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The Reentry of Large Orbital Debris

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Abstract

The natural reentry of a large space object occasionally commands international attention, as in the orbital decays of the Skylab and Salyut 7 space stations, the nuclear-powered Kosmos 954 and Kosmos 1402 spacecraft, and the FSW 1-5 recoverable capsule. However, on average a piece of large orbital debris (radar cross-section > 1 m²) falls back to Earth once or twice a week. These objects are normally inactive spacecraft, expended launch vehicle upper stages, and hardware associated with launch vehicle and spacecraft deployments or operations. The time and geographic location of entry into the dense atmosphere is projected or recorded by U.S. national technical means. An examination of 331 such reentries which occurred during the September 1992 - December 1996 period was conducted, in part, to determine if impact zones were randomly distributed about the Earth as has been assumed, despite the planet's asymmetrical atmosphere and gravitational field. For objects in orbit for more than 30 days, reentry locations were found to be essentially uniform in terms of latitude and longitude. However, for recently launched objects (orbital lifetime less than 30 days), the reentries demonstrated a greater probability for Northern Hemisphere impacts. No significant differences were discovered among the three categories of objects: spacecraft, upper stages, and debris. The individual and aggregate masses of the subject reentries were also evaluated, and the issues of debris survivability and ground dispersal were addressed. Unfortunately, the capability to predict accurately the time and location of natural reentries does not yet exist.

1. Overview of Satellite Reentries

Within two months of the inauguration of the Space Age with the orbiting of Sputnik 1, the fallout of man's space exploration - a literal rain of orbital debris into the Earth's upper atmosphere - had also commenced. Since the Sputnik 1 launch vehicle decayed from orbit on 1 December 1957, approximately 16,000 space objects, ranging from approximately 10 cm to more than 25 m in length and cataloged by the U.S. Space Surveillance Network (SSN), have followed suit (Figure 1). Thousands more trackable debris, created by severe spacecraft and upper stage fragmentations, are known to have also decayed from orbit before the objects could be officially cataloged. Moreover, millions of man-made particles smaller than 10 cm generated during normal deployment processes and satellite breakups are estimated to have fallen back to Earth.

A small percentage (< 10%) of the acknowledged reentries have been controlled for the purpose of recovering crew or materiel or of safely disposing of the vehicle, usually into a broad ocean area. The U.S. Space Shuttle represents the former, while the Russian unmanned Progress M resupply ship is typical of the latter. However, during the past four decades more than 14,000 reentries have occurred naturally with no attempt to govern their potential Earth impact zones. In all, these reentries account for more than 100 metric tons of materials entering the Earth's atmosphere annually.

The ability of a space object to survive reentry and to strike the surface of the Earth is highly dependent upon its design and composition. Materials like titanium and stainless steel possess a greater likelihood of surviving reentry than do copper and aluminum. Figure 2 illustrates the demise altitude for various size spheres of these materials as calculated by the Object Reentry Survival Analysis Tool

(ORSAT) simulation, developed by personnel from NASA Johnson Space Center and Lockheed Martin Engineering and Sciences. Some of the first recognized objects to survive reentry were 11 pieces of stainless steel skin and a spherical pressure bottle from the February 1962 reentry of the Atlas booster which launched John Glenn. Later that same year, a piece of metal from the 5 September reentry of Sputnik 4 (launched 15 May 1960) landed on a street intersection in Manitowoc, Wisconsin.

The most celebrated reentries of derelict spacecraft have been Kosmos 954 (January 1978), Skylab (July 1979), Kosmos 1402 (February 1983), and Salyut 7/Kosmos 1686 (February 1991). The first and third events were noteworthy due to the presence of hazardous materials (enriched U^{235} plus fission products) on board, whereas the second and fourth reentries involved vehicles of more than 40 metric tons. Debris from at least three of the four cases survived reentry and reached the ground.

2. Study Objectives and Methodology

Despite the considerable number of reentries of large orbital debris, no case of personal injury caused by reentering debris has been confirmed. Five Japanese seamen were reportedly struck by falling debris on 5 June 1969 near Sakhalin Island, but the origin of the objects has not been established (Reference 1). In January 1997 a woman in Tulsa, Oklahoma was apparently hit by a very lightweight fragment of orbital debris, but she was not harmed (References 2 and 3). Even property damage has been slight, e.g., following the reentry of Salyut 7/Kosmos 1686 which produced scattered reports of minor damage on the ground (References 4-6). Historically, death and property damage from space launches has greatly exceeded that from reentering orbital debris.

Since most small debris probably disintegrate in the upper atmosphere and never reach the ground in a recognizable form, emphasis has been placed on the consequences of the reentry of large orbital debris. The NASA Safety Standard governing orbital debris, NSS 1740.14 (Reference 7), devotes an entire section to assessing the survival of space objects during reentry due primarily to the recommendation to remove space objects from low Earth orbits within 25 years from the end of mission. The NASA guideline on reentry debris recommends limiting the total casualty area of surviving debris to 8 m^2 per event, a value linked to an average risk of human casualty of no more than 0.0001 per reentry event (References 8 and 9). One of the principal objectives of this study was to determine if natural reentries of large orbital debris, including spacecraft, upper stages, and their components, are uniformly dispersed over the globe, taking into account inclination/latitude restrictions. The effects of known asymmetries in the Earth's atmosphere and gravitational field were particularly targeted for investigation. The influence of time in orbit was also of interest.

The essential reentry data for this study was provided by U.S. Space Command in Colorado Springs, Colorado, employing the assets of the SSN and other national technical means. As a standard operating procedure, U.S. Space Command executes a reentry assessment (formerly known as a tracking and impact prediction or TIP) on objects with a radar cross-section of 1 m^2 or greater as well as other objects of interest. This process normally begins 1-2 weeks prior to the initially projected reentry date, and reentry time and location predictions are typically issued at T minus 10 days, 7 days, 4 days, 2 days, 1 day, 12 hours, 6 hours, and 2 hours, followed by a final, post-event assessment report. Figure 3 graphically depicts such predictions leading up to the 18 May 1997 reentry of the Kosmos 2340 upper stage debris (International Designator 1997-015C, U.S. Satellite Number 24763) with an estimated mass of 300 kg.

3. Results of Reentry Analysis

A 52-month period (September 1992 - December 1996) was selected for the study period. During this interval approximately 950 reentries occurred, of which nearly 100 constituted directed de-orbits, i.e., performed reentry propulsive maneuvers. Of the remaining 850 natural orbital decays, slightly more than half fell below the 1 m^2 size threshold for reentry assessment by U.S. Space Command. For approximately 90% of the large orbital debris - a total of 331 objects - probable reentry locations, defined as upper atmospheric interface, were determined by U.S. Space Command and forwarded to the NASA Johnson Space Center for analysis.

These man-made satellites, representing 550 metric tons (or > 10 metric tons per month on average), included 46 spacecraft, 180 upper stages, and 105 miscellaneous debris. An examination of the reentry location distribution by hemisphere revealed only a minor asymmetry with 187 (56.5%) reentries in the Northern Hemisphere compared with 144 (43.5%) reentries in the Southern Hemisphere. By category, upper stages exhibited almost exactly the average hemispherical distribution (56.7% to 43.3%), whereas payloads demonstrated a reverse trend (43.5% to 56.5%) and debris displayed an even sharper distinction (61.9% to 38.1%).

Since distribution based solely on satellite category lacked credibility, further analysis was performed. The database was divided into roughly equal sections with orbital lifetimes greater than 30 days (161 objects) and those with orbital lifetimes less than or equal to 30 days (170 objects). For objects in orbit more than one month, the probability of reentering in the Northern or Southern Hemisphere was essentially equal: 51% to 49% (Figure 4). However, for objects in orbit for one month or less, the percentages of Northern and Southern Hemisphere reentries were sharply different: 62% to 38% (Figure 5). This asymmetry can be attributed to the fact that all space launches during the period were from Northern Hemisphere sites and a considerable majority of short-lived ($\leq$ 30 days) space objects possess initial arguments of perigee in the Northern Hemisphere. The older orbital debris population is characterized by a more uniform distribution of arguments of perigee and, hence, a more even distribution of hemispherical reentry points.

Within a hemisphere, the latitude band of reentry is a function not only of the argument of perigee but also of the orbital inclination. Figure 6 depicts the number of reentries by 15° intervals. More than 40% of natural reentries begin in the Northern Hemisphere between 0 and 45°, where the majority of the world's population resides. Note, however, that the actual impact points of surviving debris will normally be several hundred kilometers downrange from the calculated reentry point.

4. The Survivability of Large Orbital Debris

As noted early in this paper, most natural reentries involve small objects which are likely to survive the atmospheric reentry process. Of those which do reach the surface of the Earth, in whole or in part, more than 70% will impact bodies of water, as seen in Figures 4 and 5. Even objects which hit land probably will come to rest in sparsely populated regions like Siberia, the Canadian tundra, or the Australian outback due to their large expanses. Hence, the actual hazard to people and property on Earth remains slight.

Fully 80% of the mass of all objects in this study was found in abandoned upper stages, which may possess a mass of four metric tons or more. Although historically upper stages have been assumed to largely disintegrate during reentry, the early 1997 reentry of a Delta 2 second stage clearly demonstrated that this is not always the case. In the early morning hours (local) of 22 January the 930-kg Midcourse Space Experiment (MSX) upper stage (International Designator 1996-024B, U.S. Satellite Number 23852) fell back to Earth over the central United States, sending debris over Oklahoma and Texas.

The two largest pieces recovered were the stainless steel propellant tank (mass ~230 kg) and a titanium pressurant sphere (mass ~30 kg). The propellant tank (Figure 7) landed near Georgetown, Texas (30.6° N, 97.6° W), and the sphere came to rest near Seguin, Texas (29.6° N, 98° W). A third, very lightweight fragment landed in Tulsa, Oklahoma, as noted in Section 2. Interestingly, this last piece of debris landed considerably uprange and about 30 minutes after the other two, apparently due to a high area-to-mass ratio. The ORSAT computer simulation of the descent trajectories of the two large objects confirmed their probable survivability and verified their downrange separation, assuming a standard breakup altitude of 78 km (Figure 8). The three other titanium spheres which were part of the upper stage are believed to have fallen in Texas unnoticed. The character of all three of the recovered debris did not suggest any connection with a launch vehicle or space object, leading one to theorize that most such debris, if found, is misidentified.

The imminent reentries of Kosmos 398 (mass ~2500 kg) in December 1995 and of the FSW 1-5 capsule (mass ~700 kg) in March 1996 prompted several reentry specialists from around the world to share tracking data and reentry point projections. Special command posts were established in the U.S., the Russian Federation, Europe, and Japan to exchange information on a near-realtime basis. The Inter-Agency Space Debris Coordination Committee (IADC), a group of orbital debris experts representing the major space agencies of the world, has since taken up the issue of the uncontrolled reentry of risk objects, defined as objects with hazardous materials on board or of a mass and design which is likely to result in significant debris reaching the surface of the Earth. After the Mars-96 accident in November 1996, the Gore-Cernomyrdan Commission also pledged to investigate the possibility of a more direct exchange of information on reentering risk objects in the future.

Currently, however, the accuracies of reentry propagations are inadequate to support precise impact predictions. The largest uncertainties arise from incomplete information about the attitude and stability of the object during reentry and about atmospheric density variations. An error of only two minutes in reentry time may translate into a shift of impact location of 1,000 km. In the case of the reentry of the FSW 1-5 capsule, the last predictions by U.S., Russian, and European specialists were off by approximately half an hour, which corresponds to one-third of a revolution about the Earth - a difference of more than 13,000 km. Moreover, the dispersal pattern of debris impacts from a single reentry can easily stretch over hundreds of kilometers, as seen with the MSX upper stage reentry.

5. Summary

The historical assumption of random reentry by naturally decaying satellites has been verified for objects in Earth orbit for more than 30 days. However, for objects with orbital lifetimes of less than 30 days, which represent 51% of all large orbital debris studied, a bias for Northern Hemisphere reentries was found. No discernible effects of atmospheric or gravitational variations were identified. Although the survivability of components of large orbital debris may be underestimated, the risk to people and property from reentering objects is remote. The ability to predict accurately the reentry time and location of orbital debris more than a few hours prior to the event remains a challenge to space surveillance specialists.

6. Acknowledgment

The assistance of Lt. Gary Mathis (USN) of U.S. Space Command in compiling the reentry location database is gratefully appreciated.

7. References

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2. N. Marshall, "Strange Object Hits Tulsa Woman After Bright Flash in Sky", *Tulsa World*, 23 January 1997, pp. A-1, A-3.

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8. *Ibid.*, pp. 7-1 through 7-7.

9. S. A. Bouslog, K.-C. Wang, B. P. Ross, and C. B. Madden, *Reentry Survivability and Risk Analysis*, JSC-27232, NASA Johnson Space Center, September 1995.

Figures

1. Annual number of cataloged satellite reentries.

2. Demise altitude of spheres as a function of material and diameter.

3. Prediction errors prior to the reentry of satellite 1997-015C.

4. Assessed reentry locations of naturally decaying orbital debris with lifetimes greater than 30 days, September 1992 - December 1996.

5. Assessed reentry locations of naturally decaying orbital debris with lifetimes equal to or less than 30 days, September 1992 - December 1996.

6. Large orbital debris reentry locations by latitude band.

7. MSX upper stage propellant tank at impact site near Georgetown, Texas, January 1997 (NASA Johnson Space Center photo number S97-03205, taken by author).

8. ORSAT computer simulation of the descent trajectories of two surviving objects from the MSX upper stage.

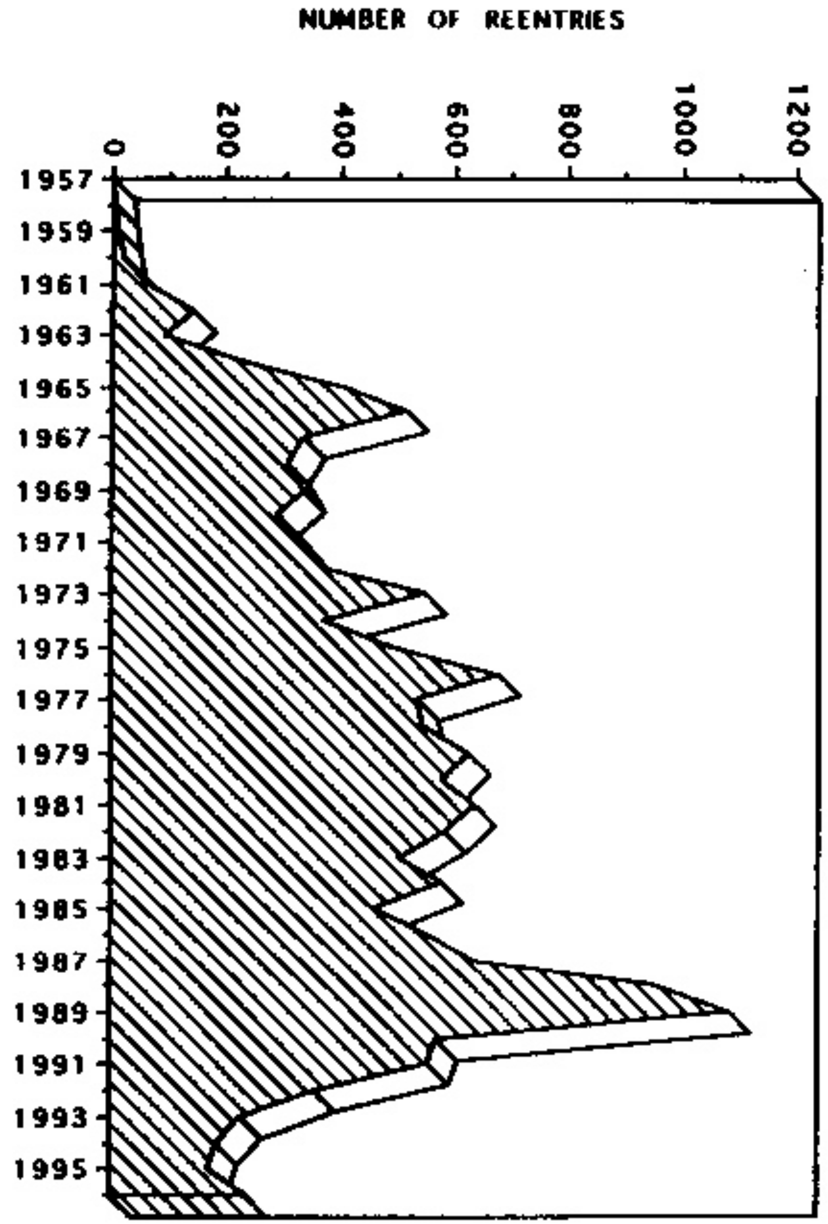

NUMBER OF REENTRIES
0
200
400
600
800
1000
1200
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995

Figure 1

DEMISE ALTITUDE AS A FUNCTION OF DIAMETER OF SOLID SPHERE FOR VARIOUS MATERIALS USING MORSAT

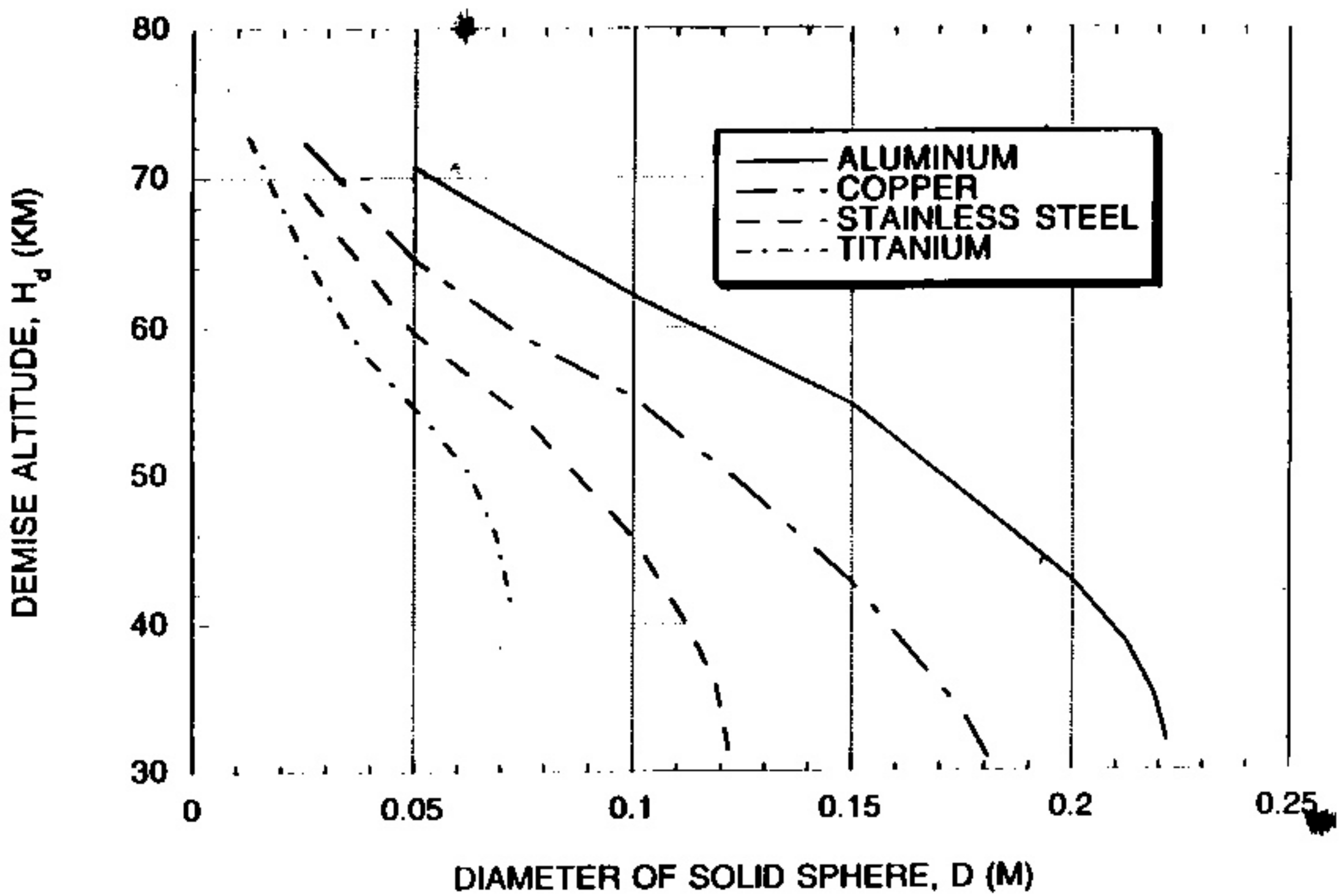
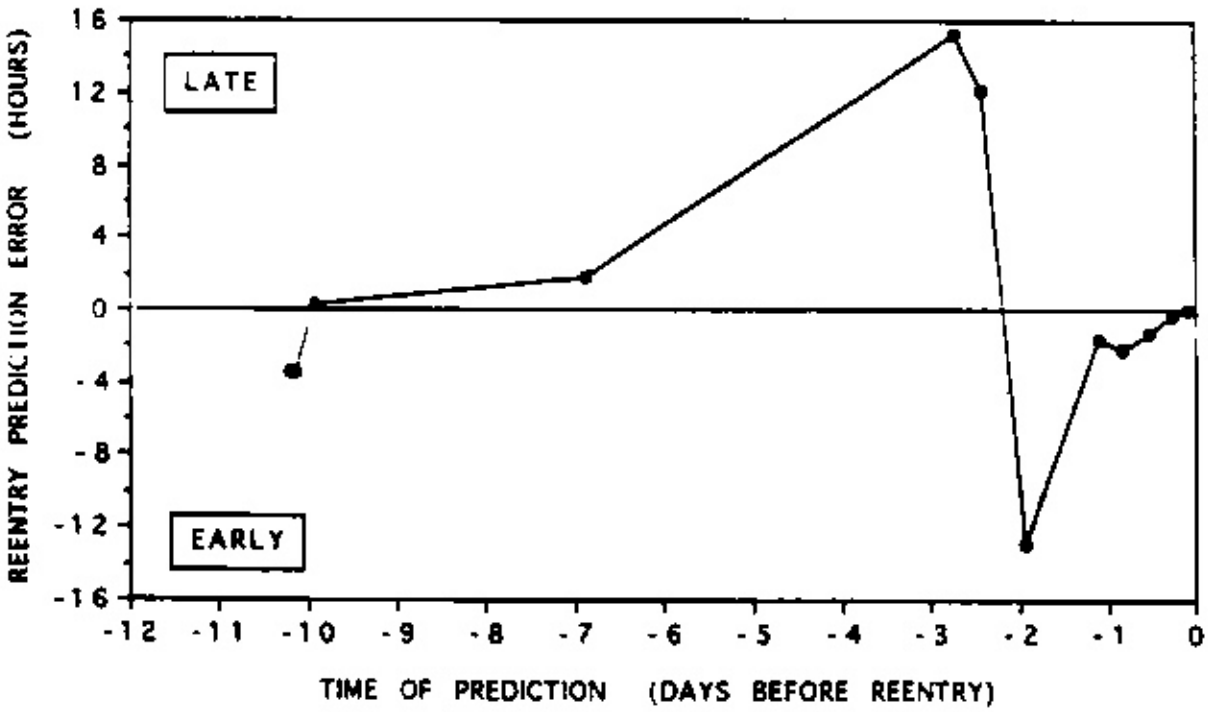


Figure 2

Figure 3



LATE
EARLY
16
12
8
4
0
-4
-8
-12
-16
REENTRY PREDICTION ERROR (HOURS)
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
TIME OF PREDICTION (DAYS BEFORE REENTRY)

>30 Day Lifetime Reentries : 1992-1996

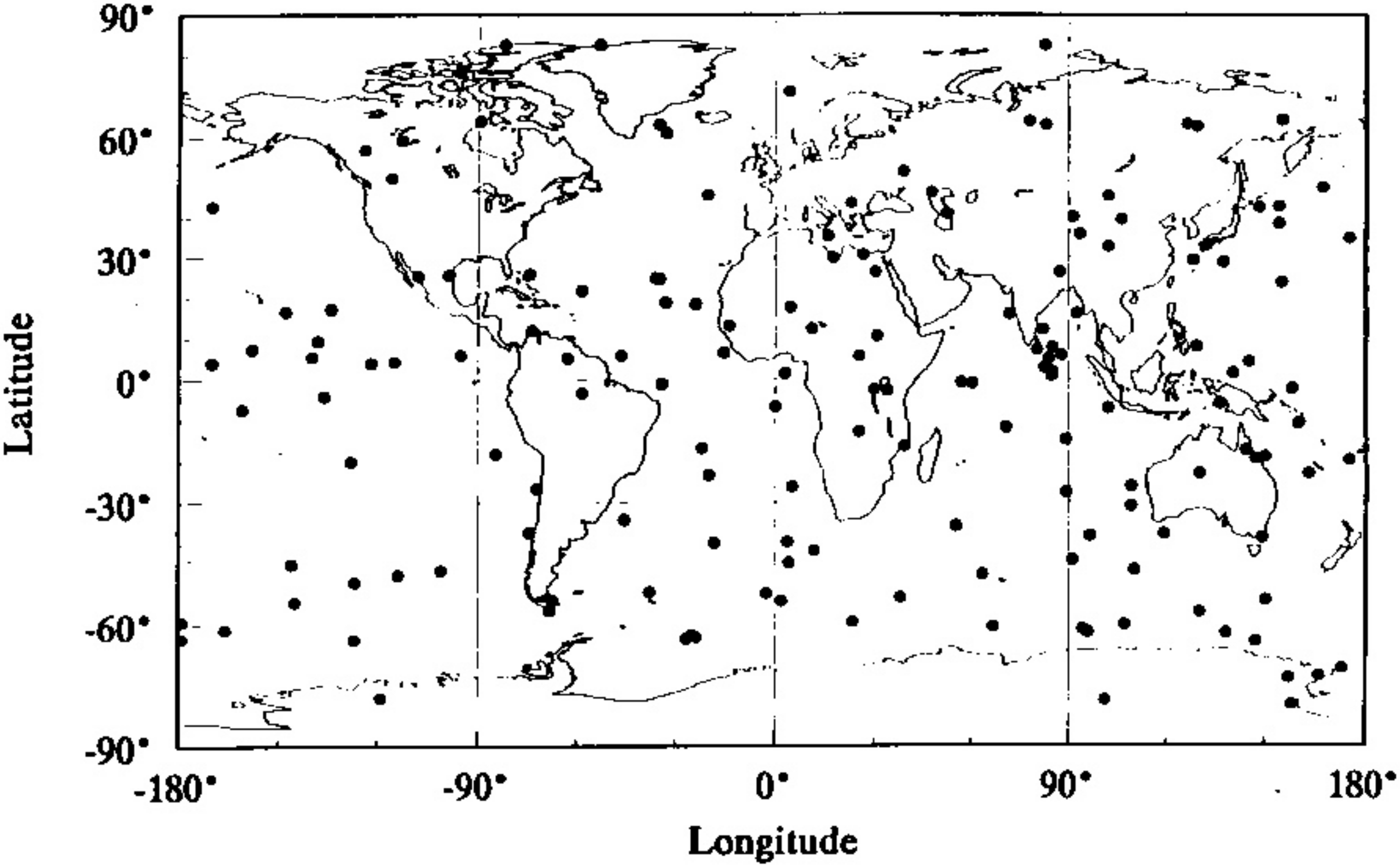


Figure 4

<30 Day Lifetime Reentries : 1992-1996

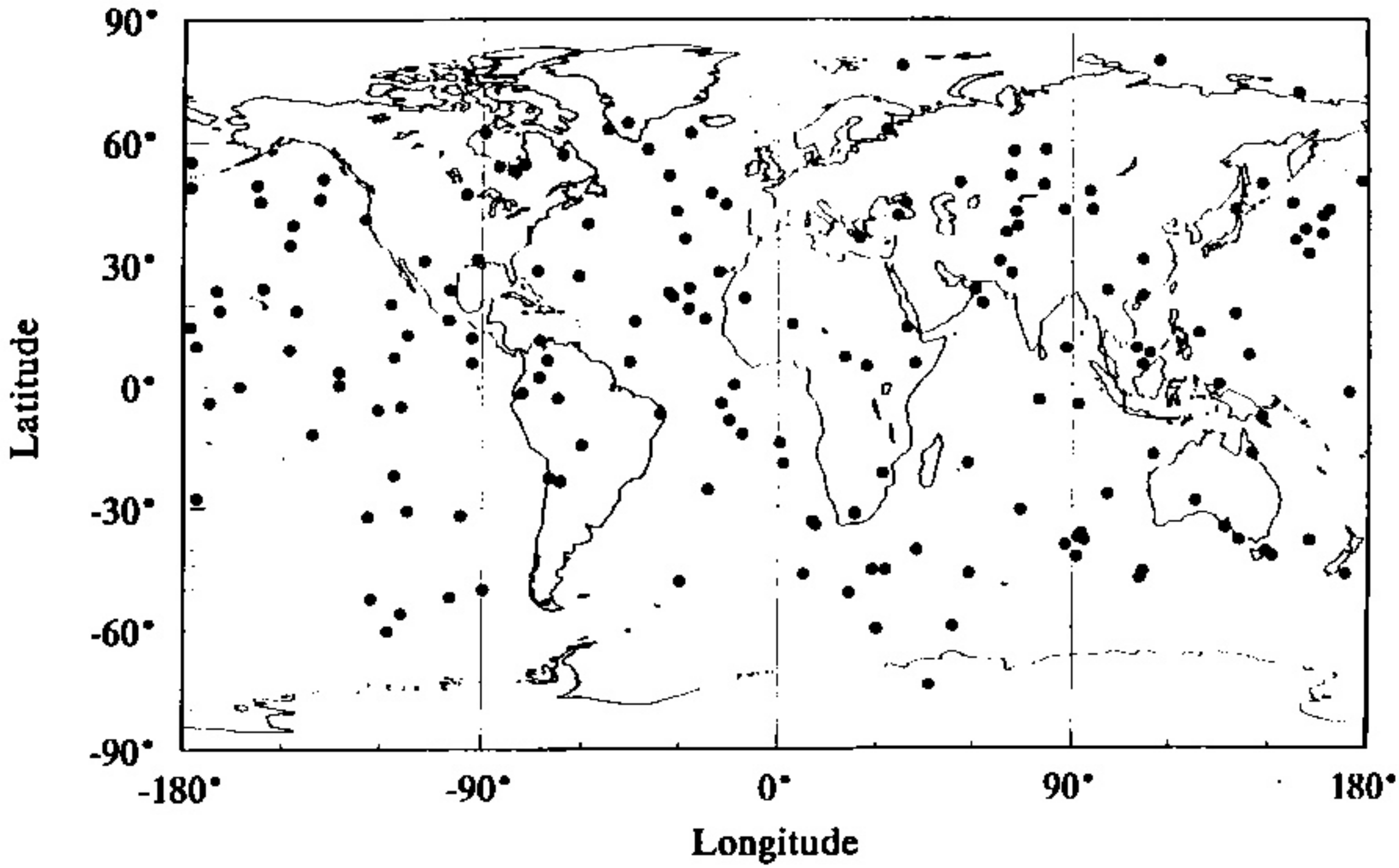
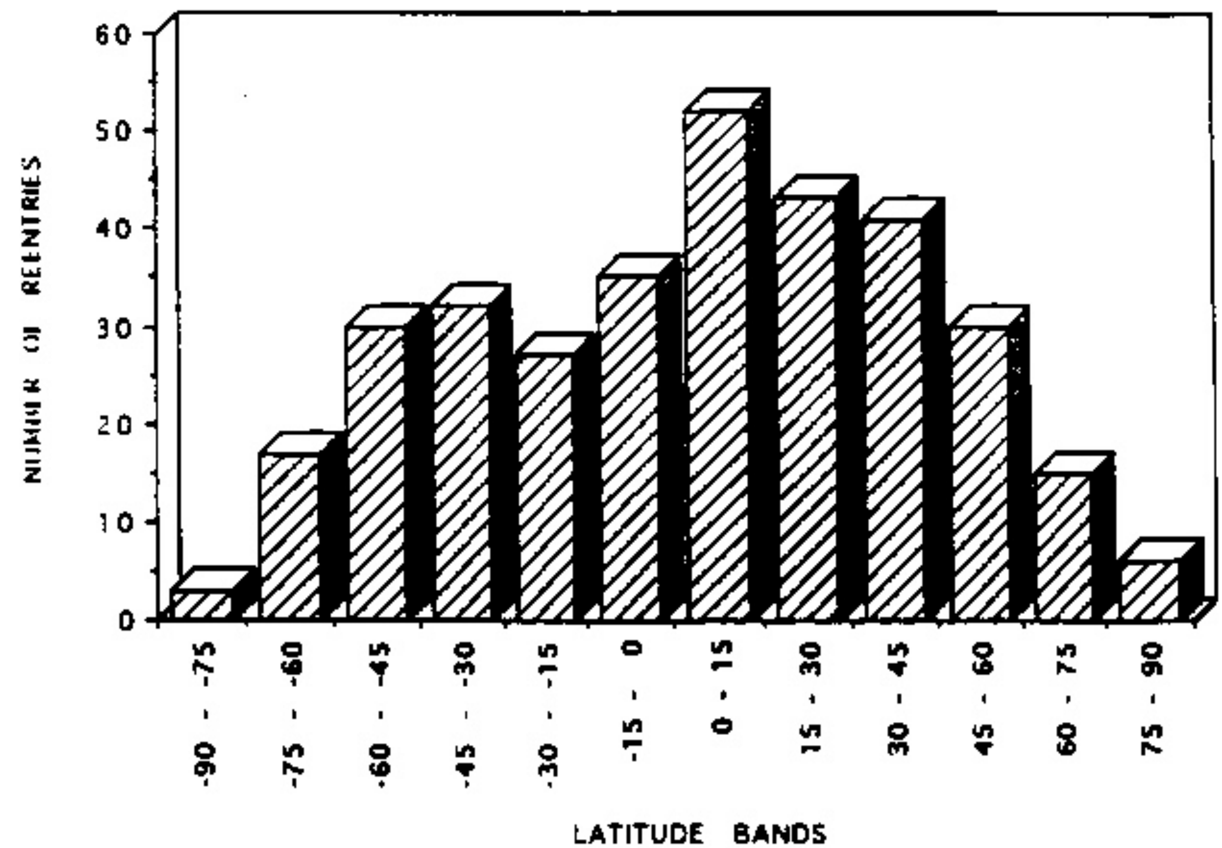
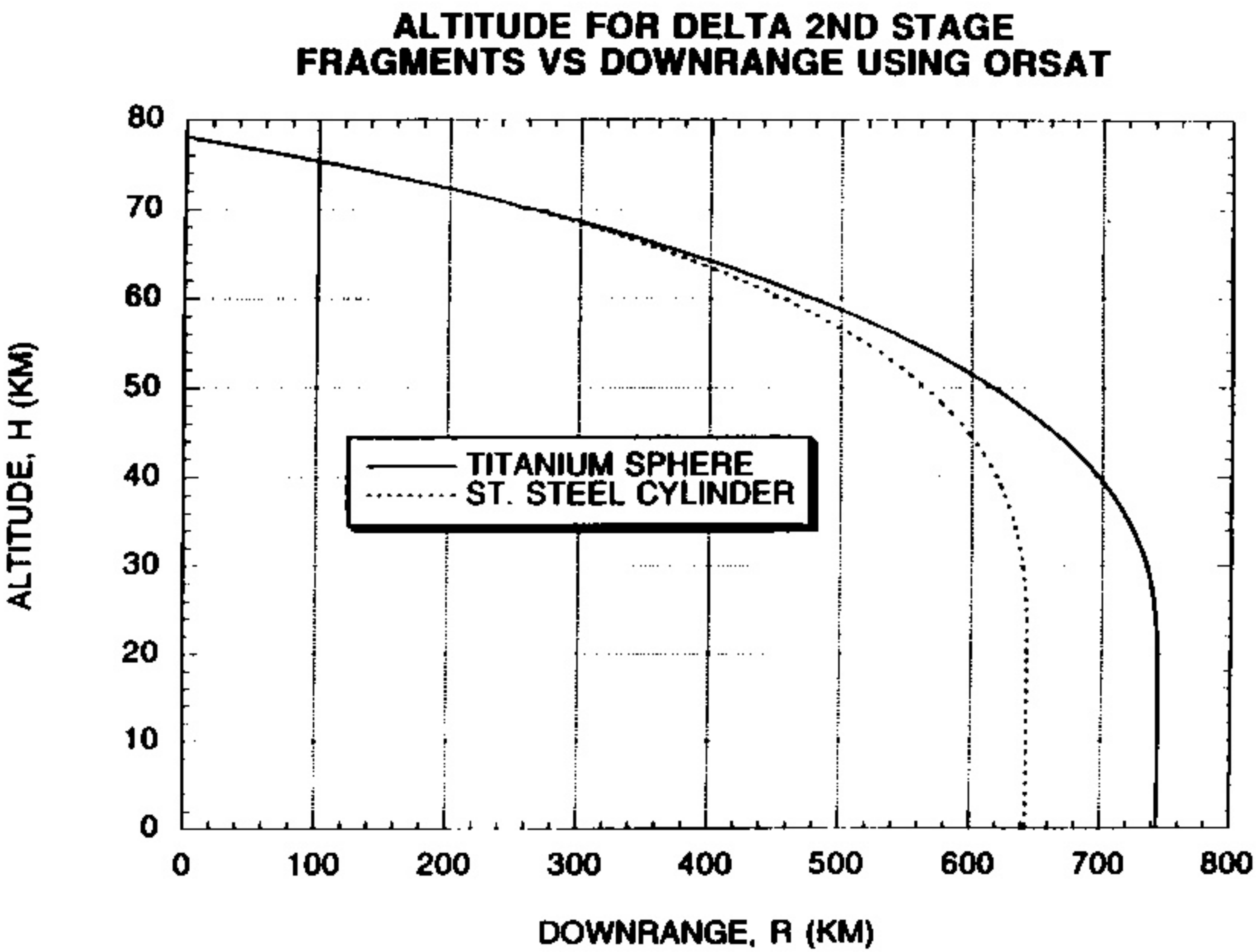


Figure 6



NUMBER OF REENTRIES
0
10
20
30
40
50
60
-90 - -75
-75 - -60
-60 - -45
-45 - -30
-30 - -15
-15 - 0
0 - 15
15 - 30
30 - 45
45 - 60
60 - 75
75 - 90
LATITUDE BANDS

Figure 7



ALTITUDE FOR DELTA 2ND STAGE
FRAGMENTS VS DOWNRANGE USING ORSAT
ALTITUDE, H (KM)
80
70
60
50
40
30
20
10
0
100
200
300
400
500
600
700
800
TITANIUM SPHERE
ST. STEEL CYLINDER
DOWNRANGE, R (KM)

Figure 8

August 4, 1997

Nick

This is an interesting paper.

It might be worthwhile to identify the launch risks by citing the Long March failure of last year and the associated deaths.

Aerospace and the Foreign Technology Division for many years collected everything they could. The thing I remember is that most of what was recovered were spherical or ellipsoidal tanks and they appeared to survive because they were heavier metals which spun and distributed the heat load while other shapes heated and melted. It might be interesting to see if they have some comparable geographic distribution data.

In the analysis by category there is no discussion as to whether the >30 and <30 day populations had the same composition of s/c, u/s and debris. Are not most of the objects with less then 30 days upper stages or operational debris rather than spacecraft?

The terminology as to distribution by category "lacked credibility" (p. 3) seems a poor choice, I think what you want to convey is that it doesn't provide any functionally useful insights.

In all of these comparisons would it be useful to do Chi square to evaluate probabilities?

Figure 1 would be enhanced if one overlaid the solar cycle to illustrate that 92-96 was a period near solar minimum.

Figure 2 needs a definition of demise altitude.

Figure 3 needs a change of scale for the last 24 hours; the figure doesn't convey what the text says about the difficulty of predicting entry.

It might be well to make the point that the entries 1992-1996 is the date of entry and that many of the launches occurred in earlier years. What was the distribution of launch dates? It might also be worth noting this four year interval had minimal LEO activity compared with the 60's and what is ahead.