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NASA'S NEW BREAKUP MODEL OF EVOLVE 4.0

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ABSTRACT

Analyses of the fragmentation (due to explosions and collisions) of spacecraft and rocket bodies in low Earth orbit (LEO) have been performed this year at NASA/JSC. The overall goals of this study have been to achieve a better understanding of the results of fragmentations on the orbital debris environment and then to implement this understanding into the breakup model of EVOLVE 4.0. The previous breakup model implemented in EVOLVE 3.0 and other long-term orbital debris environment models was known to be inadequate in two major areas. First, it treated all fragmentational debris as spheres of a density which varied as a function of fragment diameter, where diameter was directly related to mass. Second, it underestimated the generation of fragments smaller than 10-cm in the majority of explosions. Without reliable data from both ground tests and on-orbit breakups, these inadequacies were unavoidable. Recent years, however, have brought additional data and related analyses: results of three ground tests, better on-orbit size and mass estimation techniques, more regular orbital tracking and reporting, additional radar resources dedicated to the observation of small objects, and simply a longer time period with which to observe the debris and their decay. Together these studies and data are applied to the reanalysis of the breakup model. In this paper we compare the new breakup model to the old breakup model in detail, including the size distributions for explosions and collisions, the area-to-mass and impact velocity assignments and distributions, and the delta-velocity distributions. These comparisons demonstrate a significantly better understanding of the fragmentation process as compared to previous versions of EVOLVE. Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

Since the 1970's, the NASA Orbital Debris Program Office has modeled the debris clouds generated by on-orbit explosions and collisions in terms of fragment size and velocity distributions. Prior to the effort described herein, the last major changes to these breakup models occurred in the 1980's (Reynolds, 1990). The models were largely based on a limited set of controlled terrestrial experiments of explosions and hypervelocity impacts. The number of tests, the initial conditions, and the variation of parameters, including the test articles, were highly constrained. In addition, the amount of data from on-orbit breakup events was scarce.

As well as serving as stand-alone models for simulating the initial characteristics of debris clouds in Earth orbit, the breakup model critically affects the output of NASA's long-term satellite population environment model, EVOLVE. Following a decision in early 1996 to improve the NASA breakup model, in 1997 a team of civil servants and contractors at the NASA Johnson Space Center undertook the task of a thorough review and revision of the explosion and collision breakup models. The principal objective was to create new fragmentation models of higher fidelity, founded on broader experimental databases. The single-valued functions for number, area-to-mass ratio, and velocity were to be replaced by more representative distributions. This effort was part of a larger task to update the EVOLVE model itself (Krisko et al., 2000).

Creation of the revised NASA Standard Breakup Model (Reynolds et al., 1998) depended strongly on data collected since the early 1980's, including

(1) the Solwind (P-78) (Kling, 1986) and the USA 19 (Delta-180) (Johnson, 1986, and Kling, 1987) deliberate hypervelocity collisions in low Earth orbit in 1985 and 1986, respectively;

(2) the ground-based Satellite Orbital Debris Characterization Impact Test (SOCIT) series in 1991 and 1992 (McKnight et al., 1995)

(3) the Ariane upper stage sub-scale explosion tests supervised by the European Space Agency (Fucke and Sdunnus, 1993); and

(4) an extensive compilation of historical orbital data (*i.e.*, two-line element sets) for explosion and collision debris used to determine ejection velocity and area-to-mass ratio distributions (Reynolds et al., 1998).

This paper can only highlight some of the important characteristics of the new breakup model and contrast them with NASA's previous breakup model. All historical model assumptions and databases were challenged during this effort. A more detailed summary of these changes and their rationale can be found in Reynolds et al., 1998.

BREAKUP MODEL FEATURES

A satellite breakup model, at a minimum, should define the size, area-to-mass ratio, and ejection velocity of each generated fragment. Since these parameters are not constant for all debris, distributions as a function of a given parameter, *e.g.*, mass or characteristic length, are necessary. In addition, the initial conditions of the breakup, *e.g.*, the total mass of the parent object or the collision velocity, can be highly influential.

Since multiple breakup events of the same type of object, for instance a Delta second stage, will not produce exactly the same debris cloud each time, the breakup model should also address variances about the derived distributions. This is particularly important when executing large Monte Carlo simulations such as EVOLVE 4.0.

Size Distributions

Previous NASA breakup models had employed mass as the independent variable in developing functions for the number of debris created. Size or characteristic length, L_c, was then derived assuming the particles were essentially spherical in nature with a density of aluminum for objects smaller than 1 cm and with a diminishing density for larger debris according to

$$\rho\,(d) = 92.937(d)^{-0.74} \quad , \tag{1}$$

where ρ = debris density in kg/m^3 and
d = debris diameter in m and is equivalent to L_c.

In the new NASA model, L_c is the preferred independent variable since it is more directly linked to both the on-orbit and terrestrial breakup data. This also permits the production of more realistic, non-spherical debris in the model. Finally, the application of the new size distribution models in EVOLVE 4.0 produces a Monte-Carlo style variation in the distribution, unlike EVOLVE 3.0 in which, for example, each explosion of a satellite of the same size produced exactly the same number of debris for a given size or larger.

Explosions

One of the fundamental changes in the new explosion model has been the abandonment of the concept of different size distributions based on so-called low and high intensity explosions. A thorough examination of on-orbit explosion debris, as well as a reassessment of data collected in the well-known Atlas tank explosion (Edwards, 1963), cast doubt upon the validity of this prior distinction. Under this concept, small debris creation would sharply level-off at debris masses less than 0.1 kg for low intensity explosions, *e.g.*, residual propellant-induced explosions of upper stages. High intensity explosions, *e.g.*, spacecraft deliberately destroyed with explosive charges, were modeled assuming that 90% of the mass followed the low intensity distribution, while 10% of the mass followed a distribution which produced much larger numbers of small debris (Figure 1).

Examinations of cataloged debris from numerous breakups suggested that debris production followed a simpler power law distribution down to the sensitivity limit of the United States' Space Surveillance Network (SSN), *i.e.*, down to approximately 10 cm. Seven such breakup clouds are shown in Figure 2. Furthermore, a review of small particle data from observations taken by the Haystack radar in orbital regimes where breakup debris was assessed to be the dominant source revealed an apparent continuation of this same relationship to approximately 1 cm when compared directly to the known fragmentation debris population in the same orbital regime. This is illustrated in Figure 3. The Haystack detection curve above 10 cm includes intact spacecraft and rocket bodies, as well as operational and fragmentation debris.

Taking into account natural variations due to structure and energy, the number of explosive fragments of size L_c or larger, in meters, is governed by the following equation:

$$N(L_c) = 6L_c^{-1.6} \; . \tag{2}$$

This relationship appears to be valid for upper stages with masses of 600-1000 kg. When examining the known debris from explosion of other parent masses and types, e.g., battery malfunctions, Soviet/Russian ocean surveillance satellites, Soviet early warning satellites, and Soviet anti-satellite tests, a simple scaling factor, S, was found to be a good approximate solution. Hence, the final form of the EVOLVE 4.0 relationship for the number of explosion debris is

$$N(L_c) = S6L_c^{-1.6} \quad , \tag{3}$$

where S is a type-dependent, unitless number.

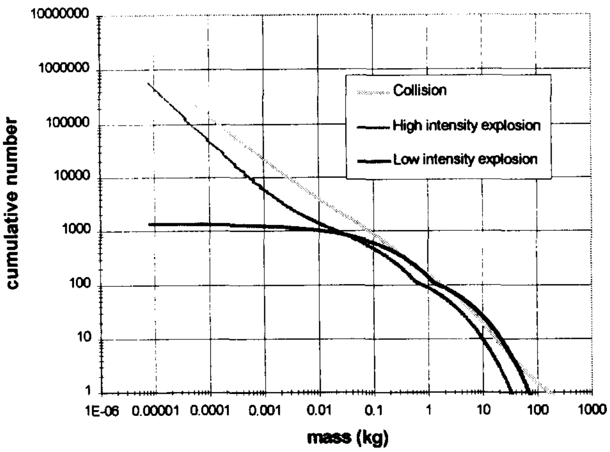

Fig. 1. Former NASA debris size distributions for explosions and collisions.

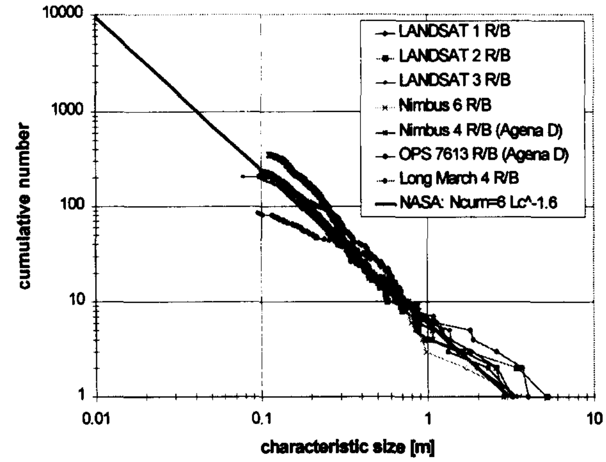

Fig. 2. Sample debris size distributions from seven upper stage breakups, as derived from SSN data.

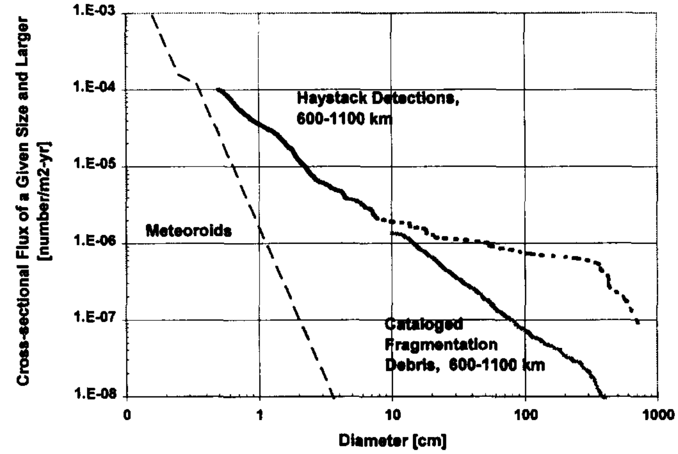

Fig. 3. Extension of debris population using the Haystack radar.

Collisions

Collisions between two satellites may be non-catastrophic, characterized primarily by fragmentation of the smaller object and by cratering of the larger object, or catastrophic, wherein both objects are totally fragmented. The difference between a catastrophic and a non-catastrophic collision is determined by the ratio of the mass of the larger object to the mass of the smaller object and the collision velocity. If the relative kinetic energy of the smaller object divided by the mass of the larger object is equal to or greater than 40 J/g, then the collision is catastrophic.

Based upon numerous laboratory hypervelocity impact experiments, including the highly instrumented SOCIT series as well as the on-orbit collision of the Solwind spacecraft (Figure 4), a power law distribution for the number of fragments of a given size and larger has been developed:

$$N(L_c) = 0.1(M)^{0.75}L_c^{-1.71} \,. \tag{4}$$

In the above equation, L_c is in meters and the value of M is defined as the mass (in kg) of both objects in a catastrophic collision. In the case of a non-catastrophic collision, the value of M is defined as the mass (in kg) of the smaller object multiplied by the collision velocity (in km/s). The fixed average collisional velocity of EVOLVE 3.0 has been replaced by a more realistic collision velocity dependent upon the altitude of the encounter in EVOLVE 4.0. This new variable collision velocity is also very important in the calculation of the probability of collision (as shown later in this paper).

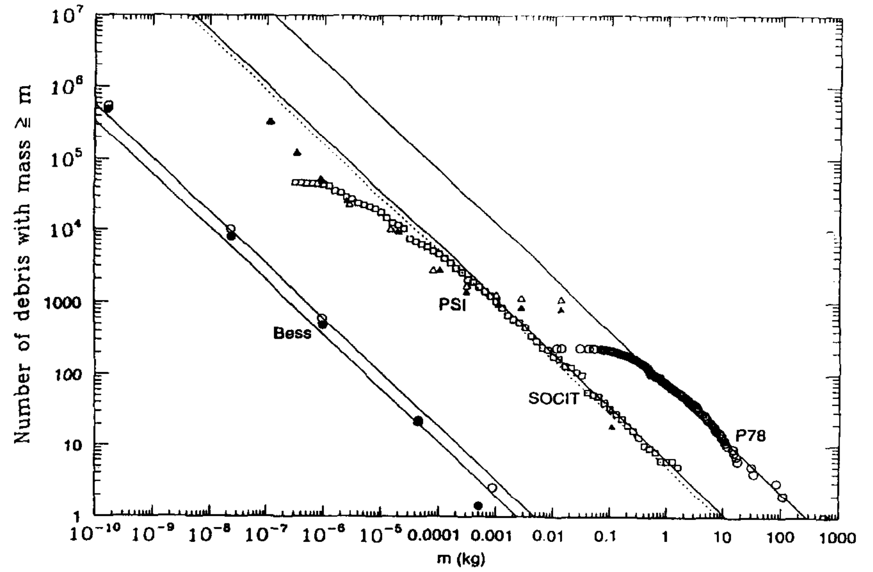

Fig. 4. Sample debris size distributions from on-orbit and terrestrial hypervelocity collisions.

Area-to-mass Distributions

Perhaps the most significant change in NASA's satellite breakup model can be found in the new treatment of area-to-mass ratio, A/M, for fragments. Based upon extensive analyses of thousands of fragmentation debris cataloged by the SSN and upon terrestrial experiments, A/M distributions have been developed for both spacecraft and upper stages. This is in contrast to the single-valued function for A/M in EVOLVE 3.0. Current databases do not yet support a distinction between A/M for explosions and those for collisions.

For debris L_c greater than 11 cm, A/M distributions have been derived by analyzing the decay rates of cataloged debris. For example, using a χ^2 fit to orbital decay characteristics for 1,780 upper stage explosion fragments led to the discrete distributions shown in Figure 5. Similar data were developed for spacecraft fragments.

In general, these ratios are a good approximation of the actual average A/M. However, as the calculated A/M increases to large values (> 1 m^2/kg), the effects of solar radiation pressure cannot be ignored. Thus, for such objects, the calculated A/M is more effective for computing orbital lifetime in EVOLVE 4.0 than for determining the mass of the debris through a relationship with L_c.

The distribution function for upper stage fragments with L_c larger than 11 cm is given by

$$D_{A/M}^{R/B}(\lambda_c,\chi) = \alpha^{R/B}(\lambda_c)N(\mu_1^{R/B}(\lambda_c), \sigma_1^{R/B}(\lambda_c),\chi) + (1 - \alpha^{R/B}(\lambda_c))N(\mu_2^{R/B}(\lambda_c), \sigma_2^{R/B}(\lambda_c),\chi)\,, \tag{5}$$

where $\lambda_c = \log_{10}(L_c)$

$\chi = \log_{10}(A/M)$ is the variable in the distribution

N = the normal distribution function: $N(\mu,\sigma,\chi) = [1/\sigma(2\pi)^{0.5}]\, e^{-(\chi-\mu)^2/2\sigma^2}$

$$\alpha^{R/B} = \begin{cases} 1 & \lambda_c \le -1.4 \\ 1-0.3571(\lambda_c+1.4) & 1.4 < \lambda_c < 0 \\ 0.5 & \lambda_c \ge 0 \end{cases}$$

$$\mu_1^{R/B} = \begin{cases} -0.45 & \lambda_c \le -0.5 \\ -0.45-0.9(\lambda_c+0.5) & -0.5 < \lambda_c < 0 \\ -0.9 & \lambda_c \ge 0 \end{cases}$$

$$\sigma_1^{R/B} = 0.55$$

$$\mu_2^{R/B} = -0.9$$

$$\sigma_2^{R/B} = \begin{cases} 0.28 & \lambda_c \le -1.0 \\ 0.28 - 0.1636(\lambda_c + 1) & -1.0 < \lambda_c < 0.1 \\ 0.1 & \lambda_c \ge 0.1 \end{cases}$$

The corresponding distribution function for spacecraft fragments with L_c larger than 11 cm is given by

$$D_{A/M}^{S/C}(\lambda_c,\chi) = \alpha^{S/C}(\lambda_c)N(\mu_1^{S/C}(\lambda_c), \sigma_1^{S/C}(\lambda_c),\chi) + (1 - \alpha^{S/C}(\lambda_c))N(\mu_2^{S/C}(\lambda_c), \sigma_2^{S/C}(\lambda_c),\chi)\,, \tag{6}$$

where

$$\alpha^{s/c} = \begin{cases} 0 & \lambda_c \le -1.95 \\ 0.3 + 0.4(\lambda_c + 1.2) & 1.95 < \lambda_c < 0.55 \\ 1 & \lambda_c \ge 0.55 \end{cases}$$

$$\mu_1^{s/c} = \begin{cases} -0.6 & \lambda_c \le -1.1 \\ -0.6 - 0.318(\lambda_c + 1.1) & -1.1 < \lambda_c < 0 \\ -0.95 & \lambda_c \ge 0 \end{cases}$$

$$\sigma_1^{s/c} = \begin{cases} 0.1 & \lambda_c \le -1.3 \\ 0.1 + 0.2(\lambda_c + 1.3) & -1.3 < \lambda_c < -0.3 \\ 0.3 & \lambda_c \ge -0.3 \end{cases}$$

$$\mu_2^{s/c} = \begin{cases} -1.2 & \lambda_c \le -0.7 \\ -1.2 - 1.333(\lambda_c + 0.7) & -0.7 < \lambda_c < -0.1 \\ -2.0 & \lambda_c \ge -0.1 \end{cases}$$

$$\sigma_2^{s/c} = \begin{cases} 0.5 & \lambda_c \le -0.5 \\ 0.5 - (\lambda_c + 0.5) & -0.5 < \lambda_c < -0.3 \\ 0.3 & \lambda_c \ge -0.3 \end{cases}$$

Figure 6 illustrates the application of this distribution function for 508 cataloged spacecraft breakup debris with characteristic lengths between 11 cm and 35 cm.

For objects with L_c smaller than 8 cm, a single A/M distribution functions has been derived from hypervelocity impact tests for both spacecraft and upper stages as follows:

$$D_{A/M}^{SOC}(\lambda_c,\chi) = N(\mu^{SOC}(\lambda_c), \sigma^{SOC}(\lambda_c),\chi) \tag{7}$$

$$\mu^{soc} = \begin{cases} -0.3 & \lambda_c \le -1.75 \\ -0.3 - 1.4(\lambda_c + 1.75) & -1.75 < \lambda_c < -1.25 \\ -1.0 & \lambda_c \ge -1.25 \end{cases}$$

$$\sigma^{soc} = \begin{cases} 0.2 & \lambda_c \le -3.5 \\ 0.2 + 0.1333(\lambda_c + 3.5) & \lambda_c > -3.5 \end{cases}$$

A function is used to bridge the gap between 8 cm and 11 cm.

Finally, the average cross-sectional area, A_x, is modeled as having a one-to-one correspondence with L_c as follows:

$$A_x = 0.540424\ L_c^2, \qquad \text{where } L_c < 0.00167\ \text{m} \tag{8}$$

and

$$A_x = 0.556945\ L_c^{2.0047077}, \qquad \text{where } L_c \geq 0.00167\ \text{m} \tag{9}$$

Noting the caution presented earlier in this sub-section regarding high values of A/M, the conversion to mass can be simply obtained by

$$M = A_x / (A/M)\ . \tag{10}$$

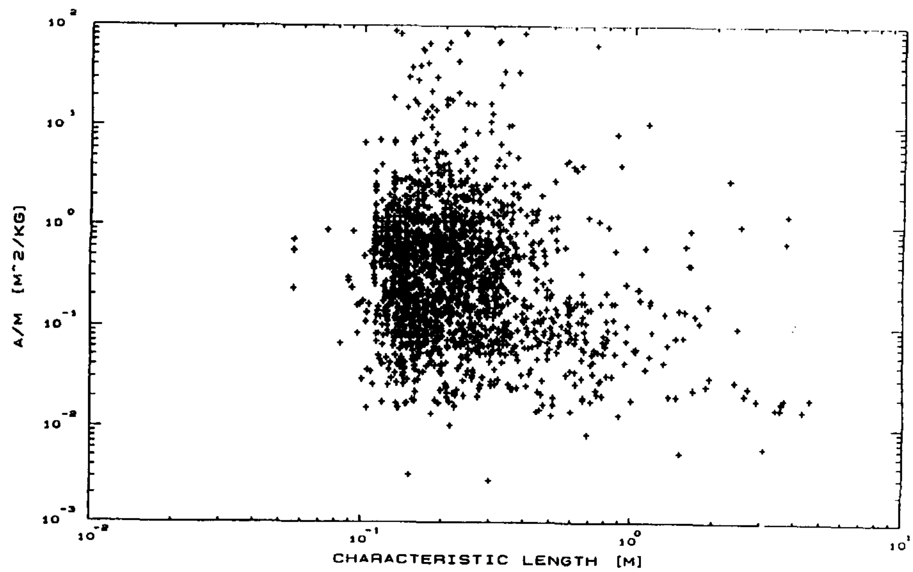

Fig 5. Derived area-to-mass ratios for 1,780 debris from on-orbit upper stage breakups.

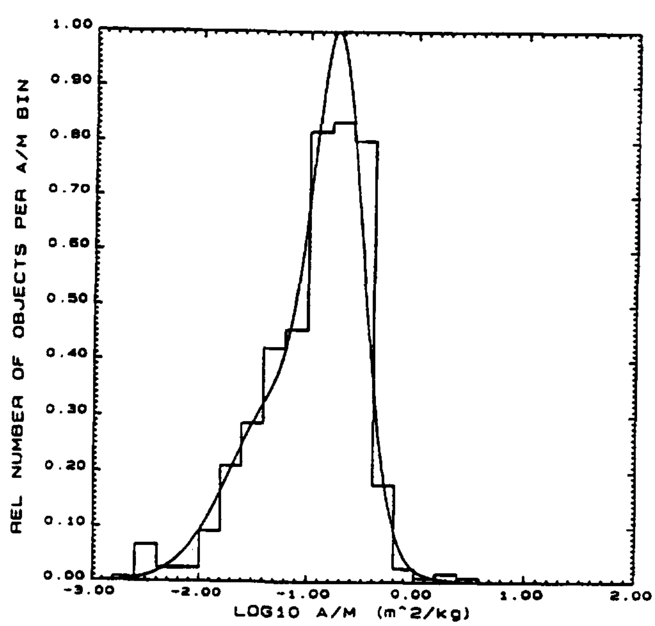

Fig. 6. Sample A/M distribution function matched to data for 508 spacecraft debris in the size regime of 11.2 cm to 35 cm.

Delta Velocity Distributions

Those familiar with EVOLVE 3.0 will also note improvements in the debris velocity distributions. Again, considerable effort was expended in determining ejection velocities for large debris from on-orbit analyses and for small debris from ground tests. For example, Figure 7 depicts the composite ejection velocities for 1,486 objects created in the breakups of Delta, Ariane, and Cosmos upper stages. With regard to expected collision ejecta velocities, the more appropriate limiting interpretation of the "characteristic" velocity (Johnson, 1985) is applied in place of a delta-function spread about the "characteristic" velocity of EVOLVE 3.0.

Using A/M as the independent variable instead of L_c, similar ΔV functional forms were found for explosions and collisions. The distribution function for the velocity distribution for explosion fragments is

$$D_{\Delta V}^{EXP}(\chi,\nu) = N(\mu^{EXP}(\chi),\sigma^{EXP}(\chi),\nu) \tag{11}$$

where $\chi = \log_{10}(A/M)$
$\nu = \log_{10}(\Delta V)$
μ^{EXP} = mean = $0.2\chi + 1.85$
σ^{EXP} = standard deviation = 0.4

Similarly, the distribution function for the velocity of collision fragments is

$$D_{\Delta V}^{COLL}(\chi,\nu) = N(\mu^{COLL}(\chi),\sigma^{COLL}(\chi),\nu) \tag{12}$$

where μ^{COLL} = mean = $0.9\chi + 2.9$
σ^{COLL} = standard deviation = 0.4

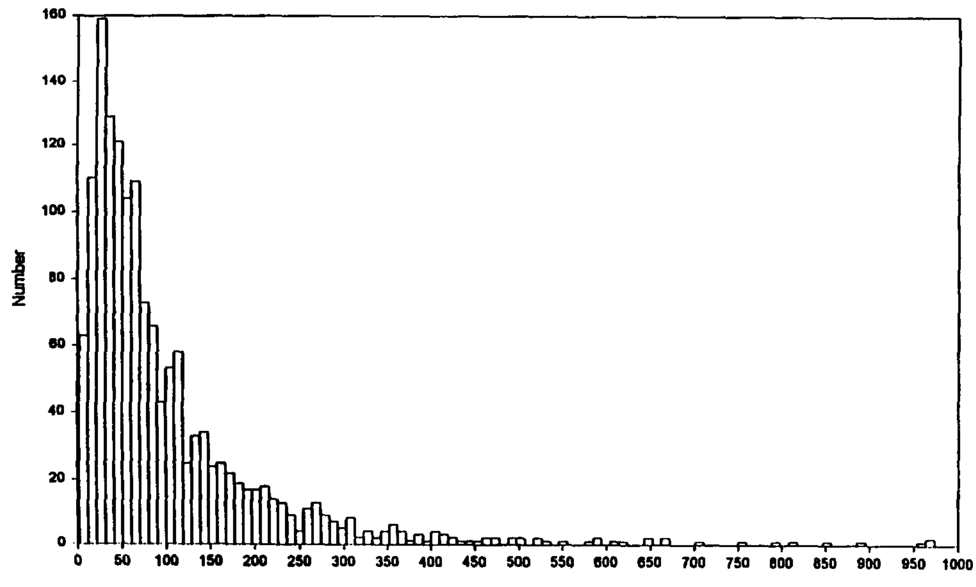

Fig 7. Composite distribution of calculated ejection velocities for 1,486 debris from Delta, Ariane, and Cosmos upper stages.

Collision Probability and Impact Velocity Distributions

EVOLVE requires two distinct velocities in order to calculate the probability of collision using a perfect gas approximation and, given that a collision event occurs, the relative velocity of the two colliding objects. These are termed the collision probability velocity and the relative velocity, respectively. The collision probability velocity is the satellite population's average velocity over a 50 km altitude bin; this average is calculated as $<1/v>^{-1}$ (Kessler, 1972) over each interval from 100 km to 2800 km altitude. Previous versions of EVOLVE utilized constant values of 7 km/s and 10 km/s for these velocities. EVOLVE 4.0 utilizes newly-derived relations for these velocities and incorporates them via tabular probability distributions.

Both distributions were calculated using a 1999 SSN satellite database. This database formed the basis of all orbital parameter distributions used in calculating the relative interaction between any two objects. The resulting collision velocity distributions are expressed in terms of altitude only; the inclination dependencies are suppressed. A comparison with a 1977 SSN satellite database indicated that these distributions are not particularly sensitive to the historical evolution of the near-Earth satellite population.

The collision probability velocity, as a function of altitude, is portrayed in Figure 8. Comparing this figure with the previously utilized constant velocity of 7 km/s indicates that collision probabilities are enhanced over nearly all altitudes. Figure 9 depicts the probability distribution as a function of event altitude. One observes that the higher relative velocities are again more probable over all altitudes.

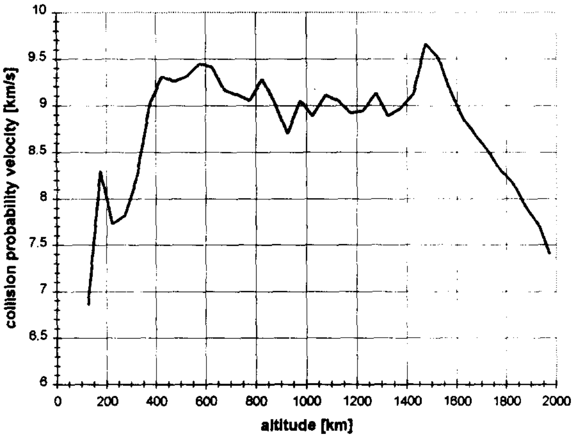

Fig. 8. Probable collision velocity as a function of altitude.

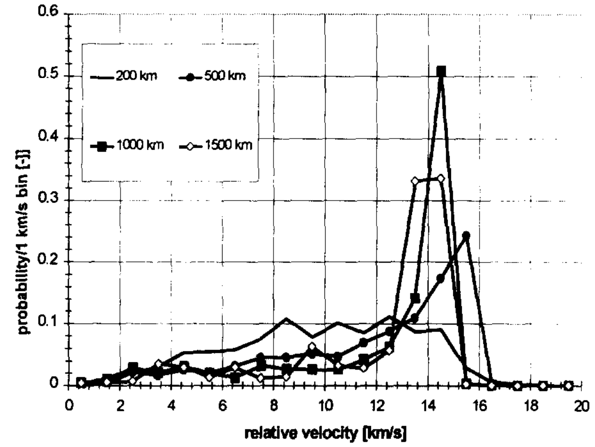

Fig. 9. Relative velocity probability distribution for various altitudes.

SUMMARY

The new NASA breakup model incorporated in EVOLVE 4.0, represents a significant advance over previous such models. The debris clouds, due either to explosions or collisions, simulated by EVOLVE 4.0 more accurately represent the fragments seen in orbit and in the laboratory. This work does not represent the final word on breakup models, but it is an important evolutionary step towards increasing the fidelity and accuracy of breakup models needed to support long-term satellite population sensitivity studies. Research continues on improving those sections of the model with data deficiencies. Whereas the size, area-to-mass ratio, and velocity distributions of future models may be of a different nature, they are unlikely to differ substantially in describing the overall characteristics of debris clouds.

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