# DEBRIS RISK ANALYSIS OF AN 800 SATELLITE CONSTELLATION USING THE SPACE DEBRIS SIMULATION (SDS) SOFTWARE SUITE

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## ABSTRACT

A debris collision hazard analysis is carried out on a large 800 satellite constellation using the Space Debris Simulation (SDS) software suite. The usage of the software focusses on the short- to medium-term effects of explosive and collision-induced breakups. Two potentially constellation-threatening scenarios are considered: 1) constellation member fragmentation and 2) constellation launch vehicle breakup. The constellation collision probability, and the debris impact energy to target mass ratio are used as indicators of the severity of the risk posed to the constellation. It is found that a collision-induced breakup of a constellation satellite poses the greatest danger to the remainder of the constellation in terms of the possibility of a secondary fragmentation.

## 1. INTRODUCTION

What follows is very much a brief summary of some of the results obtained by a study of significant scope to assess the risks posed by debris to large constellations.

### 1.1 Software

The SDS software (Ref. 1) was developed at Southampton University, under contract to the Defence Research Agency (DRA) Farnborough, to assess the risk to operational spacecraft posed by debris clouds eminating from orbital fragmentation events. The software is best suited to short- or medium-term analysis (hours to months after the initial breakup), and so complements the long-term analysis IDES program (Ref. 2), also developed at DRA Farnborough. Both explosive and collision-induced breakups can be simulated by the SDS suite, and the dynamical model of the cloud evolution includes Earth gravity and aerodynamic perturbations. The risk assessment is based on the 'target-oriented' approach implicit in the probabilistic continuum dynamics (PCD) technique (Ref. 3). There is also a novel treatment of the breakup distribution in the model to take account of non-isotropic fragmentations. The PCD approach is particularly powerful, since it avoids the need to make too many simplifying assumptions, as is sometimes the case with other methods. The SDS software has been applied to numerous case studies, including a risk assessment of Envisat-1 (Ref. 4) and the threat to manned vehicles posed by the Clementine/Titan II breakup (Ref. 5) that occurred in 1994.

### 1.2 Constellation configuration

The constellation considered in this study is a configuration comprising 800 satellites. These are distributed with 80 satellites in each of 10 equally-spaced orbit planes, as shown schematically in Fig. 1. Each satellite, of 500 kg mass, is in a near-circular, polar orbit (inclination 89 degrees) at an altitude of 700 km. The intra-plane satellite phasing is as given in Ref. 6.

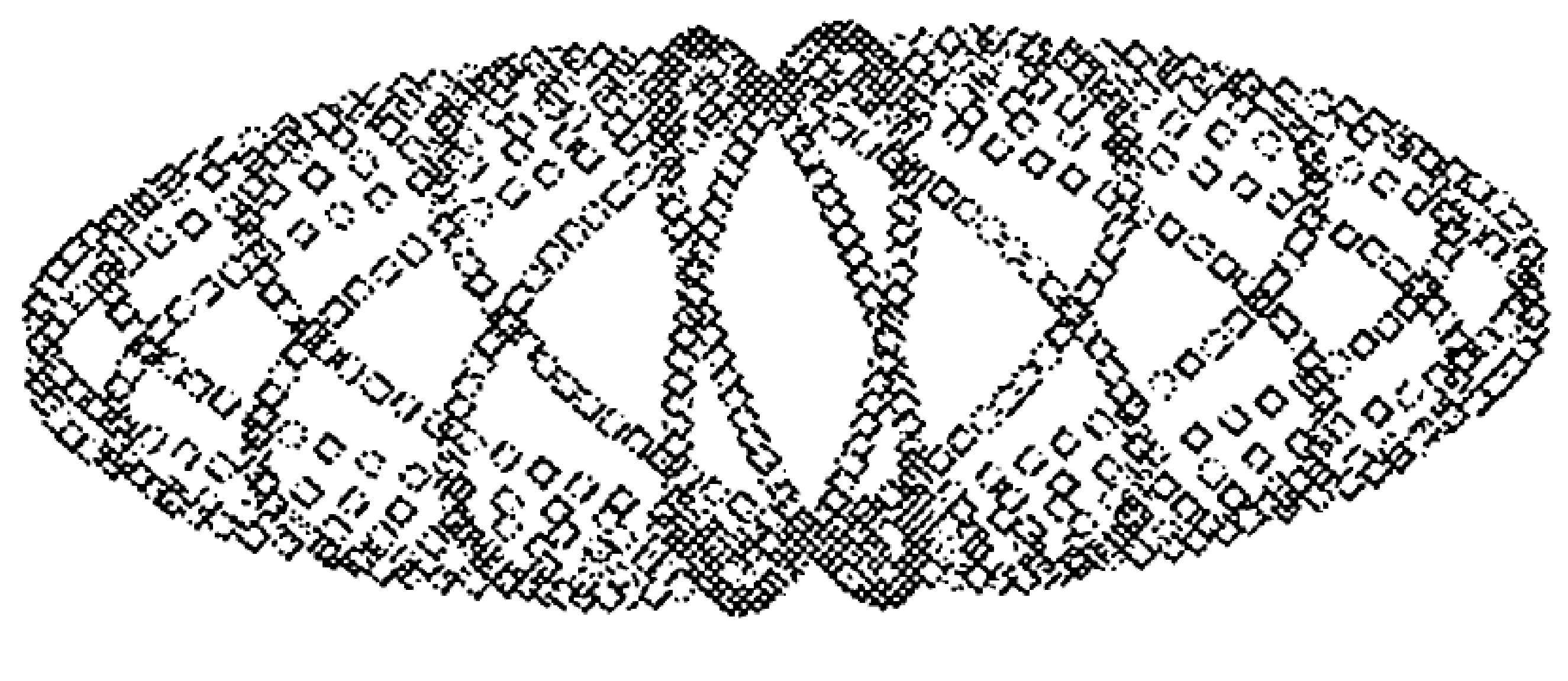

Figure 1. 800 satellite constellation configuration.

### 1.3 Simulation approach

The breakup scenarios are modelled using the SDS programs BREAKUP4.0 and TARGET4.0. The former is used to simulate the fragmentations in each case, with debris of 0.1 mm and greater in size being considered. When used for the risk assessment, TARGET4.0 considers each satellite in the constellation individually. Although computationally intensive, this approach yields information about which satellites are at risk, and when. The collision

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probability time-histories are obtained by summing the contributions from all the satellites during that time step. Similarly, the distributions made over satellite number are obtained by summing, for each satellite in turn, the collision probabilities registered over the whole duration of the simulation.

Satellite number increases with true anomaly at the time of the breakup, and orbit plane number. In the case of a satellite breakup, for example, satellites 1 to 80 reside in the breakup plane (satellite 1 being the 'breakup' satellite, and plane 1 being the breakup plane), satellites 81 to 160 reside in the next obit plane (plane 2 is 18 degrees East in right ascension of the breakup plane), and so on. Satellites with numbers 80 apart are therefore closest to being 'in-phase'. The simulations are performed typically for half a day post-breakup, with a time step of 1 minute. The values of collision probability quoted are per square metre of target.

## 2. SATELLITE BREAKUP

Active debris control, particularly with regard to battery design and end-of-life deorbit, should reduce the chance of a breakup of one of the constellation satellites. The possibility of an explosive breakup will still exist, however. Perhaps the greatest risk though will come from a collision with debris from the background population. Shielding can be used to guard against small particles, but a collision with large debris could cause complete fragmentation.

### 2.1 Collision-induced fragmentation

Fig. 2 shows the cumulative collision probability versus time for the constellation following the breakup of one of its members, through a collision with a fragment from the background population. The collision, with a 1 kg fragment at 10 km/s, completely fragments the satellite. The event is modelled by BREAKUP4.0, with fragment delta-vs of up to 2 km/s considered by TARGET4.0.

Fig. 3 shows the distribution of collision probability over satellite number. The satellites in the breakup plane experience a significantly higher risk of collision than the remainder of the constellation. This is due to the high values of debris density encountered by the breakup plane satellites, particularly close to the cloud's 'pinch' locations. However, although the risk of collision is highest in the breakup plane, the risk of a damaging event is very small, since debris encounters occur at very low relative speeds. Fig. 4 shows that the most damaging events occur in orbital planes where relative speeds are high, in particular plane 10 where 'head-on' encounters take place at nearly twice orbital speed. Fig. 4 displays the impact energy to target mass ratio, where a value of 35 to 45 J/gram has been empirically shown to correspond to the threshold for complete breakup.

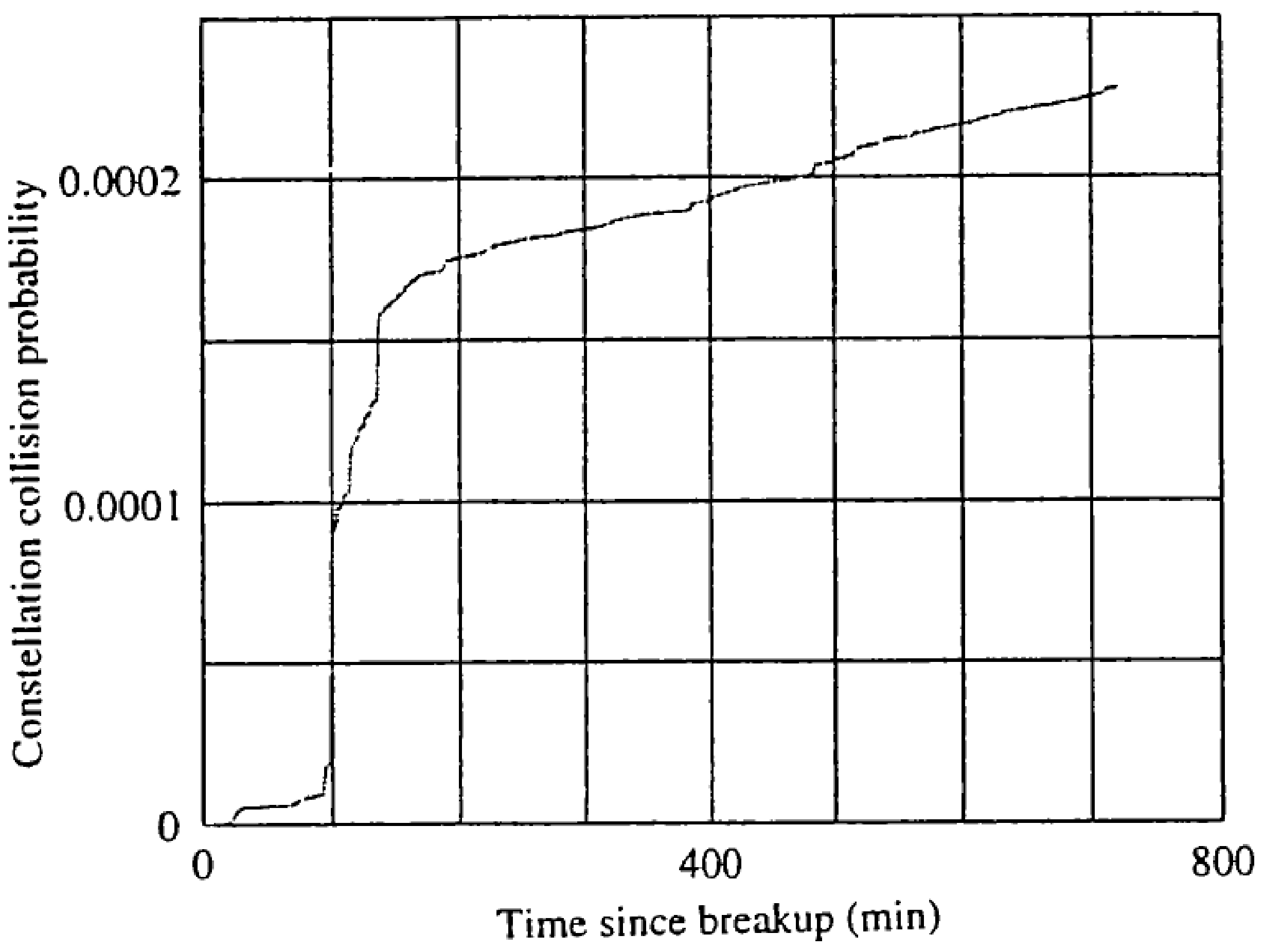

Figure 2. Constellation collision probability versus time for collision-induced breakup.

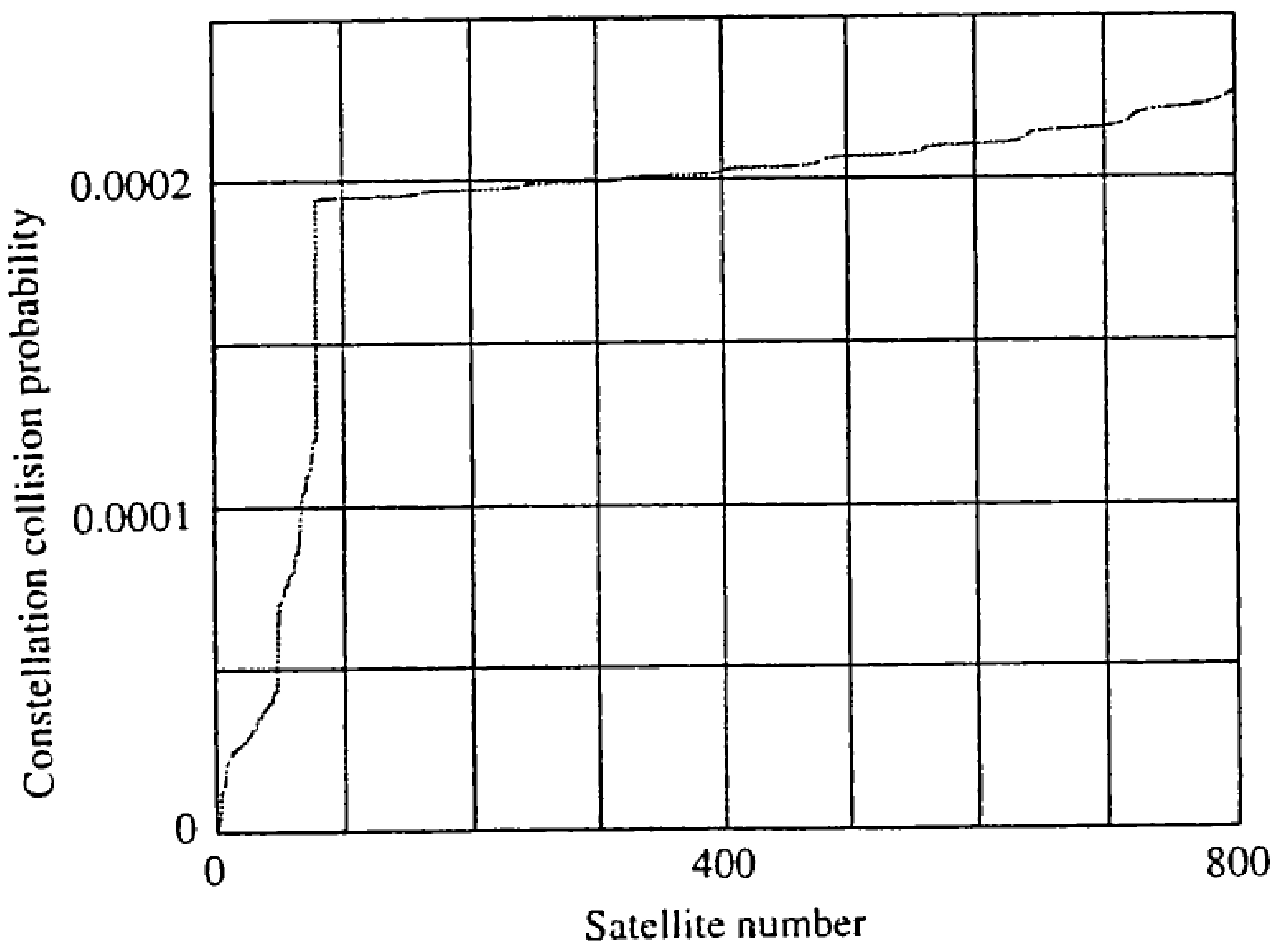

Figure 3. Constellation collision probability versus satellite number for collision-induced breakup.

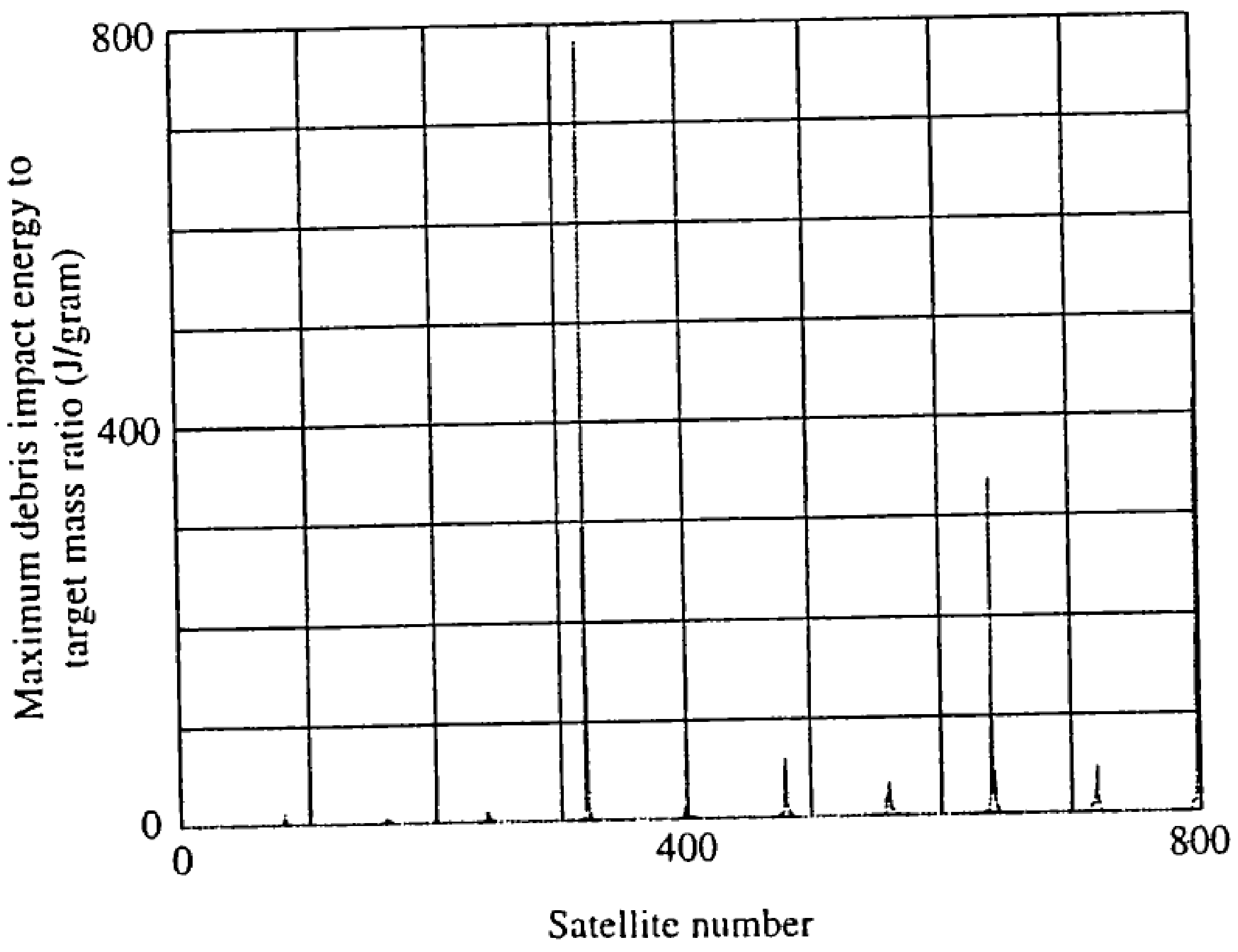

Figure 4. Debris impact energy to target mass ratio versus satellite number for collision-induced breakup.

A further feature of the simulation is that the threat does not diminish as the cloud evolves. In fact, in the example considered here the most damaging events are most likely towards the end of the simulation, several hours after the breakup event.

## 2.2 Explosive fragmentation

In the second case examined, a low-intensity explosion of a constellation satellite is simulated using BREAKUP4.0, with maximum ejection speeds of 500 m/s being considered by TARGET4.0. The constellation collision probability over time is shown in Fig. 5, which can be seen to be similar to Fig. 2 but with a lower overall risk due to the lower debris densities in the explosion cloud. However the debris impact energy to target mass ratio is virtually identical to that shown in Fig. 4.

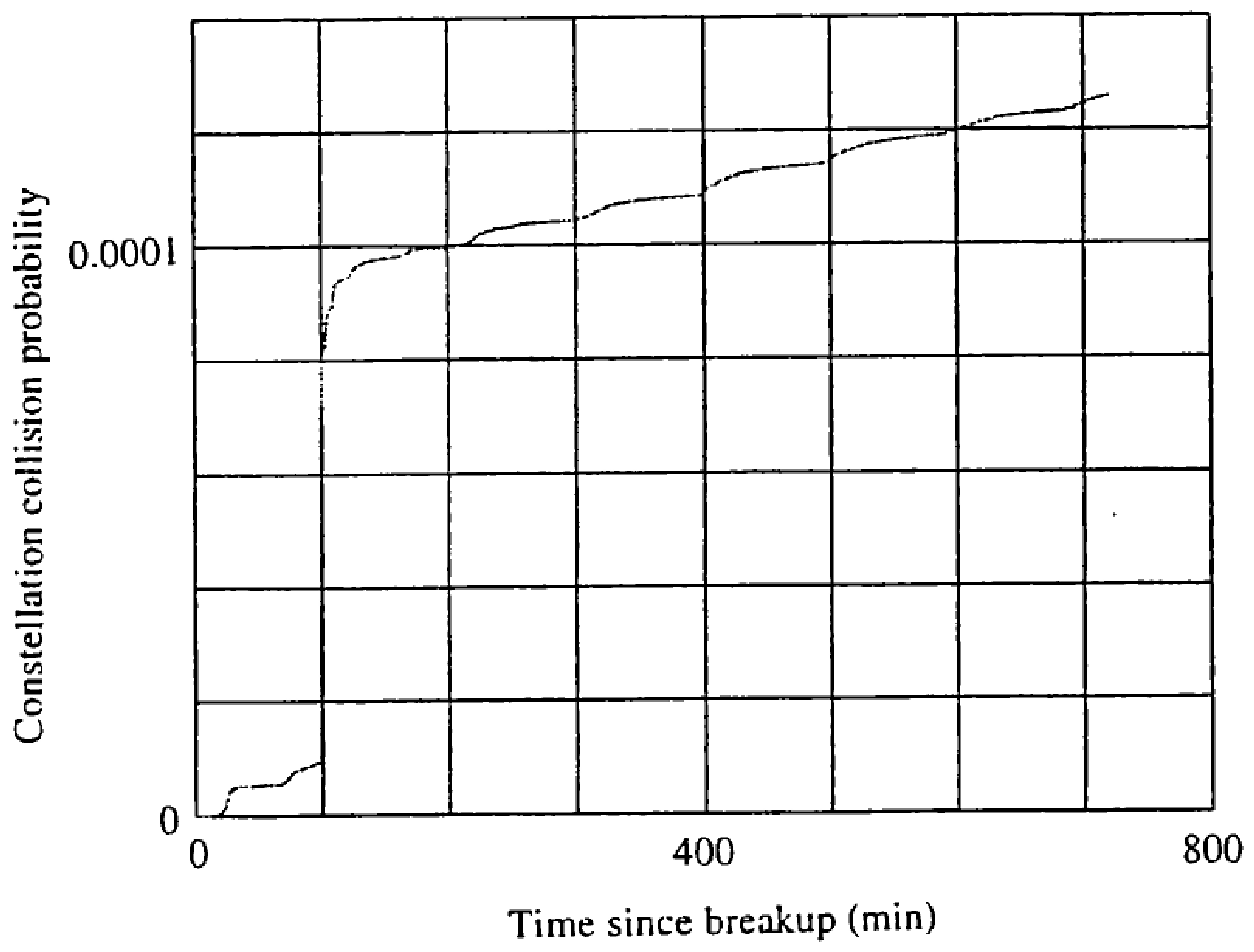

Figure 5. Constellation collision probability versus time for explosive breakup.

## 3. LAUNCH VEHICLE BREAKUP

A launch strategy and debris mitigation policy similar to that proposed for the Iridium™ constellation is assumed for the 800 satellite constellation considered here. Multiple Proton and Delta-2 launches will be assumed, and initial parking orbits below the constellation altitude will be utilised, with the satellites boosting themselves up to operational height after separation. The rocket second stages will be deorbited after use and vented of residual propellants to prevent explosions.

If the rocket bodies are successfully made 'safe' after satellite release then the risk they pose to the constellation will be negligible. If a system malfunction occurs, however, which prevents the deorbit manoeuvre, the presence of the spent stage could heighten the debris risk to the constellation. If debris were to collide with it, or if it were to explode, then the debris cloud formed could impinge upon the constellation altitude. These two scenarios are briefly considered here.

In particular, the effects on the constellation of the fragmentation of a 900 kg Delta-2 rocket body are examined. The rocket body is assumed to be in a circular orbit at 500 km altitude, with its inclination and ascending node position both equal to that of one of the constellation planes. The constellation is assumed to be complete to enable a worst case scenario to be examined. Such a situation would occur during the launch of replacement satellites.

### 3.1 Collision-induced breakup

The breakup of a Delta-2 rocket body is simulated using BREAKUP4.0, following a collision with a 1 kg debris object at 10 km/s. Fragment ejection velocities of up to 2 km/s are considered by TARGET4.0 in the subsequent collision hazard analysis. The resulting constellation collision probability is shown over time and satellite number in Fig. 6 and 7 respectively. The estimated collision probabilities are of the same order of magnitude as for the satellite fragmentation scenarios in section 2.

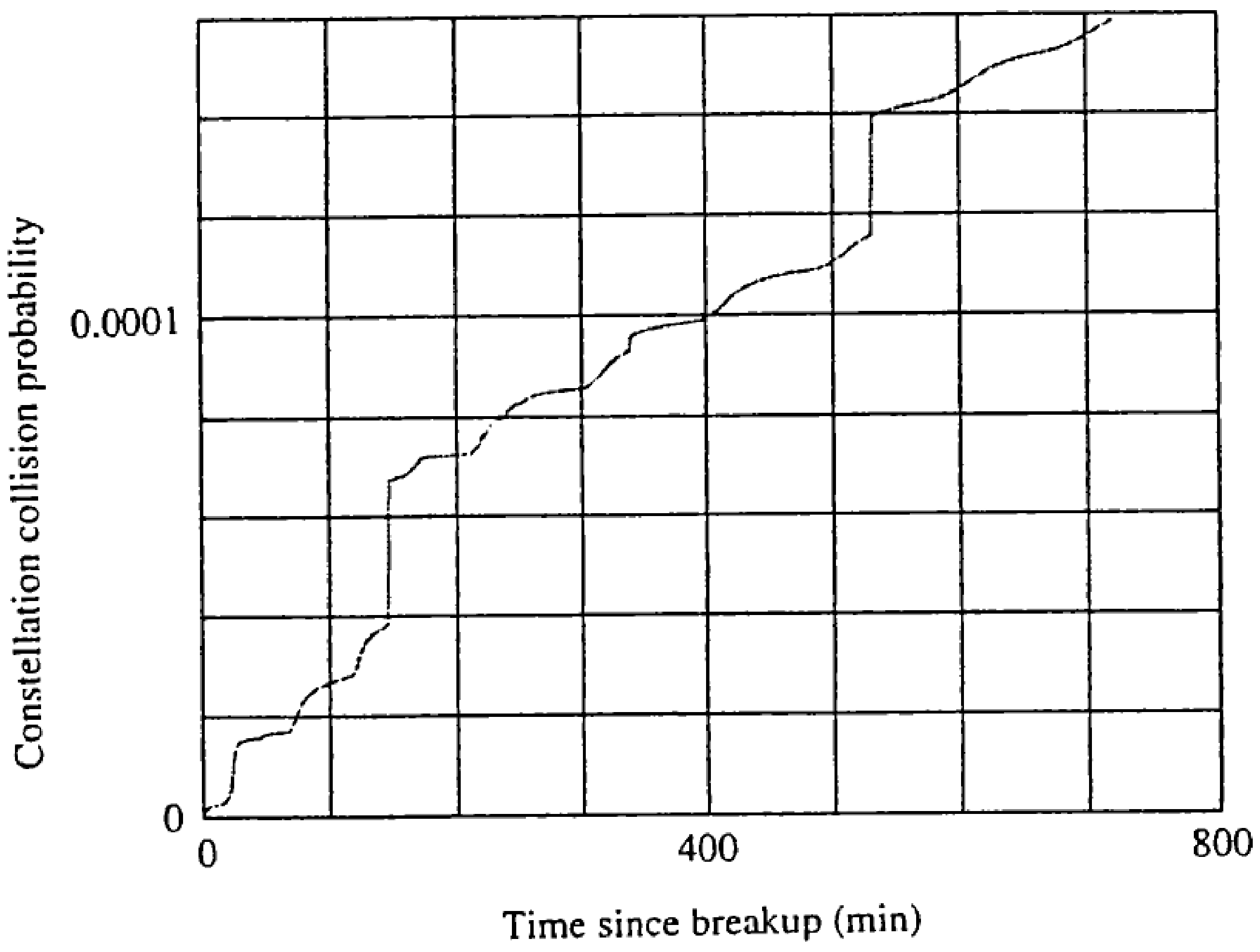

Figure 6. Constellation collision probability versus time for launch vehicle collision-induced breakup.

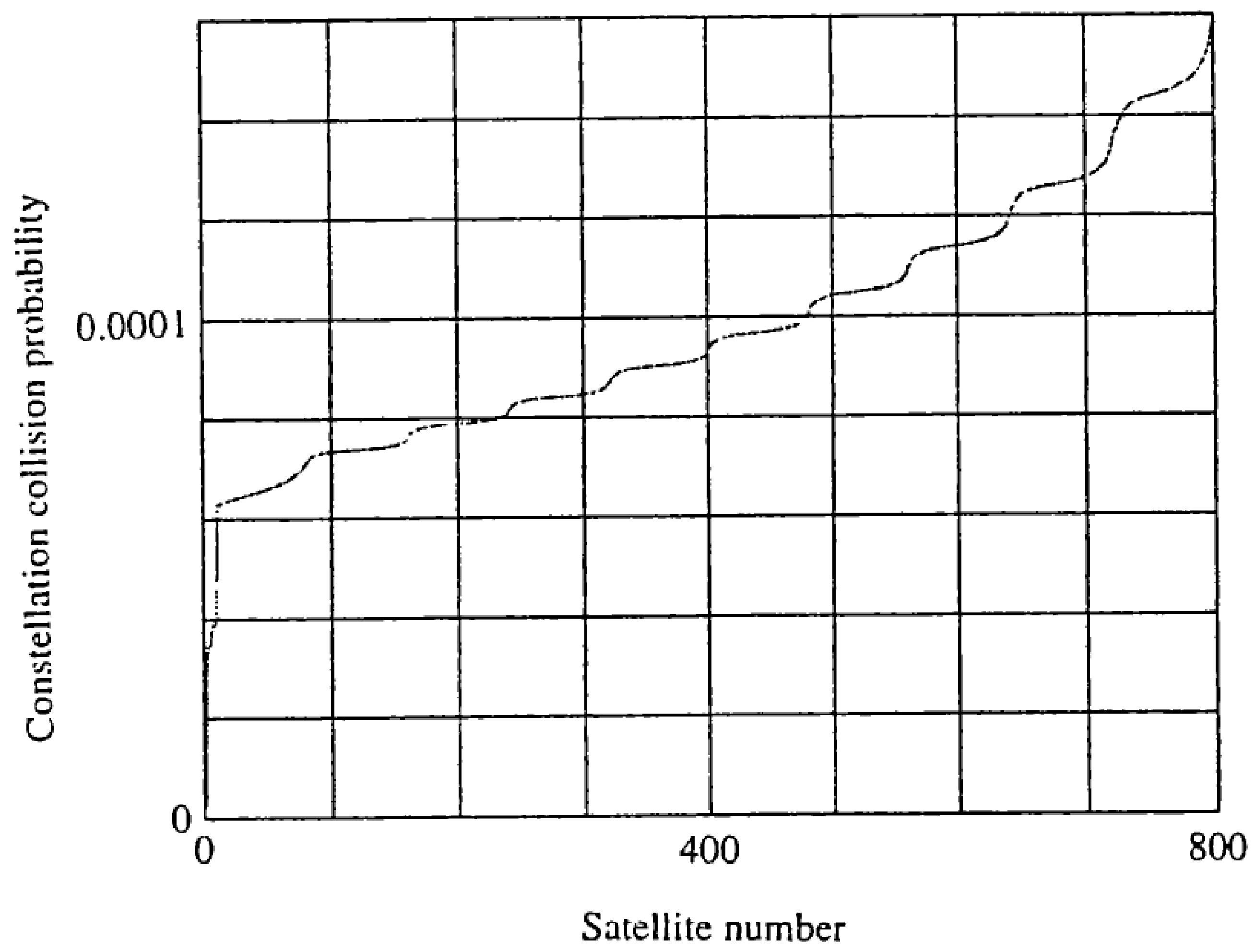

Figure 7. Constellation collision probability versus satellite number for launch vehicle collision-induced breakup.

Figure 8 shows the distribution of debris impact energy over satellite number. These are around three orders of magnitude less than in section 2, however, indicating that the collision-induced launch vehicle breakup is less effective in spreading large debris fragments up to constellation altitude.

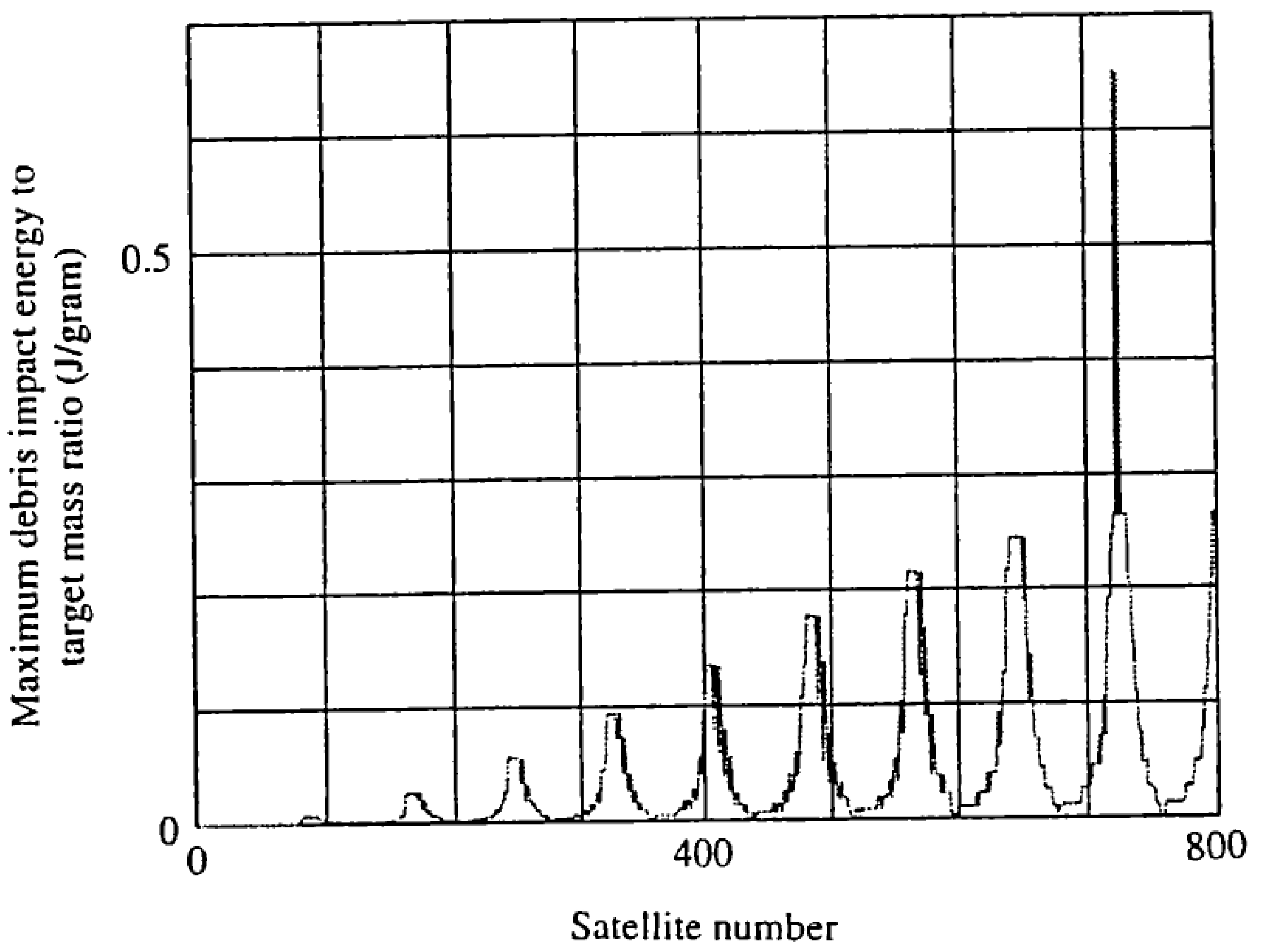

Figure 8. Debris impact energy to target mass ratio versus satellite number for launch vehicle collision-induced breakup.

3.2 Explosive breakup

The low intensity explosion of a Delta-2 second stage is simulated using BREAKUP4.0. TARGET4.0 is used to assess the collision risk to the constellation from debris ejected from the breakup, with delta-vs of up to 500 m/s considered. The constellation collison probability over time is shown in Fig. 9, where the values predicted are around two orders of magnitude less than those from a constellation satellite breakup. However, an assessment of the debris impact energy in this case reveals 'lethal' values typically up to 900 J/gram, indicating that debris large enough to fragment a constellation satellite can be encountered at the constellation altitude.

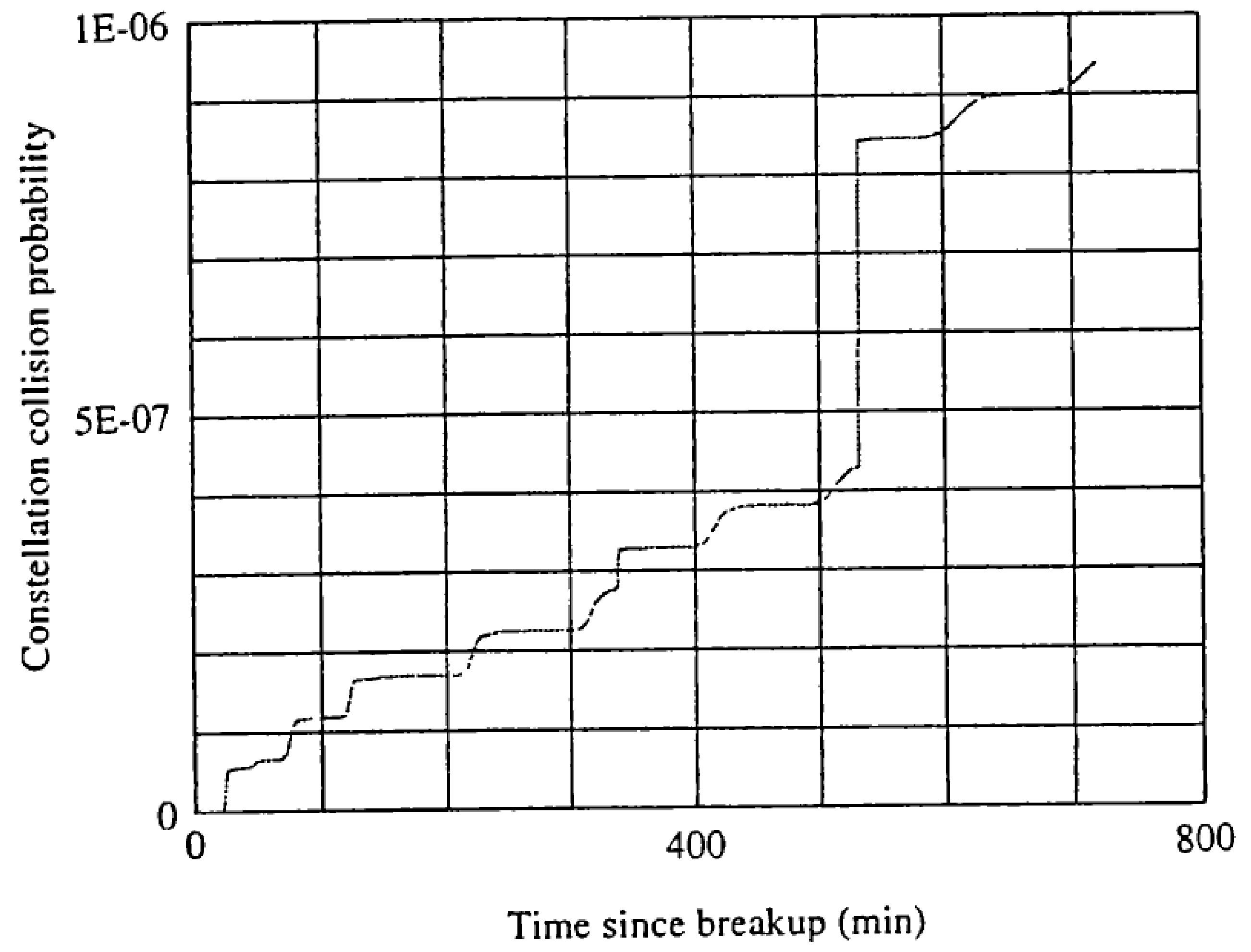

Figure 9. Constellation collision probability versus time for launch vehicle explosion.

## 4. CONCLUSIONS

The potential hazards associated with constellation operations are numerous. Breakups of both constellation satellites and launch vehicles pose a threat to the constellation as a whole, and the orbital environment in general. Locating large constellations in or close to highly-populated orbital regions heightens the probability of a collision between a constellation satellite and the background debris population.

This study shows that a collision-induced breakup of a constellation satellite poses the greatest risk to the remainder of the constellation in terms of the possibility of a secondary fragmentation. The collision probabilities associated with explosive breakups are less than those from collision-induced events, but the abundance of large fragments produced by low-intensity explosions in particular means that lethal secondary impacts are possible, even from breakups of launch vehicle stages 200 km below the constellation altitude. The satellites closest to being in-phase with the destroyed body are found to be most at risk from collision, but with those in the orbit planes furthest from the breakup orbit plane most likely to undergo a catastrophic fragmentation as a result of a debris strike.

## 5. REFERENCES

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