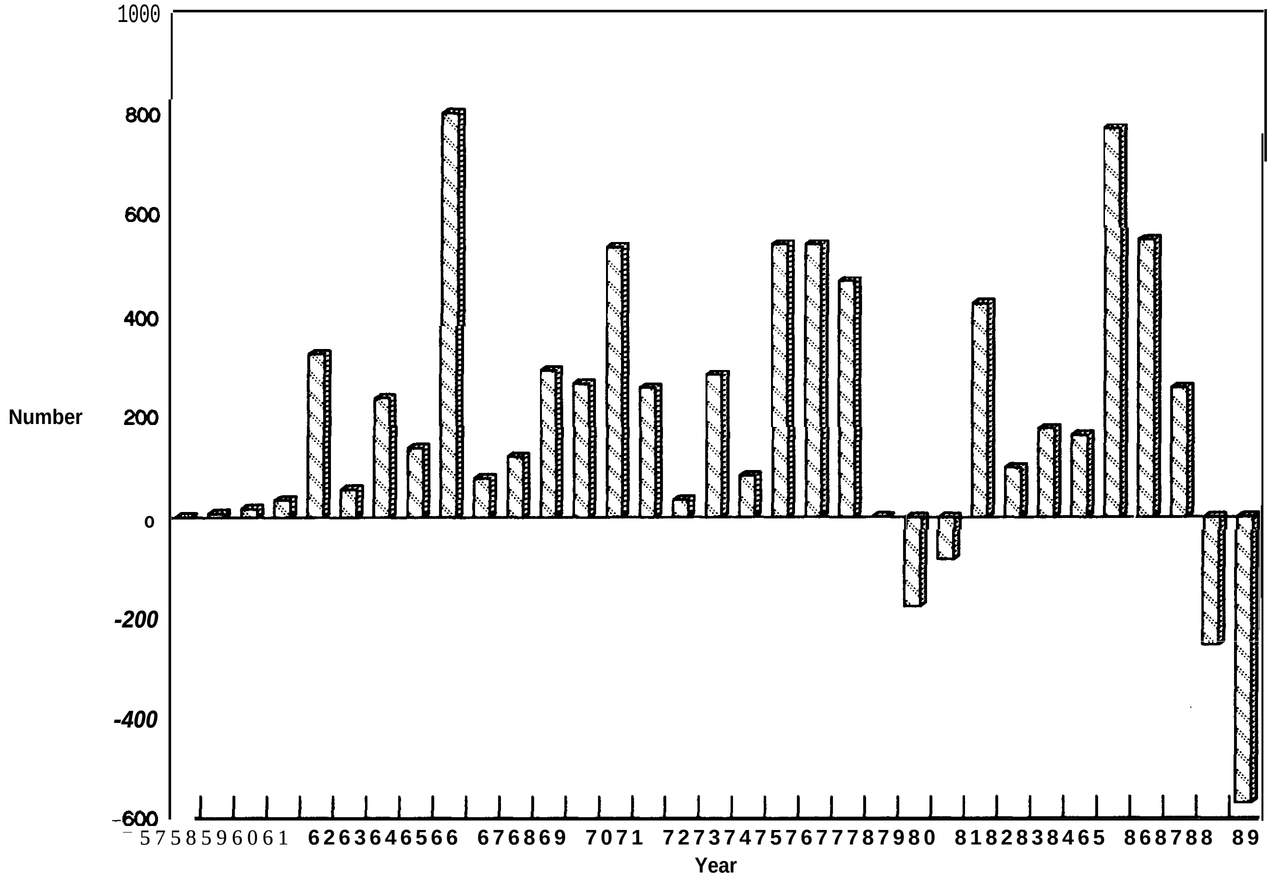
Figure 3-Yearly Changes to the Cataloged Debris Population



The chart illustrates the yearly additions or deletions from the cataloged debris population, which average about 240 per year. The increases are mainly a function of sateilite breakups rather than changes in the International launch rate. The reductions of the debris population which occurred in the periods 1979-81 and 1988-present resulted primarily from increased solar activity, which expands Earth's atmosphere and increases drag on space objects in LEO

SOURCE: Darren S McKnight, 1990

broader audience. Additional educational efforts, many already underway (box 3), are needed on all levels to assist in dispelling some of the misconceptions about orbital debris.

THE ORBITAL DEBRIS ENVIRONMENT

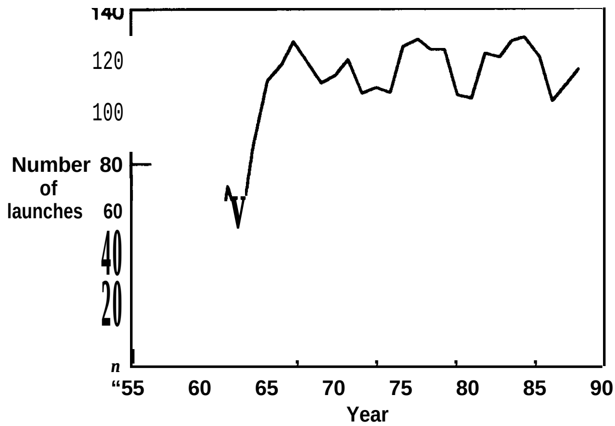
Space debris can interfere with scientific, commercial, and military space activities. In some orbits, debris deposited today may affeet these activities far in the future. This section describes the hazards posed by orbital debris and summarizes how they are generated.

Hazards to Space Operations From Orbital Debris

Functioning spacecraft face a variety of potential hazards from orbital debris:

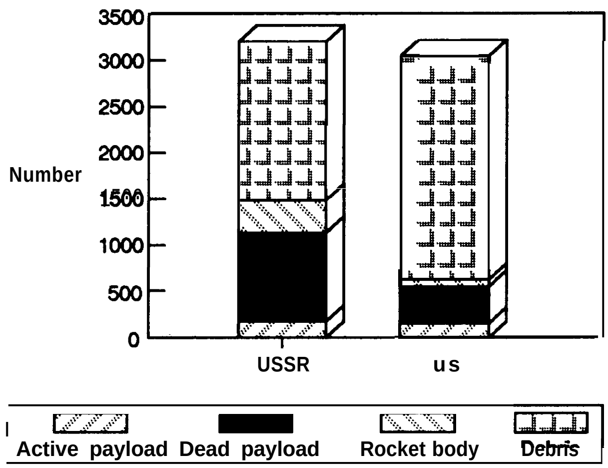
- *Collisions* of space debris with functional satellites could result in damage that could significantly impair the perform-

Figure 4-Annual Launch Rate By All Nations



SOURCE: Darren S. McKnight, 1990.

Figure 5-U.S. and U.S.S.R. Contributions to the Orbital Population of Cataloged Objects



This chart shows that the Soviet Union has nearly an identical number of active payloads as the United states but the Soviets have many more inactive payloads and spent rocket bodies in orbit than the United States.

SOURCE: Darien S. McKnight, 1990.

Box 3-Selected U.S. Efforts *To Increase Awareness of Orbital Debris*

- ***Orbital Debris Monitor-A*** commercial newsletter devoted to promoting an awareness of space environment problems.[1]
- American Institute of Aeronautics and Astronautics (AIAA)/NASA/DOD Conference in Baltimore, April 1990.
- International Institute of Space Law (IISL) meeting: "Environmental Implications and Responsibilities in the Use of Outer Space," during the 40th meeting of the International Astronautical Federation, Malaga, Spain, October 1989.[2]
- On March 30,1989, the IISL sponsored a meeting for delegates to the Legal Subcommittee of the U.N. Committee on the Peaceful Uses of Outer space.[3]
- ***Short Course*** on orbital debris at the 1990 AIAA Astrodynamics Conference, Portland, Oregon, August 1990.
- The American Institute of Aeronautics and Astronautics has established a Committee on Space Debris.
- The International Astronomical Union has established a Working Group on Interplanetary Pollution (Commission 22).

SOURCE: Office of Technology Assessment, 1990.

[1]Available from: Orbital Debris Monitor, P.O. Box 136, USAF Academy, CO 80840-0136.

[2]Papers published in the *Proceedings of the 32nd International Colloquium on the Law of Outer Space.*

[3]Published in *Proceedings of the 32nd International Colloquium on the Law of Outer Space.*

ance of a spacecraft or its subsystems. For example, according to one calculation, the Hubble Space Telescope, which was launched in April 1990, faces a chance of one in one hundred of being severely damaged by orbital debris during its planned 17-year lifetime.[37] Orbital debris has already hit active payloads.[38] Af-

[37]Michael Shera and Mark Johnston, "Artificial Earth Satellites Crossing the Fields of View of, and Colliding With, Orbiting Space Telescopes," *Publications of the Astronomical Society of the Pacific,* vol. 98, pp. 814-820, 1986.

[38]B. Cour-Palais, "Shielding Against Debris," *Aerospace America,* June 1988, p. 24. Examination of insulation blankets and aluminum louvers taken from the Solar Maximum Mission satellite (Solar Max) revealed 1,9(M) holes and pits rangingin diameter from 0.004 to 0.03 centimeters. Over half of these can be attributed to particles of artificial debris, many of which were aluminum oxide particles.

ter the reentry of Kosmos 954 in 1978 a Soviet spokesman attributed the fall to an earlier (January 1978) collision with another object.[39] Kosmos 1275 may have been completely destroyed by collision with space debris.[40] Further, evidence derived mainly from statistical analyses of the increases in orbital debris and from other circumstantial evidence suggests that the fragmentation of some spacecraft may have resulted from high velocity impacts.[41] Given that the capability of tracking technology decreases as the altitude of the tracked objects increases, there is no way to establish if collisions have occurred in GEO,[42] where the current ability to catalog fragments is limited to objects larger than about one meter (see below).

- *Pollution* in the form of gases and particles is created in the exhaust clouds formed when second stage rockets are used to boost a payload from LEO into GEO. A single solid rocket motor can place billions of particles of aluminum oxide into space, creating clouds that may linger up to 2 weeks after the rocket is fired, before dispersing and reentering the atmosphere. The particles therefore represent a significant threat of surface erosion and contamination to spacecraft during that period.[43]
- *Interference* with scientific and other observations can occur as a result of orbital debris. For example, the combination of byproducts from second stage firings – gases, small solid particles and "spaceglow" (light emitted from the gases) – will often affect the accuracy of scientific data.[44] Debris may also contaminate stratospheric cosmic dust collection experiments or even interfere with the debris tracking process itself.[45] The presence of man-made objects in space complicates the observations of natural phenomena.[46] Astronomers are beginning to have difficulty determining whether an object under observation is scientifically significant or if what they observe is just apiece of debris. As the number of debris particles increases, the amount of light they reflect also increases, causing "light pollution," a further interference with astronomers' efforts. Space debris has also disrupted reception of radio telescopes and has distorted photographs from ground-based telescopes, affecting the accuracy of scientific results that might be obtained.[47]

The Nature of Space Debris

Since the first satellite break up in 1961, nearly 100 satellites have violently fragmented in orbit. Over 20,000 objects have now been cataloged by the SSN, with nearly 35 percent of this compilation a result of these breakup events (as of January 1990).[48] Cur-

[39] Johnson and McKnight, op. cit., footnote 9, p. 93.

[40] Darren S. McKnight, "Determining the Cause of A Satellite Fragmentation – A Case Study of the Kosmos 1275 Breakup," presented at the 38th Congress of the International Astronautical Federation, Brighton, U.K., 1987.

[41] Johnson and McKnight, op. cit., footnote 9, pp. 19-20.

[42] National Security Council, op. cit., footnote 2, p. 8.

[43] A.C. Mueller and D.J. Kessler, "The Effects of Particulates From Solid Rocket Motors Fired in Space," *Advances in Space Research*, vol. 5, 1985, pp. 77-86,

[44] Donald E. Hunton, "Shuttle Glow," Scientific *American*, vol. 261, No. 5, pp. 92-98.

[45] National Security Council, op. cit., fOOtnOte 2, p. 14.

[46] Paul Maley, "Specular Satellite Reflection and the 1985 March 19 Optical Outburst in Perseus," *The Astrophysical Journal*, vol. *317*, pp. L39–L44, June 1, 1987.

[47] Lubos Perek, "Impact of the Development of Space Technology on the Law of Outer Space, "Proceedings *of the 32nd Colloquium on the Law of Outer S'* (Washington, DC: American Institute of Aeronautics and Astronautics, 1990); International Astronomical Union Colloquium No. 112 on Light Pollution, Radio Interference, and Space Debris, Aug. 13-16, 1988.

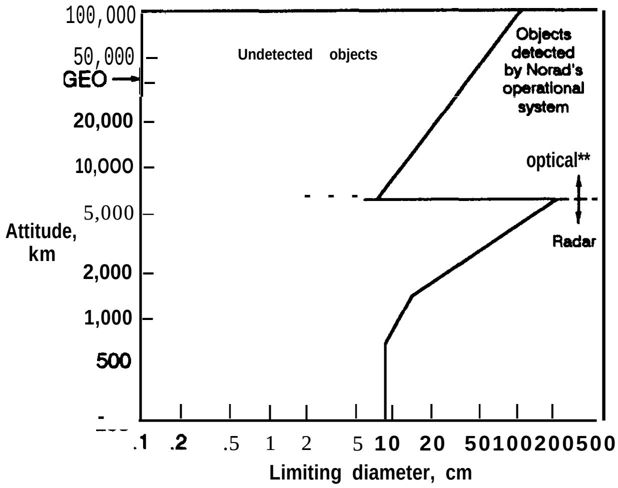
[48] Johnson and Nauer, Op. Cit., footnote 6.

rently the SSN follows about 6,500 cataloged objects. However, in LEO the SSN is limited to tracking objects 10 centimeters in diameter or larger (figure 6). Some analysts estimate that some 30,000 to 70,000 additional debris fragments ranging in size from 1 to 10 centimeters are also in orbit around Earth.[49] The probabilities of collision with these objects depends on the density of debris objects in different orbits, their relative velocities, and the cross section of the spacecraft.[50]

- *Low Earth Orbits* (LEO)
  Objects in LEO pose the greatest concern because these orbits are used the most. The very low orbits (up to about 500 kilometers) are self-cleaning within a few years; debris there encounters the upper reaches of Earth's atmosphere and bums up or falls to Earth in a short time. Although only about 39 percent of the cataloged debris resulting from spacecraft breakups is still in orbit (as of January 1990), continued contributions to orbital debris would replenish debris washed out by atmospheric drag. In fact, most debris in very low orbits derives from objects that decay slowly from higher orbits (termed "rain down").

- *Medium Earth Orbit* (MEO)
  The lifetimes of objects in MEO are extremely long. Because the spatial density of objects is low, and these orbits are used less frequently than LEO and geosynchronous orbit (GSO), debris poses less of a concern today than in other orbits. However, nations are placing an increasing number of spacecraft in these orbits, leading to future concerns. Because spacecraft last so long in these orbits, the increasing population in them could pose a possible threat to future space operations, especially in the Sun-synchronous orbits used for navigational satellites.

Figure 6- Detection* Capabilities of the Space Surveillance Network



● Once detected, an object may be tracked at greater range (altitude) than indicated here. This figure indicates the approximate maximum range at which an object may be detected by an optical or radar system operating in search mode.
● *The ability to detect space debris optically is highly dependent on the optical characteristics of the debris.

SOURCE: National Aeronautics and Space Administration.

- *Geostationary Orbit* (GEO)
  GEO, a special case of GSO, is especially important because it is a limited natural resource[51] of considerable economic value[52] for satellite communications.

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[49] P. Eichler and D. Rex, "Chain Reaction of Debris Generation by Collisions in Space - A Final Threat to Spaceflight?" presented at the 40th Congress of the International Astronautical Federation, Oct. 7-12, 1989.

[50] V. A. Chobotov, "Classification of Orbits With Regard to Collision Hazard in Space," *Journal of Spacecraft and Rockets*, vol. 20, No. 5, September-October 1983, p. 484-490.

[51] The geostationary orbit has been declared a "limited natural resource that must be used efficiently and economically" – 1982 International Telecommunication Union Convention, art. 33.

[52] For a discussion of the economic importance of GEO, see U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities, OTA-ISC-239* (Washington, DC: U.S. Government Printing Office, July 1986), ch. 6.

This orbital band[53] contains a fast-growing spacecraft population, the result, primarily, of its economic and political importance for communications satellites and other commercial applications.

GEO has a current population of almost 400 trackable objects, including about 100 active communications and other satellites. The exact quantity of objects in GEO is not known, because objects smaller than about 1 meter are currently untraceable at that distance from Earth (figure 6). One analyst estimates that it may contain another possible 2,000 non-trackable objects.[54] Objects placed in GEO will effectively remain there forever if not intentionally removed. Yet, because objects in this orbit all move in the same general direction (toward the east) at low velocities relative to each other, collisions between active, controlled satellites, and derelict spacecraft that wander about in the orbit[55] would occur at moderately low relative velocities. As a result, experts estimate that the current hazard from orbital debris is less than the hazard from meteoroids passing through the orbit. Because of the lower velocities, chain reactions are less likely to occur than in LEO. However, as more active satellites are placed in this important orbit, and as greater numbers of uncontrolled, inactive satellites drift around in it, destructive collisions could become inevitable.[56] Destructive collisions will also be more probable as inactive satellites that drift throughout the GEO band gain increasingly higher velocities as a result of small gravitational and other forces. At current densities for GEO debris and satellites, some analysts estimate that a large functioning satellite (30 - 50 meters square) will experience a 0.1 percent chance of being hit during its total operational lifetime.

However, by the end of the century, if current trends for the number of satellites placed in GEO continue, that chance may increase dramatically to about 5 percent per year if no mitigating actions are initiated.[57] T If this estimate becomes reality, the typical satellite in GEO, which is expected to operate 10 years, would then experience a 40 percent chance of being struck by debris during its operational life.

Sources of Orbital Debris

Operational activities provide the source of much space debris, including the largest objects. Nearly 50 percent of the total mass of space debris derives from spent upper stages that are left in orbit after depositing their spacecraft in orbit. Individually, they are less massive than spacecraft, but present a relatively large cross-section to other space objects. Because upper stages are often placed in high, long-lived orbits,[58] they can become a major source of debris. The exhaust from solid rocket upper stages, which places small

[53] Strictly speaking, satellites in GEO deviate slightly from an ideal geostationary orbit, and travel in geosynchronous orbits somewhat inclined to the Equator. Their orbits thus define an orbital band about the Equator.

[54] D. H. Suddeth, "Debris in the Geostationary Ring, 'The Endless Shooting Gallery,'" *Orbital Debris*, NASA Conference Publication 2360, NASA, 19S5, pp. 349-364.

[55] Functional spacecraft are highly controlled by their operators. After control ceases, over time, &u? a result of solar pressure and perturbations from the gravity fields of the Earth, Moon, and Sun, non-functional spacecraft develop small additional velocities that send them both along and perpendicular to GEO. The result is that non-functional satellites will drift out of control along and across GEO.

[56] Donald J. Kessler, "Technical Issues Associated with Orbital Debris in GEO," *Orbital Debris Monitor*, vol. 2, No. 4, Oct. 1, 1989.

[57] Johnson and McKnight, op. cit., footnote 9, p. 80.

[58] For example, the upper stages that take spacecraft to geosynchronous transfer orbit (GTO) on their way to geosynchronous orbit, continue to travel in highly eliptical orbits and spend most of their time far away from the Earth.

particles of aluminum oxide in orbit, can also be considered operational debris. Paint flakes and particles from thermal insulation are also released into space during space operations.

Conducting operations in space has also resulted in the ejection of miscellaneous hardware into orbit. For example, spacecraft are generally separated from their upper stages by explosive devices that may eject dozens of small fragments. In addition, the process of deploying a spacecraft on orbit often involves the release of protective shields, covers, and other incidental hardware items. Even ice from the Shuttle waste management system has been suspected of contributing to orbital debris.[59] Finally, inactive spacecraft that have remained in space beyond their useful lives also contribute to the debris population.

Fragmentation is the most significant source of orbital debris by number. Since 1961, 25 breakups have contributed more than 100 cataloged fragments apiece; eight events exceeded 240 pieces each.[60] What makes fragmentation such a hazard is the continual spread of fragmentation remnants about the center of mass of the original spacecraft (box 4). Fragmentation derives from a variety of causes that fall into three general classes: accidental failures related to the propulsion systems, deliberate actions, and unknown causes.

- ***Propulsion-related failures*** often produce a striking amount of debris because they result from explosions of the propellant, either while carrying spacecraft into high orbits, or, in the case of liquid-fueled rockets, afterward, because some propellant is left in the stage. Some of the latter explosions have occurred from several months to 3 years after the stages delivered their spacecraft to orbit.[61] The chances of such explosions have been greatly reduced; ESA Japan, and the United States now often vent their upper stages following payload delivery.
- *Deliberate destruction* of satellites in space, as opposed to accidental explosion, is another source of orbital debris; most of these have been carried out by

Box 4– ***The Evolution of a Debris Cloud***

Prior to breakup, a satellite follows a fairly well-defined elliptical path about Earth. After a fragmentation, whether caused by structural failure, explosion, or external impact, a debris cloud will expand over time, eventually creating a wide toroidal band about the earth.

The explosion or collision that causes the fragmentation of a satellite propels pieces of debris in all directions. Some debris will receive an impulse along the initial satellite orbit, some in opposition, and some at right angles. As a result of the velocities impartd to each fragment, the cloud will evolve into a toroidal cloud; it takes hours to days for an ensemble of debris fragments to reach this phase. Over time the torus will spread into a band about Earth, bounded only by the inclination and altitude extremes of the debris. This last phase will be reached months to years after the initial breakup. Figure 7 illustrates the evolution of a debris cloud. All satellites with an altitude within the cross-section of this wide toroidal band may encounter this debris cloud.

The rate at which the debris cloud moves into these phases is a function of the velocity imparted to the fragments: the greater the velocity, the more quickly the cloud evolves. The rate at which the cloud spreads is also a function of the parent satellite's altitude and inclination.

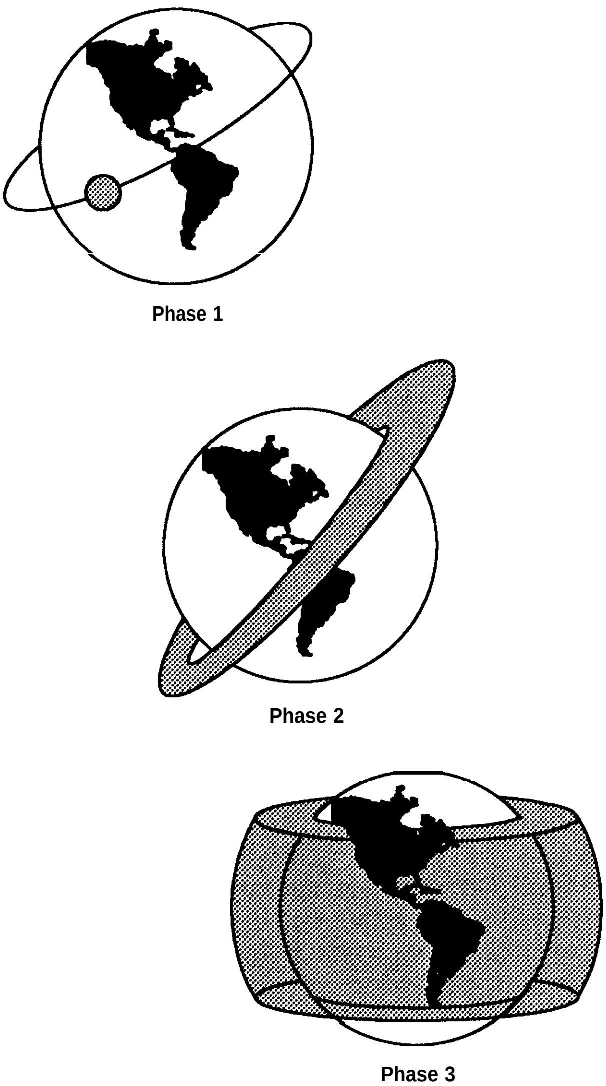
SOURCE: Darren S. McKnight, 1990.

[59] Analysis of a hole that extended through three layers of a 17-layer thermal blanket on the Solar Max satellite suggested that it may have been caused by ice from the Shuttle. L.S. Schramm, et. al., "Particles Associated with Impact Features in the Main Electronics Box (MEB) Thermal Blanket from the Solar Max Satellite," ***Lunar and Planetary Sciences***, vol. 17, 1986. Ice particles are, however, extremely short lived.

[60] Johnson and Nauer, op. cit., footnote 6.

[61] Explosions of the Delta ELV second stage have contributed a large number of debris fragments. See National Security Council, op. cit., footnote 2, pp. 17-18. A third stage of the Ariane launcher has also exploded in orbit. See Johnson, op. cit., footnote 32.

Figure 7-The Evolution of a Debris Cloud



SOURCE: Teledyne Brown Engineering, 1988.

the Soviet Union when its military satellites reach the end of their useful lives.[62] Some have come about as a result of space weapons testing. A total of 12 breakups are attributed to space weapons tests, which amount to about 7 percent of the current cataloged debris population. Table 3 lists each weapons test breakup and its impact on the near-Earth satellite population. However, table 3 does not reflect the total amount of debris produced by these events because small objects cannot be cataloged. Many fragments do not stay in orbit long enough to be cataloged. For example, 381 objects were detected as the result of the Delta 180 Strategic Defense Initiative Organization (SDIO) experiment of 1986, but only 18 were ever cataloged.

Hypervelocity impacts. The high velocity of some space debris relative to spacecraft gives the debris extremely high energy on impact with the spacecraft (figure 8). Such "hypervelocity" impacts[63] are much more probable in LEO, where collision velocities are higher (averaging about 10 kilometers per second) than in other orbits. Impacts involving relative velocities above about 5 kilometers per second generate such temperatures and pressures that the impacting materials may va-

Table 3-Space Weapons Tests

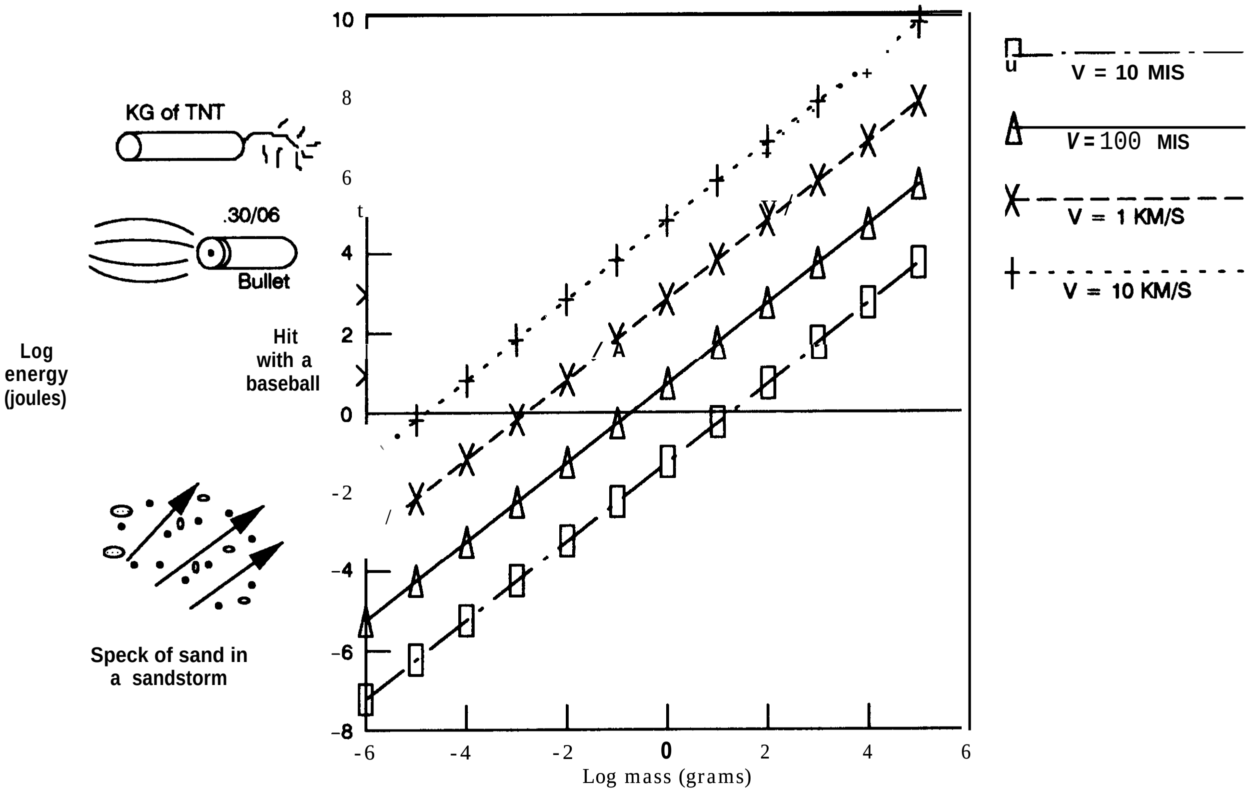
Class of breakups	No. of events	No. debris cataloged	No. debris in orbit
Phase 1:			
Soviet ASAT	7	545	296
Phase 2:			
Soviet ASAT	3	189	154
P-78 Breakup	1		
D-180 Test	1	18	0
	12	1,037	488

SOURCE: Nicholas L Johnson and D. Nauer, "History of On-Orbit Satellite Fragmentations," Teledyne Brown Engineering, CS88-LKD-001, 3d cd., Oct. 4, 1987; Nicholas L Johnson, personal communication, October 1989.

[62] Johnson and McKnight, op. cit., footnote 9, pp. 13-16.

[63] A hypervelocity impact is one that occurs at relative velocities greater than the speed of sound within the target (3-6 kilometers per second).

Figure 8-Relative Kinetic Energy Content of Space Debris Objects



SOURCE: Darren S. McKnight, 1990.

porize, producing hundreds of thousands of smaller debris objects, and gaseous products. The smaller objects themselves then become a hazard to other functioning satellites.

Lower velocity impacts create a special problem from a shielding perspective. If the object does not vaporize when it hits the outer shield, and remains relatively solid, successive layers are less effective in stopping it. In lower velocity collisions, all of the ensuing debris is likely to be large. There is no vaporization, and hence no molecular condensation.

Chain reactions. The most serious consequence of collisions with space debris is the possibility of a cascade effect,[64] or chain reaction, in which debris proliferates as collisions generate more and more debris, independent of any further introduction of man-made objects.[65]

Many current mathematical models indicate that if existing trends continue, a chain reaction of collisions, some involving hypervelocity impacts, could create a debris envi-

[64]Known as the Kessler effect. See Donald J. Kessler and B.G. CoursPalais, "Collision Frequency of Artificial Satellites: the Creation of a Debris Belt," *Journal of Geophysical Research*, vol. 83, 1978, pp. 2637-2646; D. J. Kessler, and S.Y. Su, "Contribution of Explosion and Future Collision Fragments to the Orbital Debris Environment," D. J. Kessler, E. Gruen, and L. Sehnal (eds.) "Space Debris, Asteroids and Satellite Orbits," Advances *in S' Research, vol. 5, No. 2,* 1986, pp. 2535.

[65]Val A. Chobotov, manager of the Space Hazards Section at the Aerospace Corporation in Los Angeles, estimates an 800 percent increase in collision hazards within the next 20 years. (Major John Graham, USAF, "Space Debris-A Definite Hazard to Hypersonic Flight" unpublished paper, 1988.