LA-UR- 96: 3150

Title: **SPACE DEBRIS EXECUTIVE SUMMARY**

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Submitted to: For discussions outside the Laboratory

Date: September 1996

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SPACE DEBRIS EXECUTIVE SUMMARY

Gregory H. Canavan, O'Dean P. Judd, and Robert F. Naka

Issue: Spacecraft, boosters, and fragments are potential hazards to space vehicles, and it is argued that collisions between them could produce a cascade that could preclude activity in LEO in 25 to 50 years. That has generated pressure for constraints on military space operations, so the AF SAB performed a study of technical aspects of the debris problem. The Study was independent of the efforts of the Air Force Space Command (AFSPC) as well as those of and NASA Johnson Space Center (JSC), which is the principal advocate for cascades and constraints. Most work on space debris has been performed by AFSPC and JSC, so the Study was in part an assessment of their efforts, in which both have been cooperative. The Study identified the main disagreements and quantified their impacts. It resolved some issues and provided bounds for the rest. It treated radar and optical observations; launch, explosion, and decay rates; and the number and distribution of fragments from explosions and collisions. That made it possible to address hazard to manned spacecraft at low altitudes and the possibility of cascading at higher altitudes, both of which now appear less likely.

Catalogue comparisons. The Study compared estimates of the amount and size of debris at all altitudes. Figure 1 shows that the AFSPC catalog contains objects that range from fragments with diameters of tens of centimeters to large, intact objects with areas of hundreds of square meters.[1] The Study used the AFSPC catalog ephemerides, together with JSC averaging techniques, which it tested independently, for the comparison. AFSPC and NASA fluxes agreed very well, however, both are ultimately based on AFSPC observations and catalog, so this was primarily a test of consistency and averaging techniques. The main unresolved catalog issues are the actual size resolution of UHF sensors, which is needed for Shuttle avoidance maneuvers, and the validity of the extrapolation of UHF measurements to ≈ 1 cm sizes, which JSC does to provide environments for shielding regulations. The former is a matter of sensitivity and calibration of the UHF radars, which are not maintained for this purpose. The latter is an extrapolation; AFSPC resists it because particles that small are not observable with UHF radars. Neither impacts AFSPC's ability to execute DoD missions, but they do degrade its environment predictions for other applications.

Impact rates at low altitudes. The Study reviewed debris density and flux data at Space Station and Shuttle operating altitudes of 400-500 km. Lincoln Laboratory's Haystack x-band radar data should give reliable measurements of the flux of particles larger than 1 cm. However, at the beginning of the Study, the Haystack data was about an order of magnitude below the model "conditioned" on it, which NASA uses to define the impact hazard. The Study noted that discrepancy, and as Fig. 2 shows, JSC recently revised its model into rough agreement with the data.[2] Both the Haystack data and the revised model reduce expected impact rates of > 1 cm particles by about an order of magnitude to 1-2%/year, which might not require additional shielding. Haystack data is also ambiguous because of resonances in radar cross sections, which could further reduce impact rates.

The Study inquired whether the 10-fold reduction above had reduced the shielding requirements for Space Station. Modifications would be appropriate in the NASA *Safety Report*, National Academy of Science—National Research Council book on *Orbital Debris*,[3] the Office of Science and Technology Policy (OSTP) *Interagency Report on Orbital Debris*, which is the basis for the current Interagency Study,[4] and the United Nations COPUOUS deliberations, all of which are based on the earlier JSC analyses. Although planned modifications could greatly improve optical sensor's ability for wide angle search at all altitudes, which is badly needed for other reasons, they are not sufficiently cross calibrated with radars to resolve the issues above.

Impact rates at 850-1,000 km. At the altitudes of meteorological, remote sensing, and communications satellites, Haystack data roughly agree with the NASA model for particles larger than 1 cm, as shown in Fig. 3,[5] although those fluxes would only reduce the lifetimes of large satellites a few percent. Collisions of sub-catalog particles with satellites would not multiply. Catalog particles are more effective in producing additional fragments, but Haystack data for particles larger than 10 cm lie an order of magnitude below the NASA model. They would produce about 100 m^2 x $10^{-6}/m^2$-year x 50 particles/collision $\approx$ 0.005 particles/year per large satellite, which is small compared to orbital decay.

Launch rates are a principal source of debris growth. Launch rates to LEO are projected to decline by factors of 2 to 4 over the next few decades. The primary reason is the two-fold decrease in FSU launches since the end of the Cold War shown in Fig. 4, together with the associated 2-fold reduction in the total launch rate and 3-fold reduction in the launch rate to lower LEO perigees.[6] Figure 5 shows that the total number of LEO objects with perigees below 800 km declined a factor of two as the FSU launch rate fell over the last decade.[7] This large reduction, which has not been predicted by detailed models, effectively represents an independent prediction of the likely continued decline of LEO debris over the coming decades. A second reason for the decrease is the rapid shift of defense, commercial, and civil launches from LEO to GEO for operational reasons that is shown in Fig. 6, which should cause the number of GEO launches to reach parity with LEO within the decade and exceed them in subsequent decades.[8] Without the few to few tens of launches per year supporting planned LEO communication constellations, the launch rate to LEO would fall an order of magnitude below the levels of the last decade. NASA, National Research Council, OSTP, and UN reports use the peak rates of the previous decade.

Debris composition. The major sources of debris are spacecraft, rockets, operational objects, and explosion fragments. Figure 7 shows that the total number of spacecraft and rockets on orbit have grown monotonically.[9] About 40% of those launched are still in space, where they constitute 40% of the total debris. There have been about 120 explosions, which have produced about ≈ 7,000 LEO fragments, or ≈ 60 fragments per explosion. JSC uses 300 fragments per explosion, which is a factor of 5 higher, for "conservatism." While fragments are currrently the most numerous objects, they stopped growing two decades ago. Thus, rockets and payloads are an increasing fraction of the debris.

AFSPC uses conservative estimates of launch rates, explosion rates, fragments per explosion, and mitigation measures. JSC analyses use the high launch, explosion, and fragmentation rates of previous decades, e.g., NASA assumes 300 fragments per explosion, which is the largest number ever observed, rather than the average, which is 60, for which there is no basis in data or theory. Applying 300 fragments per explosion to all 120 explosions would give 36,000 objects, which is 50% larger than the total number of objects ever cataloged and 500% larger than the number of fragments ever cataloged in LEO.

U. S. Space Debris Policy makes minimizing debris a goal for all agencies. The DoD has largely met this goal by burning boosters to completion to avoid explosions. However, about 75% of the fragmentations to date have been of non-U.S. systems, including CIS explosions that are the greatest threat to long term stability. Since fragments stopped growing several decades ago, it would appear that most benefits of the U.S. policy were realized before it was put into place. While eliminating fragments altogether would only decrease the debris about a third, deorbiting payloads or boosters have significant penalties, so it is worthwhile to continue to reduce fragments and operational debris.

Collisions. The Study independently estimated the debris collision rate, obtaining the total rate of 0.05 collisions per year, with significant contributions from low altitudes, 950 km, and 1,450 km shown in Fig. 8,[10] in good agreement with NASA estimates. The Study attempted to check this estimate through an approximate calculation of the mass on orbit for comparison with JSC, but the AFSPC catalog contains only radar cross sections; it does not carry mass or a reliable approximation to it. JSC has a mass catalog, but it was not possible to obtain it during the Study. The Study also made surveys of the areal densities of fragments from laboratory railgun, field missile explosions, and on orbit fragment ballistic coefficients. The first two gave consistent results; the last were too noisy due to the rough trajectories available to the study. The overall uncertainty in catalog mass appears to be few tens of percent, which does not significantly affect the Study's analysis and conclusions, as the calculation of collision rates only requires the catalog areas; masses are not used.

Fragmentation. The Study independently evaluated the catalog debris fragmentation rate, producing the value of about 2.7 fragments/year shown in Fig. 9, which has significant contributions from low altitudes and 950 km and a small contribution from 1,450.[11] That gives 2.7 fragment/year / 0.05 collision/year ≈ 55 fragments/collision, for the empirical parameters determined by DNA railgun and Atlas explosion tests.[12] The number of fragments/collision varies 30-50% for parameters broadly consistent with those tests; the maximum for any parameters is about 100 fragments/collision. The Study's value is in agreement with a number of independent analytic and numerical estimates, but it is not in agreement with NASA's estimate JSC of 480 catalog fragments/collision, which is a factor of 6 to 10 higher.

This discrepancy was discussed in three meetings at JSC. NASA scientists did not disagree with Study values, they only stated that their 480 particles per collision is a conservative estimate based on the fragments from large explosions.[13] Apparently, NASA uses the *maximum* number of particles observed from *explosions* as a substitute for the calculated and experimentally measured value of the *average* number of fragments per *collision* in its calculations. This substitution overestimates the number of catalogue fragments produced per collision by an order of magnitude relative to theory, laboratory, field, explosive, and impact experiments, producing levels of cascading in a few decades in NASA calculations that would take centuries in calculations using measured rates. Those assumptions are also used in the NASA calculations that are the basis for the National Research Council and OSTP reports and UN deliberations.

Orbital decay. The Study checked the consistency of AFSPC and JSC catalogs of fragments from past explosions and confirmed that they decay to the present debris distribution, which tested debris production, averaging, and decay algorithms. This comparison also bounded the models that can usefully model debris growth or decay. It did not explicitly evaluate the models used by AFSPC and NASA, which are not fully documented in the literature. The version of the NASA orbital decay model used for stability calculations appears to significantly overestimate fragment lifetimes, which decreases stability thresholds.

Debris growth. The Study's analytic models were tested by accurately predicting the current LEO catalog, as shown in Fig. 10.[14] For consistent inputs, Study and NASA analyses agree, producing approximately the same debris growth rates for what are thought to be the same input parameters. The principal uncertainty is relating the Study's use of the measured average fragments per collision to JSC's 5 to 10-fold larger number of fragments per collision. For nominal conditions—i.e., historical launch and explosion growth rates, 60 fragments per explosion, 80 fragments per collision, and standard orbital decay—the Study model produces little debris growth and no cascading for the next century, as shown in Fig. 11.[15] The number of objects does increase, but that is due to the accumulation on orbit of fragments from launch and explosions, to which cascading adds only a few percent. For those conditions, JSC predicts 10-fold growth, 60% from cascading due to their higher number of fragments per collision. These NASA calculations are the principal projections cited in the National Research Council's *Orbital*

Debris [16] and OSTP's *Interagency Report* [17]

Stability. The National Research Council[18] and OSTP reports cite JSC's analysis, which indicates that the debris around the peaks at 950 and 1,450 km is strongly unstable. Those conclusions resulted from the use of a single component, large object model, which does not properly treat the stabilizing effect of the rapid decay of smaller fragments. The Study corrected that error by developing a two component model including fragments.[19] Figure 12 shows that it recovers the incorrect result of the single component model in the limit of no fragments, and shows that when both components are treated, in the absence of external sources, the catalog is stable at all altitudes—by a large margin below about 1,300 km, and a narrower margin at higher altitudes.

External sources from launch, deployment, and explosions exist and are dominant above about 900 km, where they cause secular growth, which must be stopped before it reaches levels where cascading is self sustaining.[20] Figure 13 shows the current, projected, and critical sources in the altitude regime of concern. The peak at 950 km requires action within a few hundred years. Decreasing the sources by the projected order of magnitude there by then should maintain strong stability. The growth at 1,450 km could require action in a few decades, if the FSU resumes launches to that altitude. NASA calls for immediate de- or re-orbit of all large objects are based on overly simplistic analysis. Study results indicate that the low altitudes can wait, but high altitude sources should receive prompt attention. Launch and fragmentation reduction should be effective.

GEO fragments are spread over volumes several orders of magnitude larger than those at LEO; thus, impact and growth rates are reduced accordingly. Figure 14 from the National Research Council *Orbital Debris*, which is based on NASA-JSC analysis, shows that 20 explosions would produce less of a debris hazard than the normal meteoroid background at GSO.[21] Thus, the debris problem at GSO is small for the foreseeable future. Most DoD, civil, and commercial launches are shifting to GSO for operational advantages, which provides a clean environment for important payloads for centuries as well as reducing the sources at LEO, which is being left to commercial activities that are capable of policing themselves.

Findings. The Study addressed and resolved a number of issues in launch, explosion, collision, fragmentation, and decay physics. It showed AFSPC and NASA catalogs to be consistent, apart from completeness and extrapolation to centimeter sized objects, which does not impact AFSPC's DoD responsibilities. The Study helped to bring NASA's predicted and measured 400-500 km environments into accord, advanced the interpretation of ambiguous radar data on small objects, showed that impacts at 900-1,000 km would reduce satellite lifetimes slightly and would not cascade.

Current, official projections were used to bound the effects of future launch and explosion rates. Launch rates LEO should fall sharply due to reduced FSU launches and the shift to GEO. The benefits of the current debris policy have saturated. The Study performed independent evaluations of catalog collision rates, which are in good agreement with NASA's, and fragmentation rates, which exposed an order of magnitude conservatism in NASA's estimates. It found subtle but important differences in treatments of orbital decay.

For similar assumptions, the Study's models yield similar results to NASA's, but there are large disagreements about assumptions—despite the extensive theoretical and experimental basis for those used by the Study. The key issues are the amount of conservatism in NASA analyses of launch, explosion, fragmentation, and decay rates. For nominal rates, Study models produce little debris growth and no cascading for conditions where JSC models predict 10-fold growth, largely due to cascading. The difference was traced to the number of fragments per collision. Until these issues are resolved, it is appropriate to view the AFSPC estimates as the baseline and NASA's estimates as very large rate excursions.

NASA analyses indicate the debris around 950 and 1,450 km is strongly unstable. The Study showed those conclusions resulted from an over simplified model, corrected it, and showed that in the absence of external sources, the catalog is currently stable at all altitudes. External sources from launch, deployment, and explosions are dominant above about 900 km. They cause secular growth that must be reduced before cascading could reach self-sustaining levels. The low altitudes should be addressed within a few centuries; the high altitudes could require prompt attention, if the FSU resumes launches to that altitude. GEO fragments are spread over very large volumes, which greatly reduces collision and growth rates. Thus, the debris problem at GSO be modest for the foreseeable future.

Recommendations. Space debris has not been shown to be an issue in the coming century; thus, it does not appear necessary for the Air Force to take additional steps to mitigate it. It would be appropriate for the AF to continue to monitor the rates of launch, explosion, collision, and decay, as well as the amount of catalogue debris, with its current sensors as part of its responsibility as the DoD agent for space. It would also be appropriate for the AFSPC to be involved in interagency and international analysis debris efforts, to publish scientific papers on the expected space environments, and to broaden the inputs to its models and empirical parameters for debris prediction in both the short and long terms.

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3. G. Cleghorn, *Orbital Debris* (Washington, National Academy of Science, National Research Council, 1995)

4. *Interagency Report on Orbital Debris* (Washington, D.C., Office of Science and Technology Policy, November 1995),

5. E. Stansbery et al, "Haystack Radar Measurements of the Orbital Debris Environment," NASA Report JSC-26655, 20 May 1994, p. 59, Fig. 5.4-8.

6. R. Naka and J. Darrah, AFSPC catalog, 1995.

7. R. Naka and J. Darrah, AFSPC catalog, op. cit.

8. "Space Log," TRW, 1995

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17. *Interagency Report on Orbital Debris* , op. cit., Figs. 11, 12, and 15.

18. G. Cleghorn, *Orbital Debris* , op. cit., Fig. 8-6.

19. G. Canavan, "Cascade Stability of the Debris Catalog Under a Two-Component Flux Model," Los Alamos report, August 1996, Fig. 1.

20. G. Canavan, "Cascade Stability of the Debris Catalog Under a Two-Component Flux Model," op. cit., Fig. 6.

21. G. Cleghorn, *Orbital Debris*, op. cit., p. 87, Fig. 4-7.

September 6, 1996

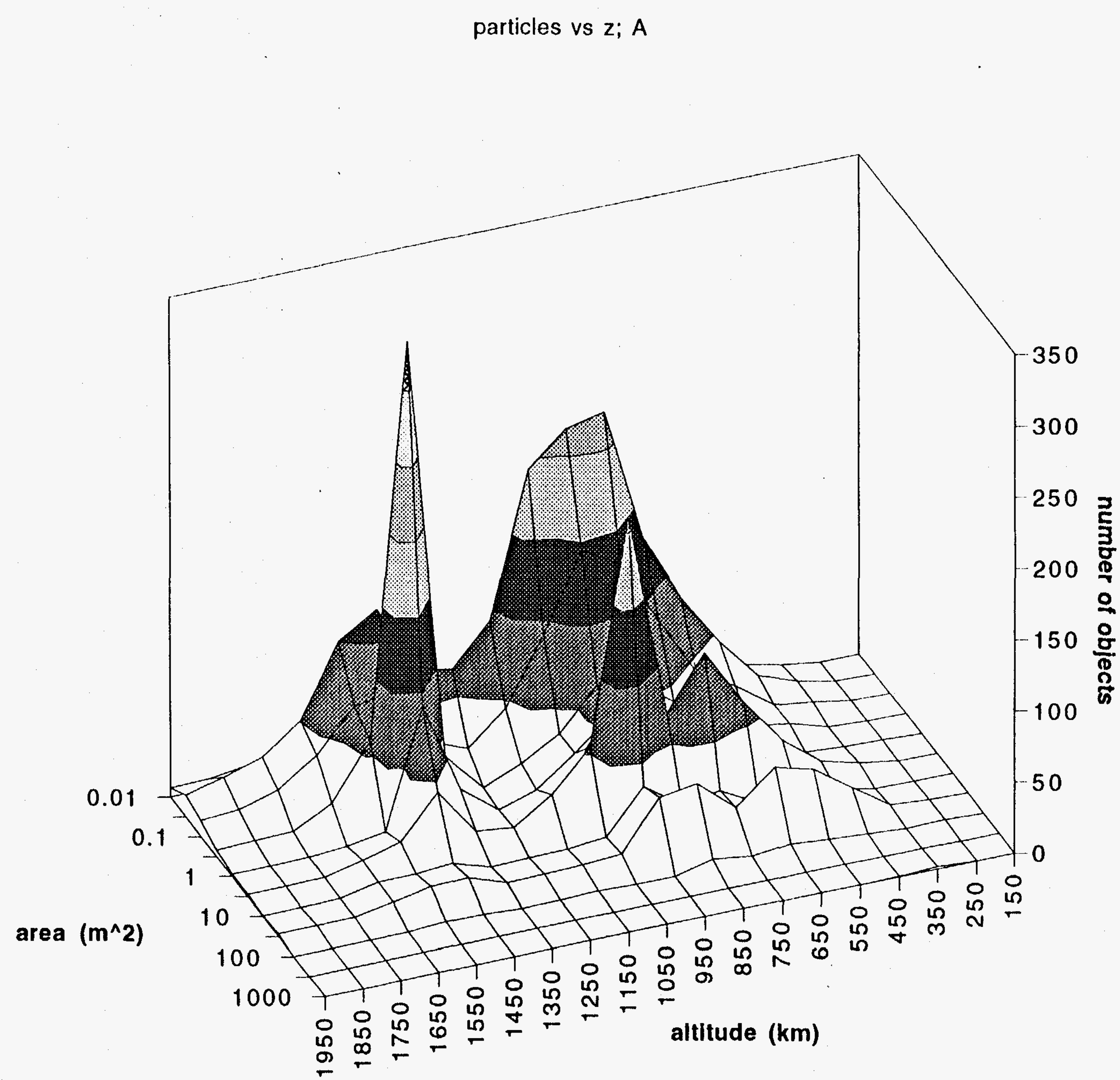
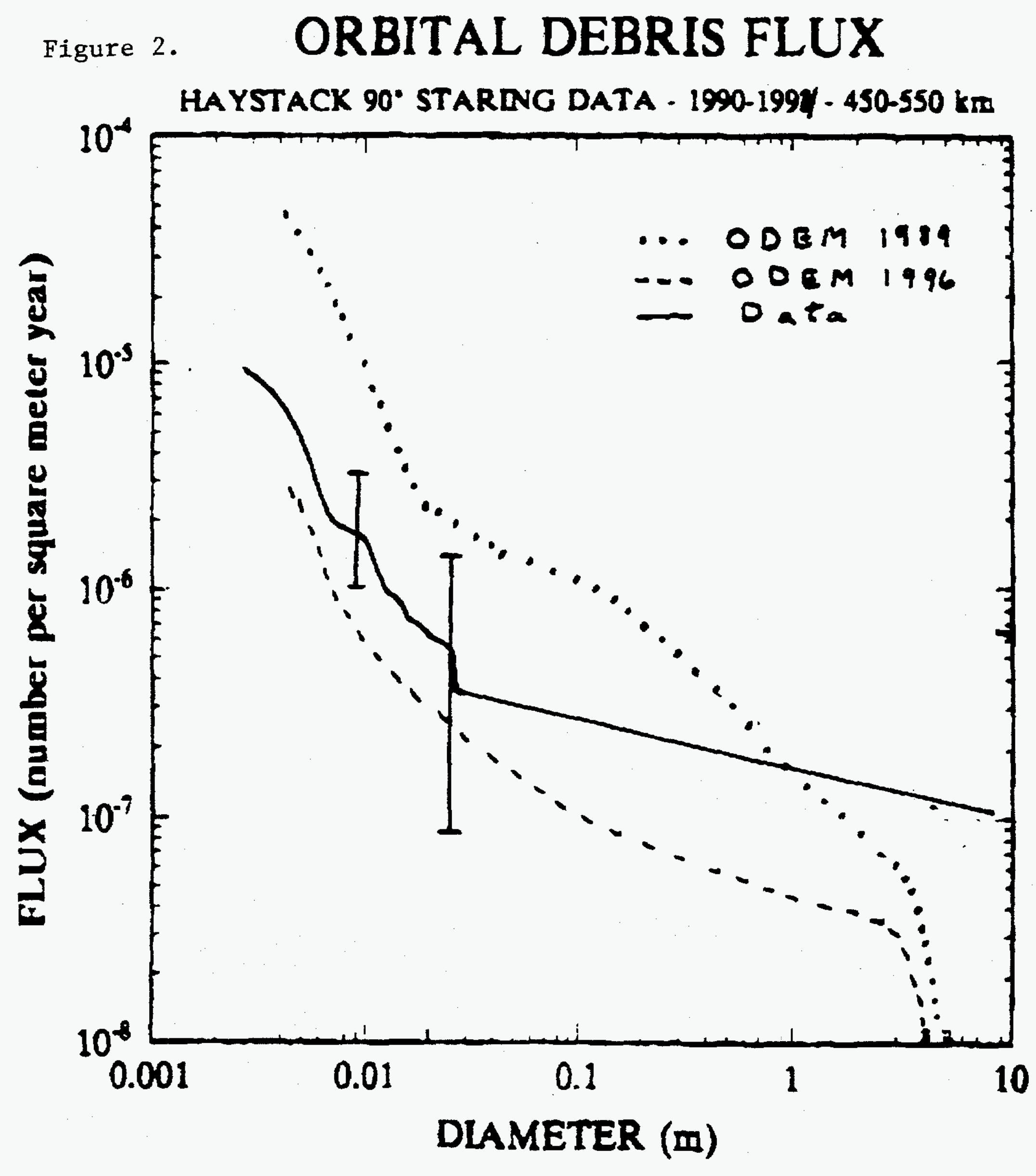


Fig. 1. Object number versus altitude and area from catalog.

Figure 2.



Measured and modeled orbital debris flux by year from 1990 to 1994 for Haystack 90° staring angle data and for the altitude range of 450 - 550 km.

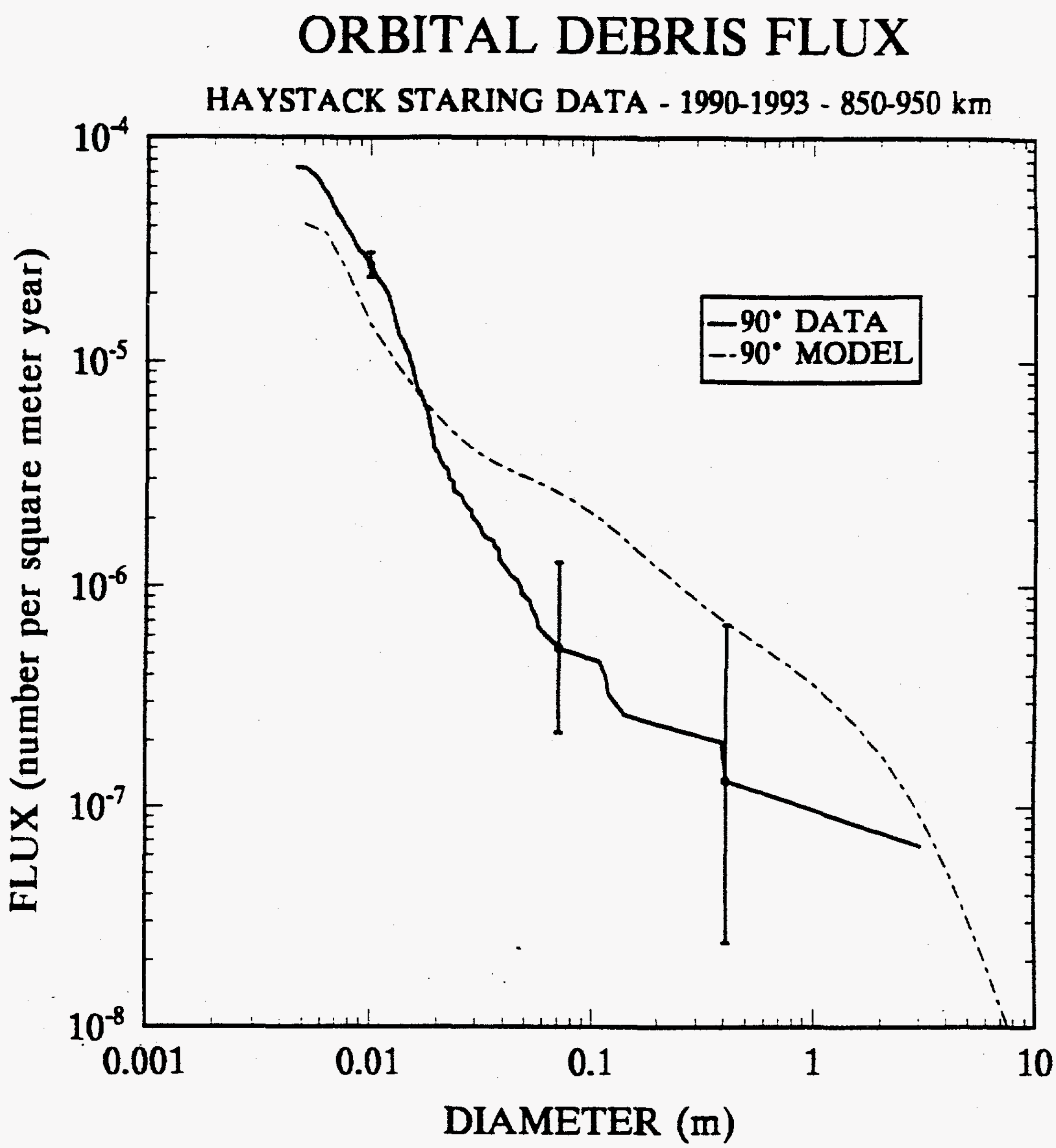


Figure 3. Measured and modeled orbital debris flux for Haystack 90° staring angle data for the altitude range of 850 - 950 km.

Source JIAF SIC

Figure 4. **Total Launches Compared to Total Launches to LEO**

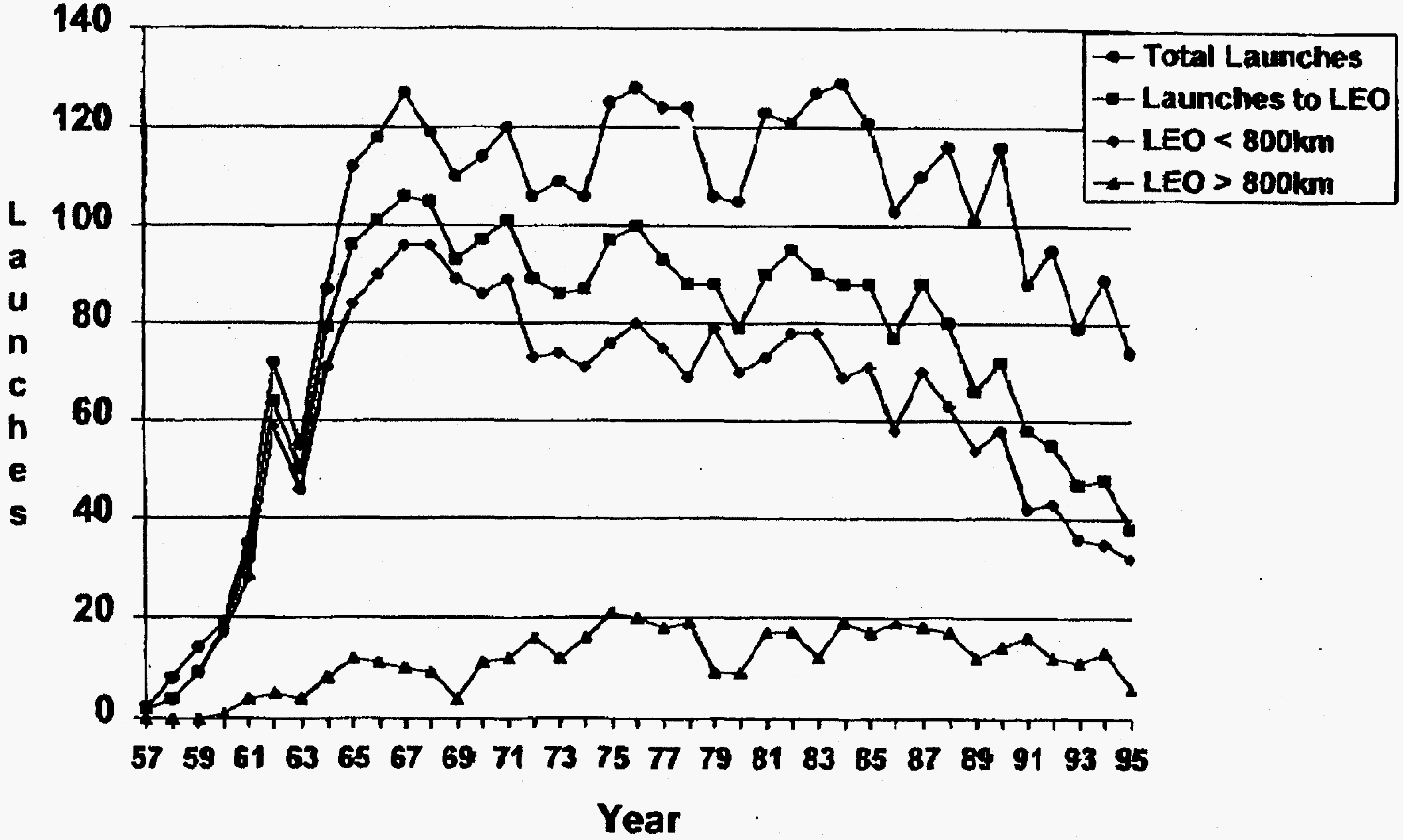


Figure 5.

Total Objects in LEO Compared to Objects with Perigee < 800 km and > 800 km

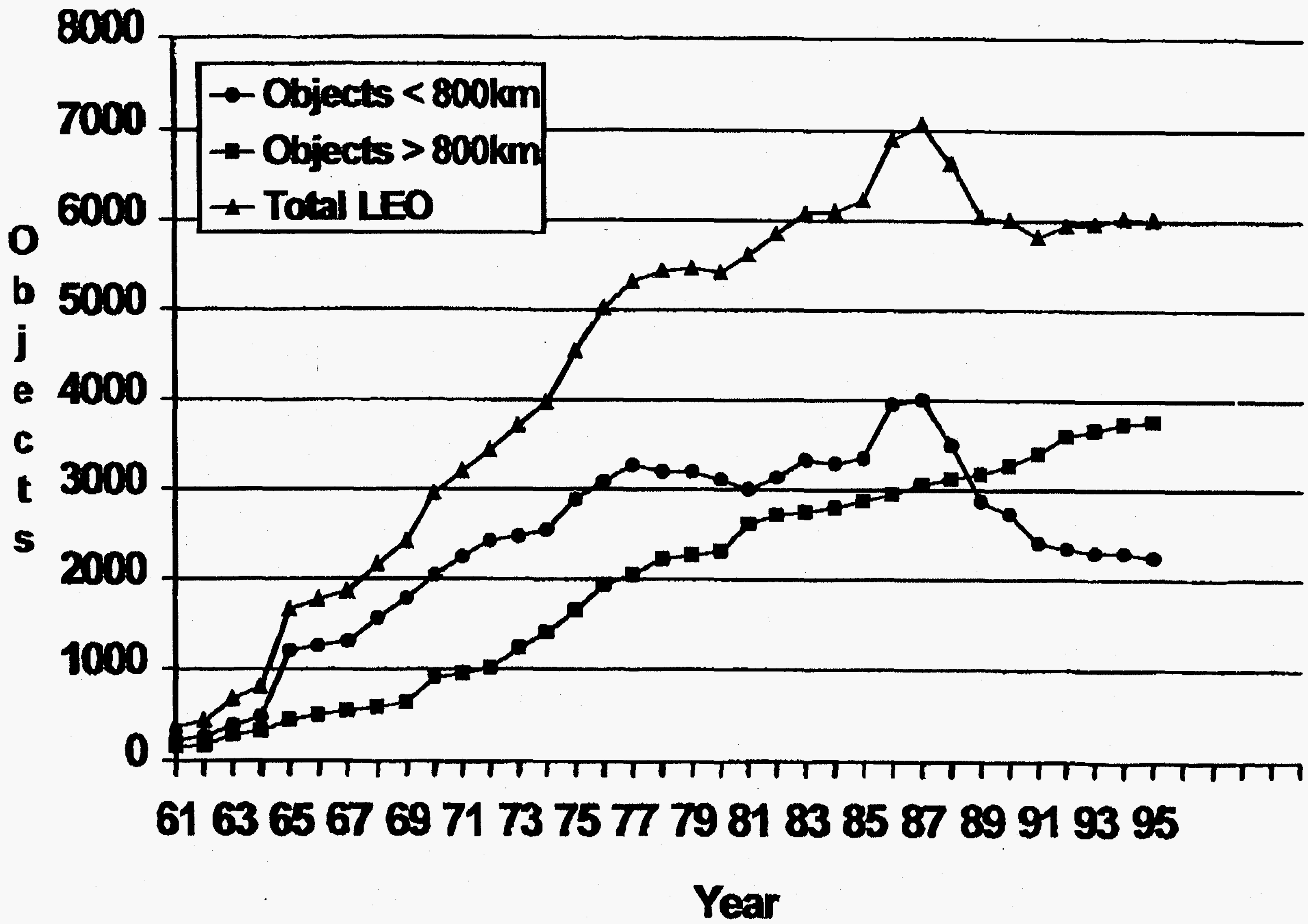
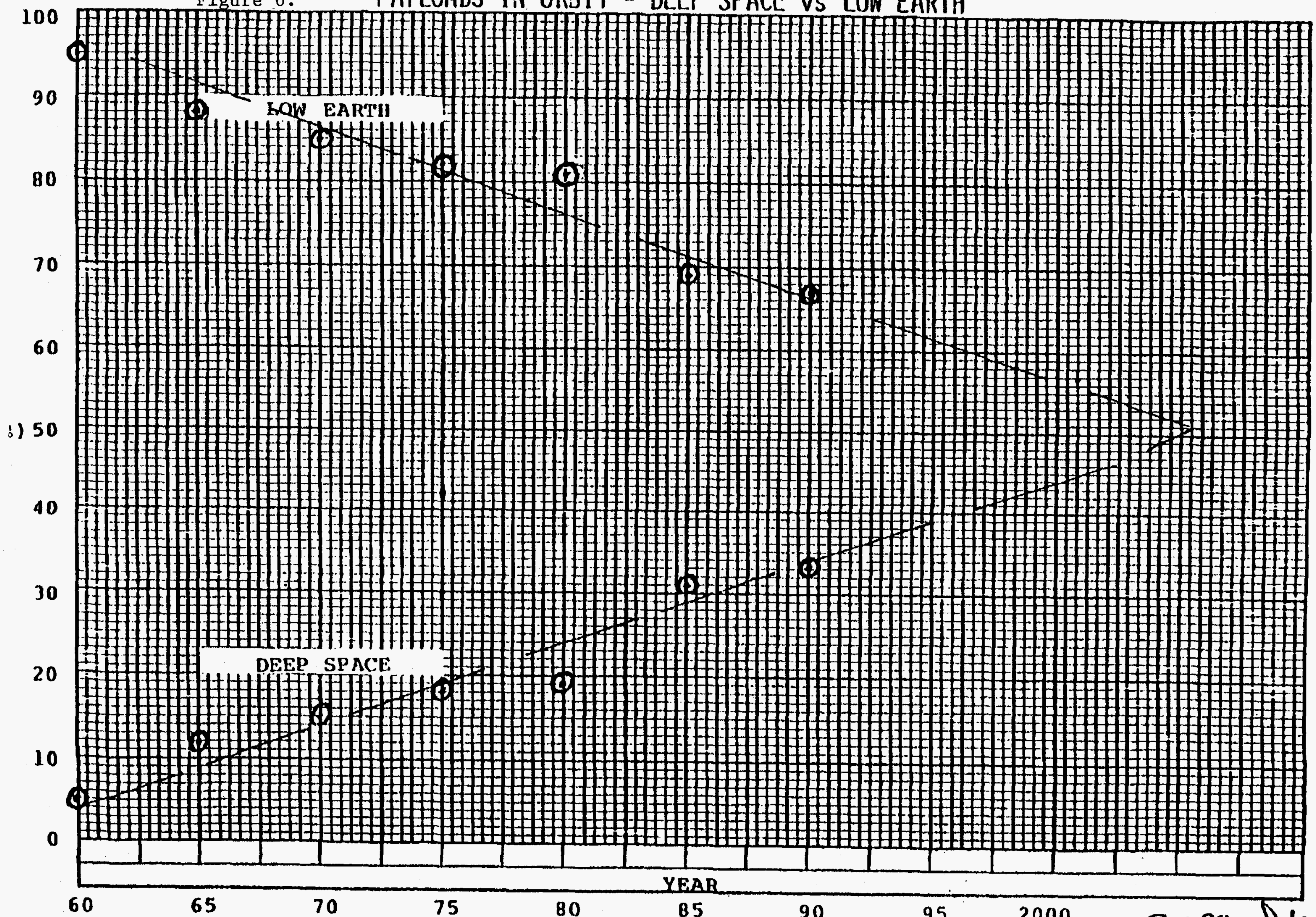


Figure 6. PAYLOADS IN ORBIT - DEEP SPACE vs LOW EARTH



Source: Air Force Space Command

Prepared by JWC/SAM received 10 MAR 94

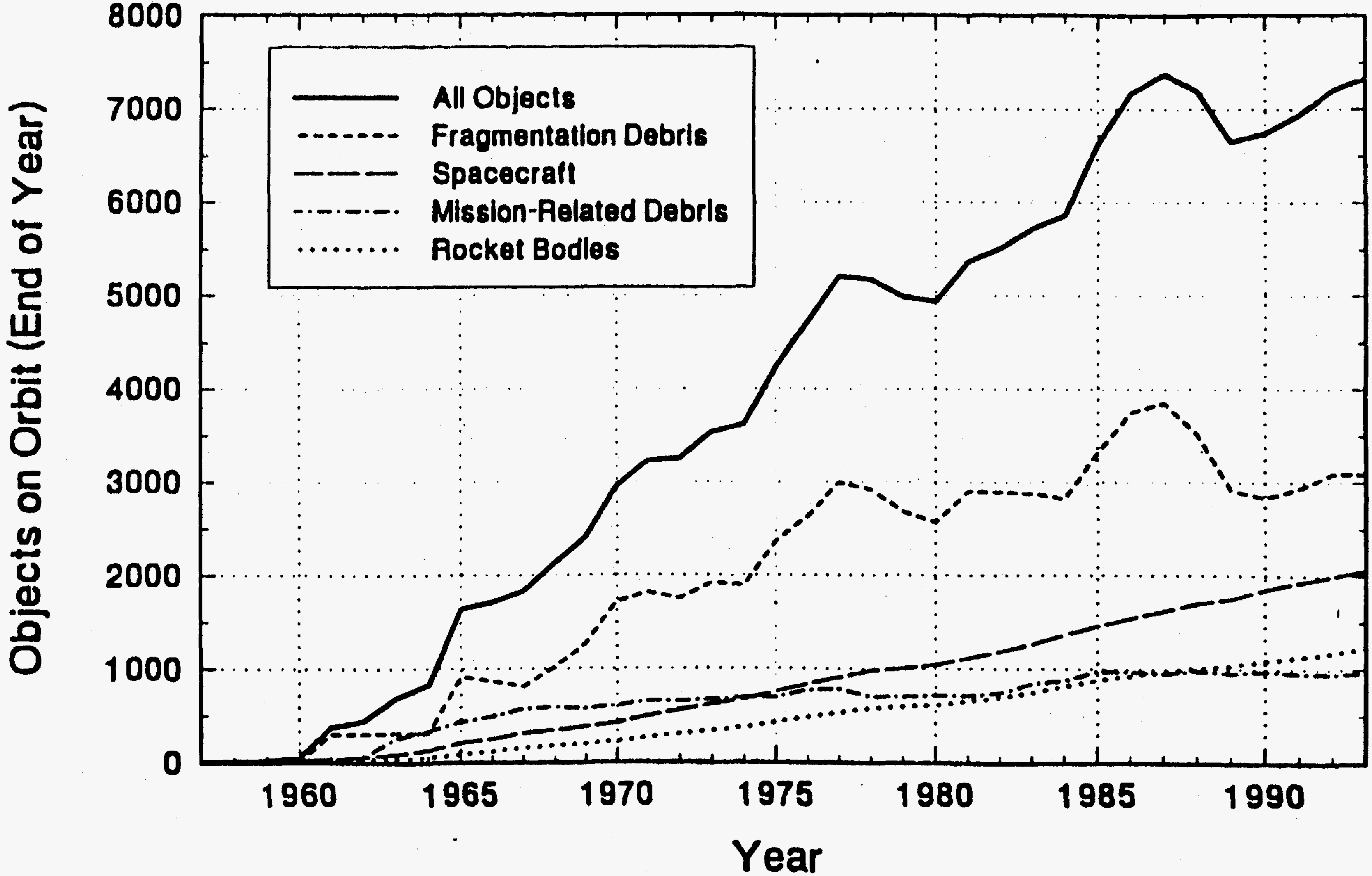


Figure 7. On-orbit cataloged population (corrected for delayed cataloging).

Source: Orbital Debris (National Research Council)

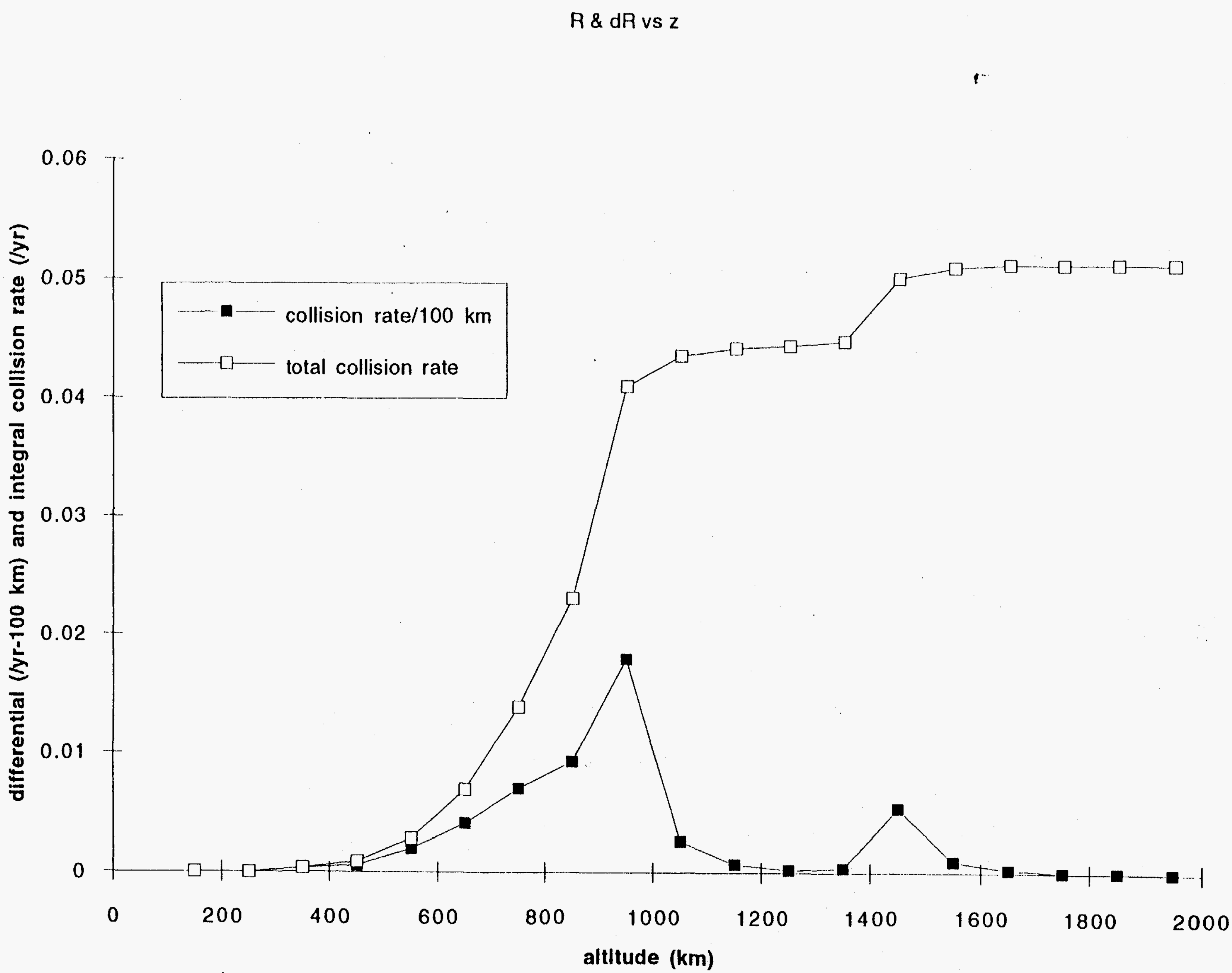


Fig. 8. Differential and integral collision rates versus altitude.

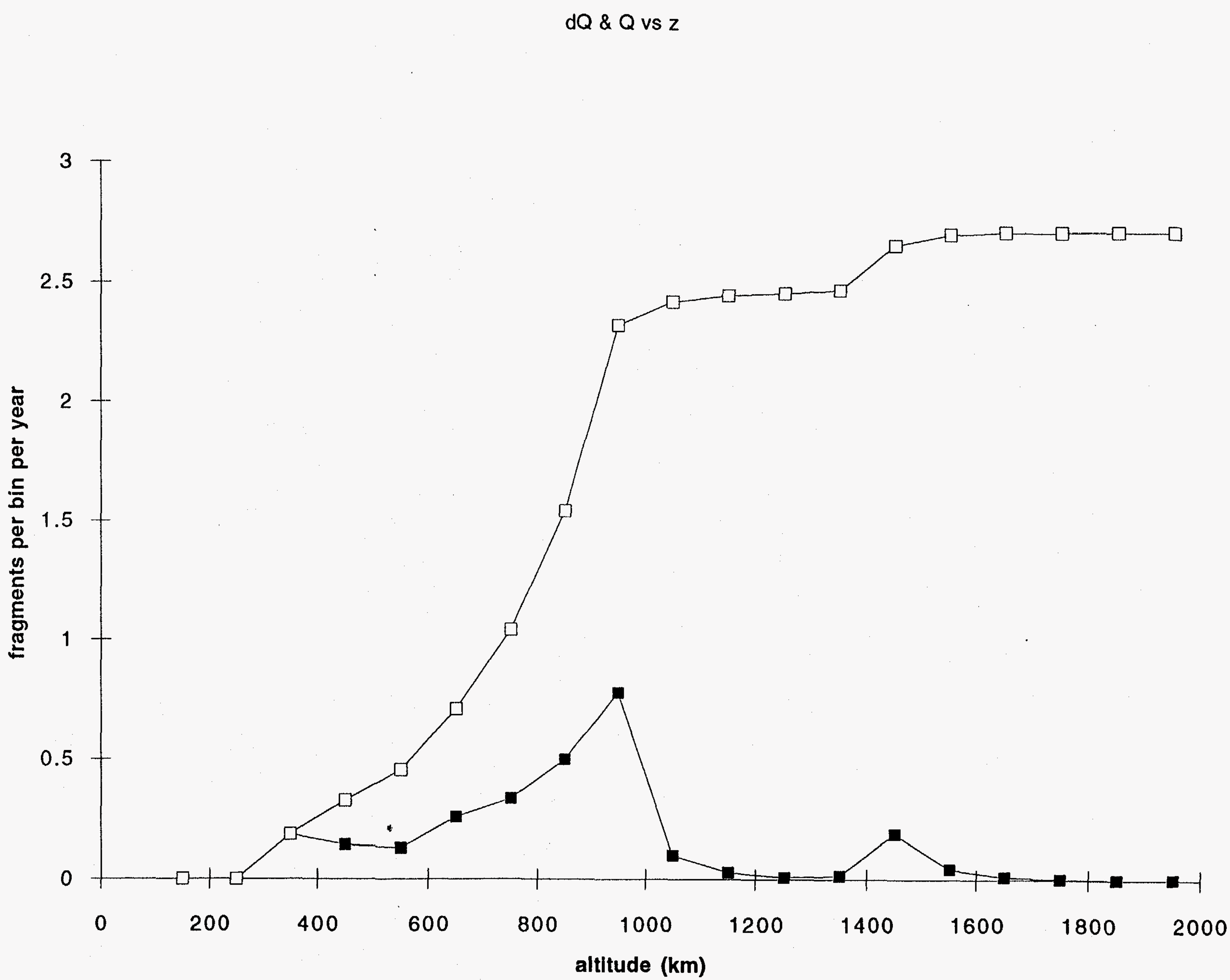


Fig. 9. Differential and integral fragment production rate versus altitude.

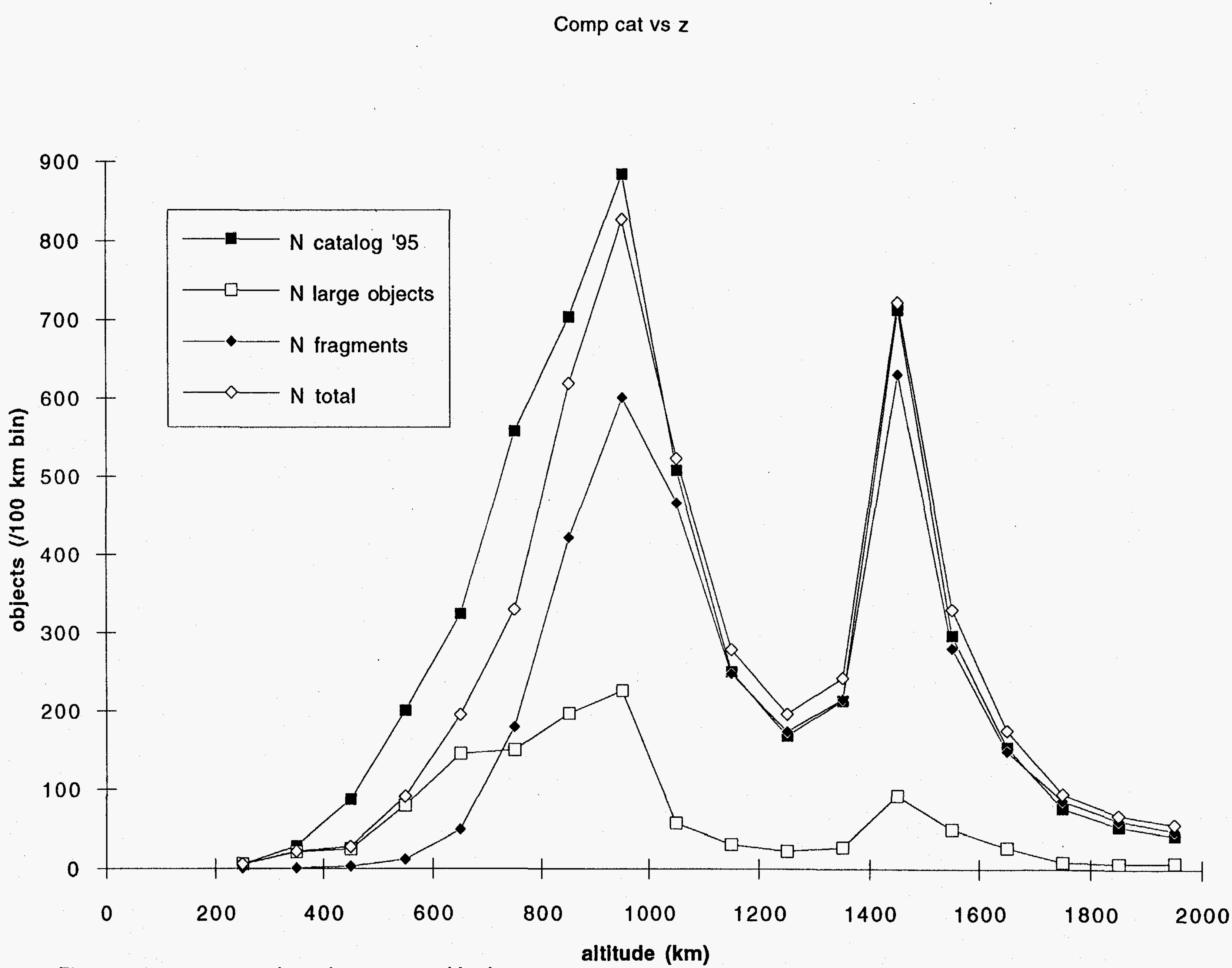


Fig. 10. Components of catalog versus altitude.

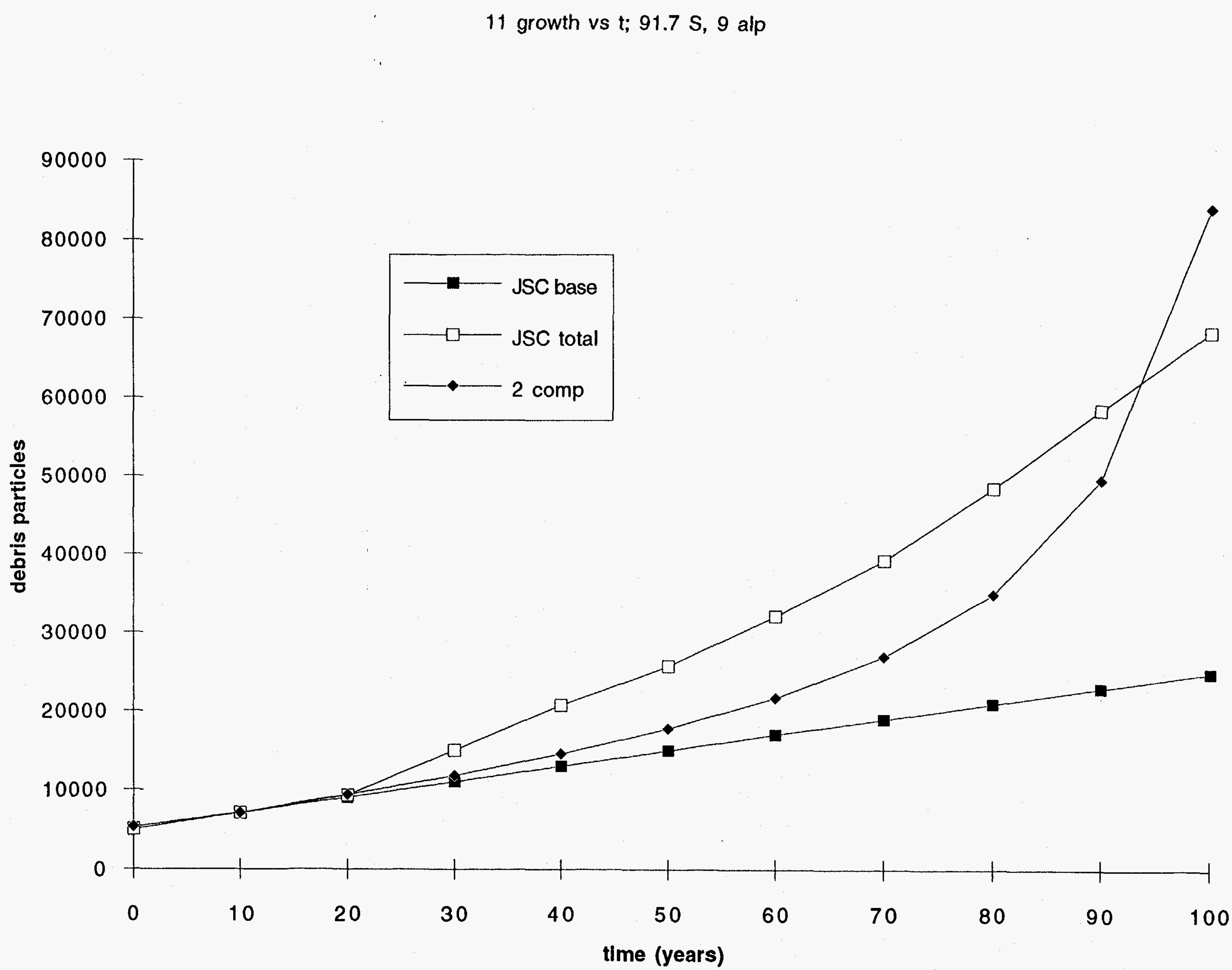


Fig. 11. Growth of total number of debris objects for 170% source and 900% cascade coefficient.

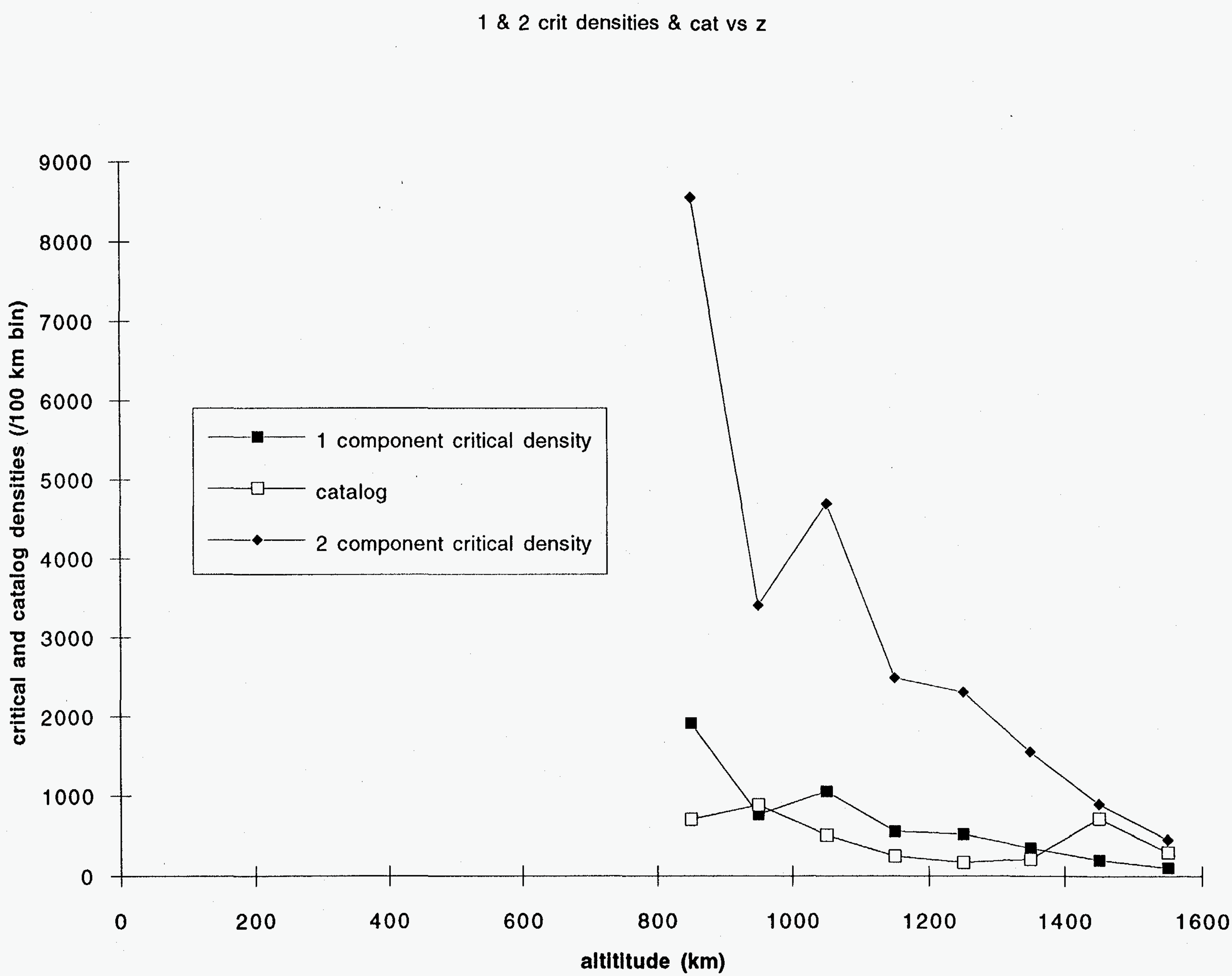


Fig. 12. One and two component critical densities and catalog versus altitude.

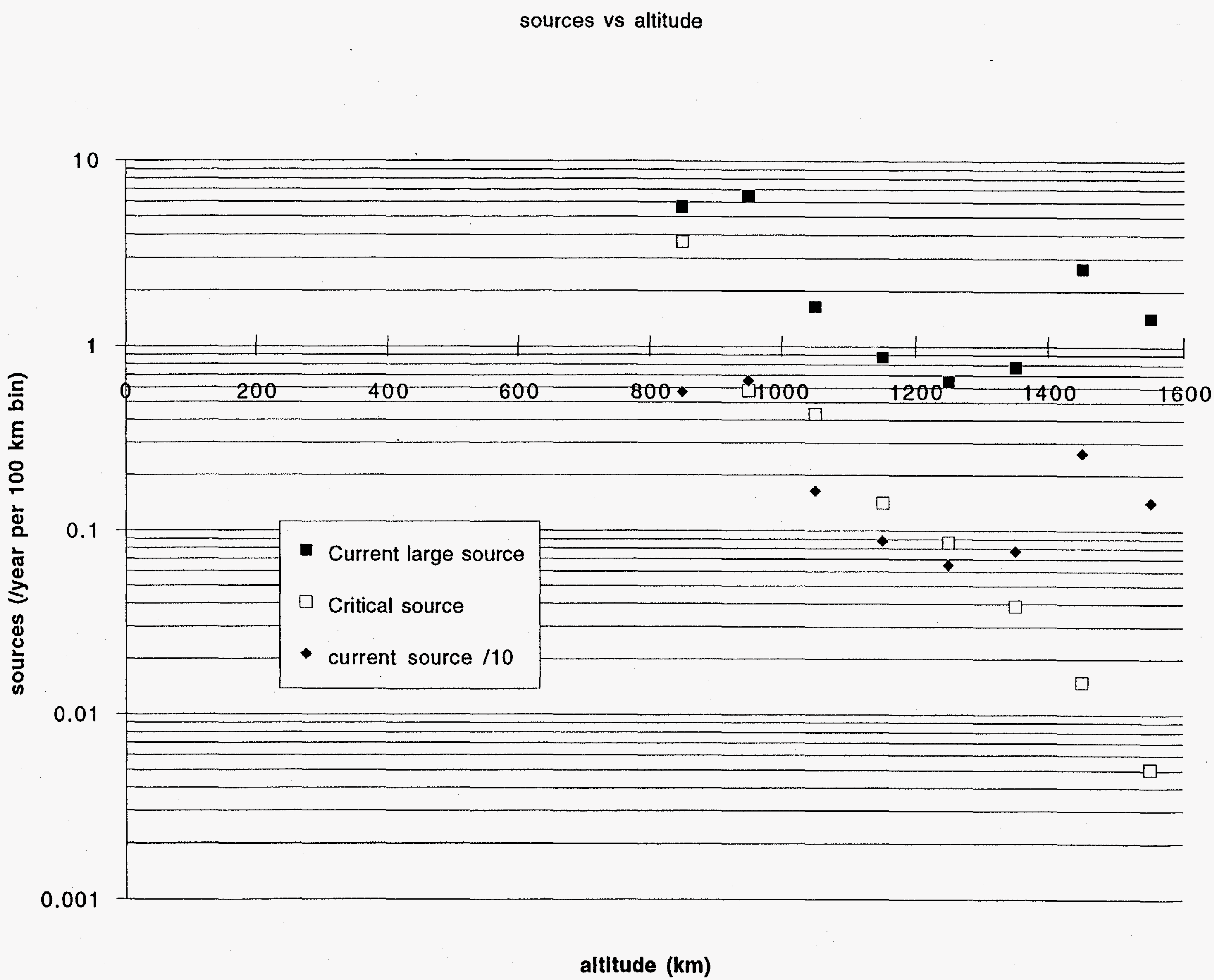
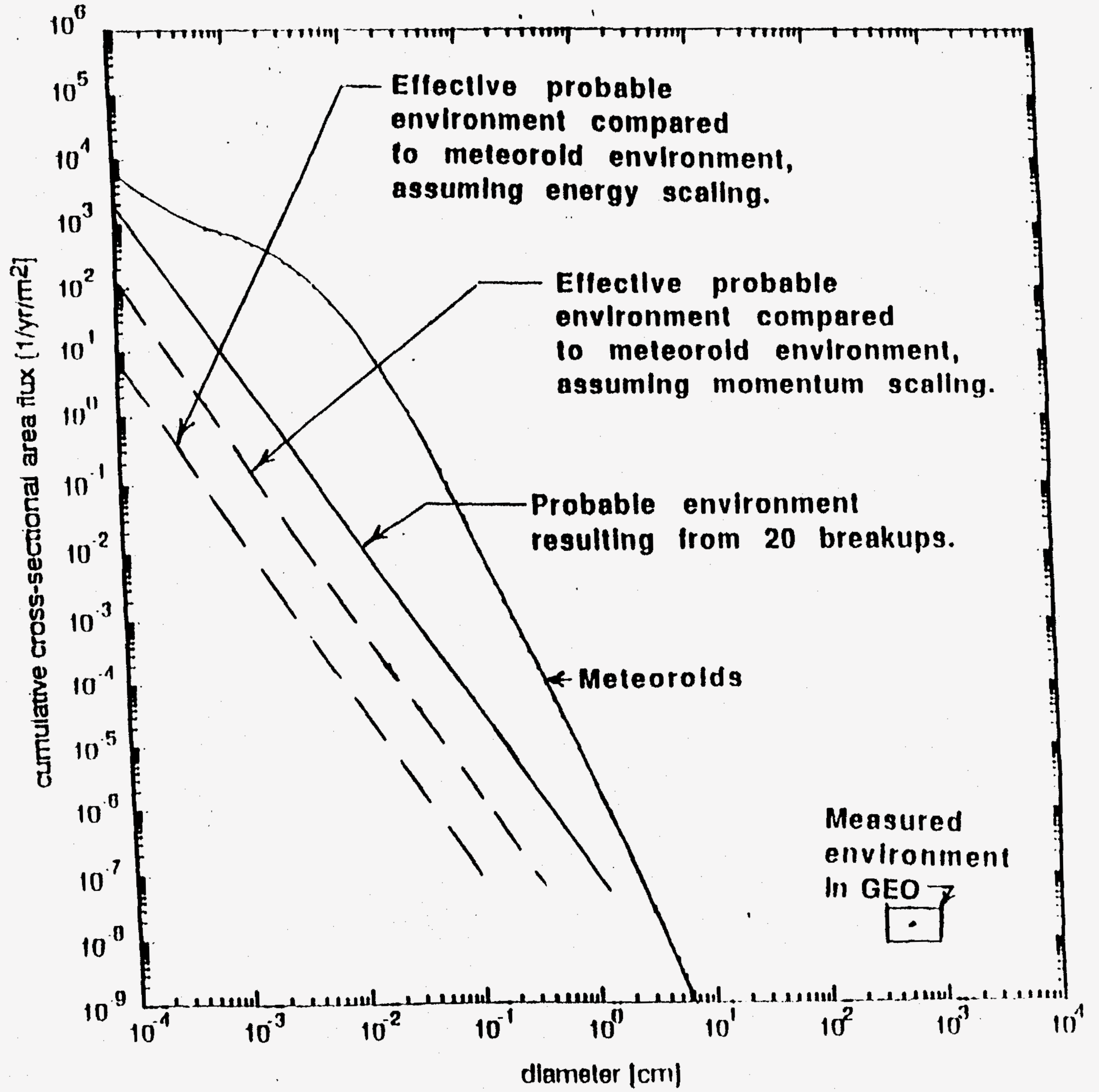


Fig. 13. Current, projected, and critical sources versus altitude.

Figure 14. Probable Orbital Debris Environment in GEO Resulting from 20 Satellite Breakups



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