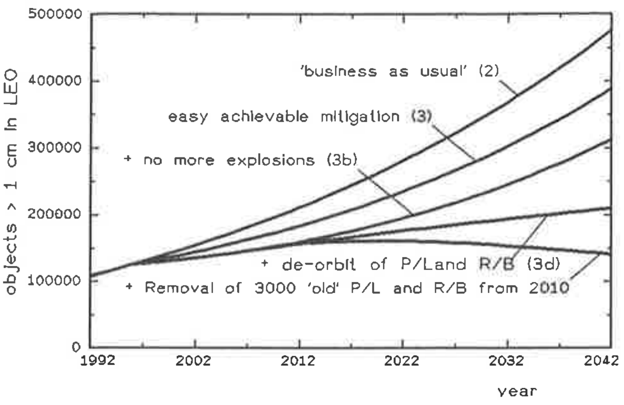

Figure 9. Evolution of the number of objects > 1 cm in LEO (CHAIN, with collisions)

Fig. 9 shows the evolution of the population including the fragment generation by collisions assuming the different debris mitigation measures calculated with CHAIN. For reasons of better comparison, averaged values are used here, leading to the smoothed curves. The composition of the populations reached in 2042, split up into the population due to launches and explosions and to the collision fragments, is depicted in Fig. 10.

The evolution of the total cross section area in orbit is nearly unchanged by the collisions due to the dominance of the R/B and P/L. Hence, the results presented in the respective Fig. 4 and 5 (lower parts) are still valid. The conclusions concerning the necessity of the mitigation measure de-orbit of R/B and P/L of chapter 2.3.1 are not only confirmed, but clearly corroborated. Now, the benefit of the reduction of the area and mass in orbit by the de-orbit measures can be seen already directly as a reduction of generated collision fragments (cf. scenarios 3b, 3d in Fig. 10).

But again, even the scenario 3d is leading to a smaller, but steady increase of the population, indicating that the critical population has already been exceeded. This can be made even more clear while looking at the rate of destructive collisions per year, as depicted in Fig. 11 and 12. The population of collision fragments is always some kind of 'running behind', so that the rate of destructive collisions is the better and earlier indicator for possible cascading effects. Even for scenario 3d, the collision rate has nearly quadrupled compared to 1992. Only the subsequent active removal of numerous large objects (simulated scenario: 3000 R/B and P/L already in orbit) can reduce the collision rate to an uncritical low level below the current one, as can be seen from Fig. 11.

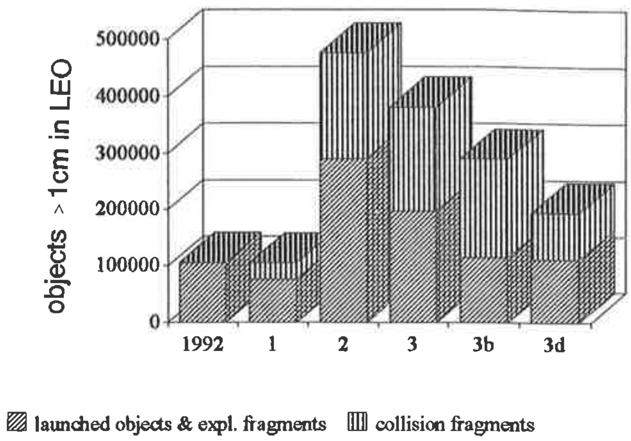

Figure 10. Number of objects > 1 cm in LEO in 2042 (CHAIN, with collisions)

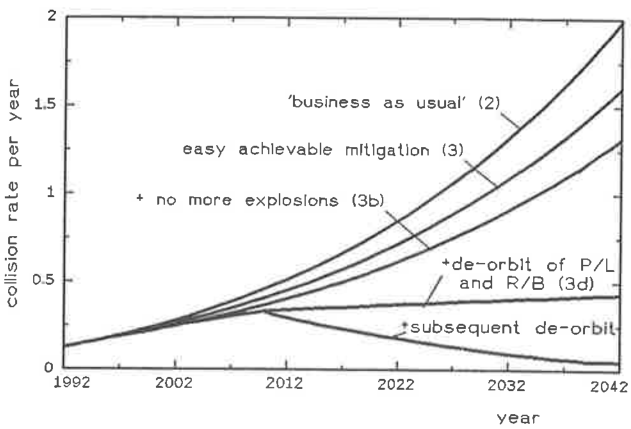

Figure 11. Evolution of the rate of destructive collision in LEO (CHAIN, with collisions)

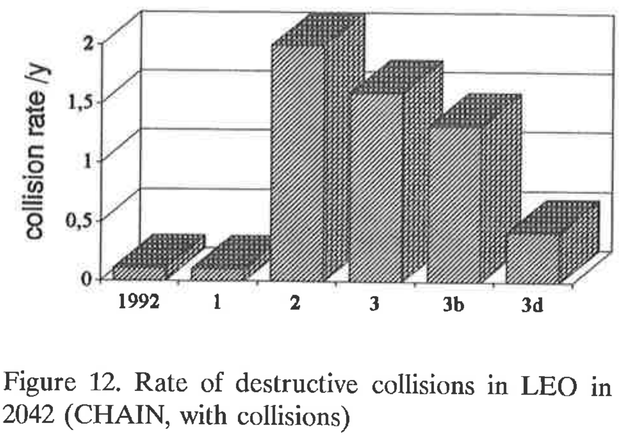

Figure 12. Rate of destructive collisions in LEO in 2042 (CHAIN, with collisions)

3. COST OF THE MITIGATION MEASURES

While discussing the necessity and the effectiveness of debris mitigation measures, their technical feasibility and their costs must be taken into account as well. Basically, it can be stated that all mitigation measures simulated in this paper as the sceanrios 3 are technically feasible, however, they would cause quite different additional costs. In this paper, only a brief overview will be given. More detailed analysis can be found in Refs. 7 and 9. The results of a rough evaluation of the costs of the various debris mitigation are depicted in Fig. 13.

- **scenario 3 'easy to achieve measures'**: should be obtainable at very low cost. Important is that the necessity of avoiding the generation of space debris has to be realized and the to be considered in design as well as operation of all S/C.

- **scenario 3a: 'no more R/B explosions'**: passivation of R/B by venting of residual propellant is nearly free of cost, once the necessary provisions have been built in. This technique has already been successfully implemented for DELTA and ARIANE upper stages.

- **scenario 3b: 'no more P/L explosions'**: prevention of payload explosions is more sophisticated. Avoidance of intentional explosions is free of cost, and the avoidance of explosions due to battery malfunctions should be solvable at low costs, once the problem is accepted and identified. The cost for other measures cannot be assessed.

- **scenario 3c/3d: de-orbiting of R/B and P/L**: de-orbiting of orbital objects is always accompanied by the expenditure of propellant. For the de-orbit thrust device, a mass penalty, i.e. an increase of launch costs, of about 5% has to be assessed for R/B and about 10% for P/L, assuming the re-entry from a circular orbit of about 1000 km altitude. For 2000 km altitude the mass penalty would be nearly twice as high. The de-orbiting of objects from 20.000 km circular altitude (e.g. GOS, GLONASS) seems economically unfeasible, the same as from GEO. For objects on high elliptical orbits, such as GTO and MOLNIYA-type launches, the mass penalty will be in the order of about 2%. Another option is the reduction of the lifetime by drag enhancement devices, but the feasibility and the benefit of this measure have not yet been proven.

- subsequent active removal is always much more difficult and expensive than preventive measures, because difficult and energy consuming Rendezvous-Manoeuvres are necessary. At the moment, no such technique is available (the SHUTTLE can only reach lower altitudes and conduct single retrieval missions)and the costs cannot be assessed. A strategy capable to fulfil such kind of a removal mission using space tethers called (TERESA) has been developed at our Institute (Ref. 10). Further research in this concern is necessary.

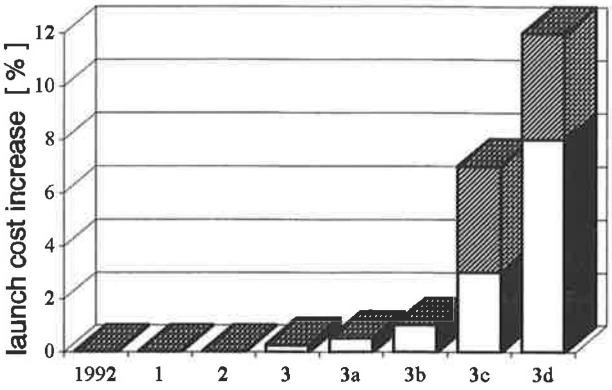

Figure 13. Increase of the launch costs due to different debris mitigation measures (rough values)

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5. CONCLUSIONS AND RECOMMENDATIONS

Already the simple evaluation of the rate of follow-on collisions is indicating that the critical population of large target objects concerning interactive collisions is probably already reached. The results of the more detailed analysis using the simulation programs POEM and CHAIN presented in this paper are corroborating very clearly that a continuation of the current way of S/F activities - leaving litter behind in earth orbit - will inevitably lead to a collisional cascading effect and an exponential increase of the fragment population within the next few decades.

Hence, the necessity of reaching effective debris mitigation measures on the short is evident. Despite all uncertainties of debris modeling in general and long term simulation in particular, the basic tendencies of these results are reliable, because the process of interactive collisions is absolutely dominated by the population of large, trackable objects (P/L and R/B), of which deterministic data is available.

Hence, it is recommended:
- to reduce the number of smaller objects in LEO on the short and mid term:
  - easy to achieve mitigation measures (e.g. venting of upper stages, avoidance of battery malfunctions and avoidance of MRO), which are causing only minor additional costs, should be taken as soon as possible. This would already result in a considerable reduction of the number of smaller objects in orbit. Debris avoidance measures should be considered in design as well as operation of all S/C.
  - banning of intentional explosions

- but on the long term, only the limitation of the number of large objects in orbit can avoid collisional cascading effects and the resulting exponential increase of number of collision fragments. Hence, despite the considerable cost increase, the de-orbit of all P/L and R/B after completion of their missions is inevitable.

- in addition, as the results are indicating, active subsequent removal of numerous large objects could become necessary in the future, once the critical population level has been exceeded.

Please note that preventive measures are always preferable and less expensive. Especially under this aspect, besides the avoidance of mission related objects and of explosions in orbit, also the de-orbit of R/B and P/L after completion of their missions should be implemented on the short inspite of the appreciable launch cost increases. International regulations are necessary in this concern to preserve balance of competition.

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