ronment that would make certain orbits in LEO unusable for most long-term operations. One model suggests that the critical population to support a chain reaction "is only about 2 to 3 times the current population and could be reached within 20 to 50 years."[66] However, the models used today, and the data that support these models, contain many uncertainties. Some debis experts question the modeling approaches taken to date.[67] Modeling technology needs improvement. In addition, observational and experimental data are needed to reduce uncertainties in data upon which the models are based.

Trends

Historically, the number of objects in the SSN catalog at the end of each year has been used to map trends in the population. Straightforward examination of limited portions of this catalog would lead to the conclusion that Earth's satellite population has grown at a rate of 5 percent per year. However, this rate does not entirely represent an increase in hazard; it also reflects an increase in our understanding of the hazard. A recent analysis has shown that delayed cataloging of debris significantly affects the determination of the cataloged growth rate.[68]

For example, because tracking techniques have improved, many of the objects added to the catalog in the 1980s were actually generated in the 1960s and 1970s but are just now being included. Figure 9 plots the history of the debris cataloged from the fragmentation of the Transit 4A (1961-Omicron) rocket body. This event was the first satellite breakup, occuring in 1961. For the last 20 years an average of 4 pieces have been added per year with over 40 fragments being added in the last 8 years.[69] The delay in cataloging these objects resulted from changes in operations, improvements in technology and, possibly, the orbital decay of the objects. Nevertheless, much of the increase in cataloged debris is the result of new contributions to the debris population.

From 1975 to 1985 the percentage of cataloged objects that are deep space objects (orbital period greater than 225 rein) has doubled from 7 percent to 14 percent.[70] Most of this growth is the result of increased activity in the geosynchronous region. Other growth results from additional surveillance and tracking sensors dedicated to these altitudes. The move toward placing spacecraft in higher altitudes is a positive trend for the cluttered LEO region. Yet, debris at higher altitudes will be more difficult to detect and will have longer orbital lifetimes. This trend may lead to an environment that will be more difficult to characterize and control.

DEBRIS REDUCTION STRATEGIES

More than 30 years of experience in designing and operating spacecraft has led to the development of a variety of strategies to limit the generation of new debris and to mitigate the effects of existing debris. These strategies vary in cost and effectiveness; overall, it is generally cheaper to limit the production of future debris than to cope with the economic losses that debris can inflict on functioning spacecraft.

[66] Eichler and Rex, op. cit., footnote 49, p. 1.

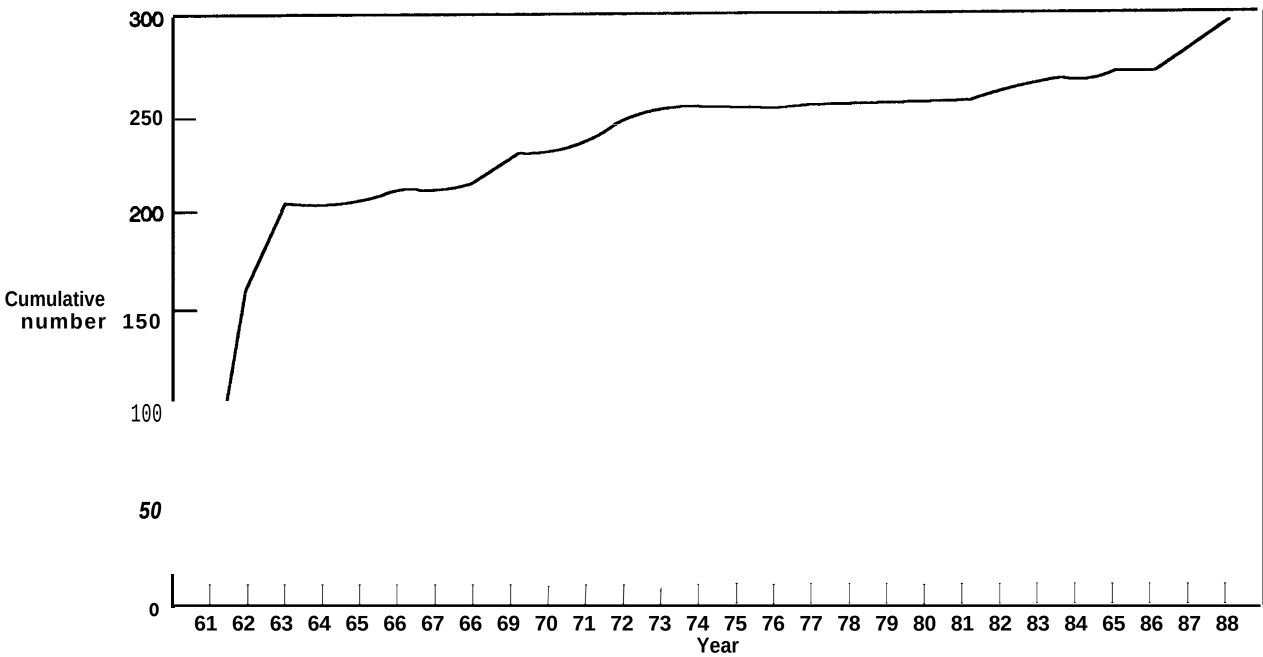
[67] Richard S. Hujsak, Applied Technology Associates, Inc., personal communication, July 1990.

[68] Darren S. McKnight, and Nicholas L. Johnson, "Understanding the True Earth Satellite Population," 40th IAF Congress, Malaga, Spain, October 1989.

[69] Ibid.

[70] W. Hall, "An Estimate of the Trackable In-Orbit Population Growth to 2010," SAIC Technical Report CS 386-S/89-1002/1C, Aug. 15, 19s9.

Figure 9-Debris Cataloged from the Breakup of the Transit 4A Rocket Body



SOURCE: Nicholas L.Johnson and David J Nauer, History of Om-Orbit Satellite Fragmentations,4th ed. (Colorado Springs, CO: Teledyne Brown Engineering, January 1990), NASA Contract, NAS 9-18209.

There are two basic classes of action that can minimize the orbital debris burden – *preventive measures* to preclude explosive failures of spacecraft and upper stages and eliminate placement in outer space of space debris objects, and *removal procedures,* which by reducing the number and mass of objects on orbit, reduce the probability and severity of on-orbit hypervelocity collisions.

Preventive Measures

The most effective near term measures are to design and operate launch vehicles and spacecraft so they have minimum potential for exploding or breaking up.[71] For example, launch vehicle upper stages should be depleted of propellants and pressurants after they have completed their mission. Batteries should include electrical protection circuits to preclude battery explosions resulting from electrical shorts. Such measures reduce or eliminate the potential for chemical explosions and reduce the severity of collisions when they occur because they also remove additional energy stored in the object. Since 1981, NASA has operated its upper stages in a manner that sharply reduces the likelihood that they would explode in space. Japan and ESA have recently adopted similar operational procedures. Costs of these procedures vary, depending directly on the design of upper stages and spacecraft, but can be measured in terms of the equivalent weight of

[71] National Security Council, op. cit., footnote 2, ch. 6.

spacecraft that would have to be given up to include such measures,[72] or the costs required to reduce the dry weight of a spacecraft.[73]

Other preventive measures include designing and building spacecraft so they resist environmental degradation from atomic oxygen and solar radiation, and devising spacecraft and upper stage separation procedures that limit the spread of operational debris. Abandoning the practice of deliberately fragmenting inactive satellites in orbits where atmospheric drag is extremely weak and debris life correspondingly long would contribute markedly to reducing generation of future orbital debris.[74]

In very low orbits (less than about 250 kilometers), atmospheric drag causes objects to fall into the atmosphere and burn up or plummet to the surface[75] over time scales of a few months to a year. Though extremely small, drag forces as far out as 500 to 600 kilometers will force space objects down over periods of a few years. High levels of solar activity[76] cause an expansion of Earth's upper atmosphere, leading to increased atmospheric drag and significant reductions in the debris population in LEO (figure 10). The reentry of the Solar Maximum scientific satellite on December 2, 1989, demonstrated this phenomenon.[77] The current cycle of increased solar activity, which has been especially strong, brought it down much sooner than expected.

The atmospheric drag experienced at these altitudes has been used on many occasions to remove upper stages and other objects that have completed their missions. For example, the Delta 180 experiment conducted for the Strategic Defense Initiative Organization[78] was carried out in low orbit so that the many small objects deployed as part of the experiment would be removed from orbit within a few days. With redesign of the upper stages, it would be possible to place upper stages in elliptical orbits that bring them into the upper reaches of the atmosphere at perigee, causing them to fall back to Earth (deorbit) relatively quickly.

Active Removal Procedures

A few observers have proposed active removal of existing debris. Some proposed methods would be prohibitively expensive and might even be counter-productive.[79] One proposed method would use an orbiting object with a very large cross section, perhaps a spherical balloon filled with some type of foam, to "sweep up" small debris over time.[80]

[72] For example, sending the upper stage carrying a satellite into Sun-synchronous orbit toward the atmosphere rather than leaving it in orbit exacts a one percent penalty on the weight of spacecraft delivered to such an orbit. See Joseph P. Loftus, Jr., E. Lee Tilton, and L. Parker Temple, III, "Decision Time On Orbital Debris," *Aerospace America*, vol. 16, June 1988, pp. 16-18.

[73] Reducing the dry weight of a spacecraft while maintaining its capability can cost more than $100,000 a pound. See U.S. Congress, Office of Technology Assessment, *Affordable Spacecraft: Design and Launch Alternatives*, OTA-BP-ISC-60 Washington, DC: U.S. Government Printing Office, January 1990), p. 7.

[74] The Soviet Union has made it a practice to fragment certain reconnaissance satellites after their useful life, presumably to prevent them from being recovered by the United States. Recently, they have fragmented these satellites in very low orbits, where the debris quickly enters Earth's atmosphere.

[75] Space objects that fall to Earth may cause damage on Earth. See Section V., *Legal Issues* for a discussion of legal regimes and remedies.

[76] For example, the solar maximum of 1980 and the one we are now experiencing that is expected to peak in 1991.

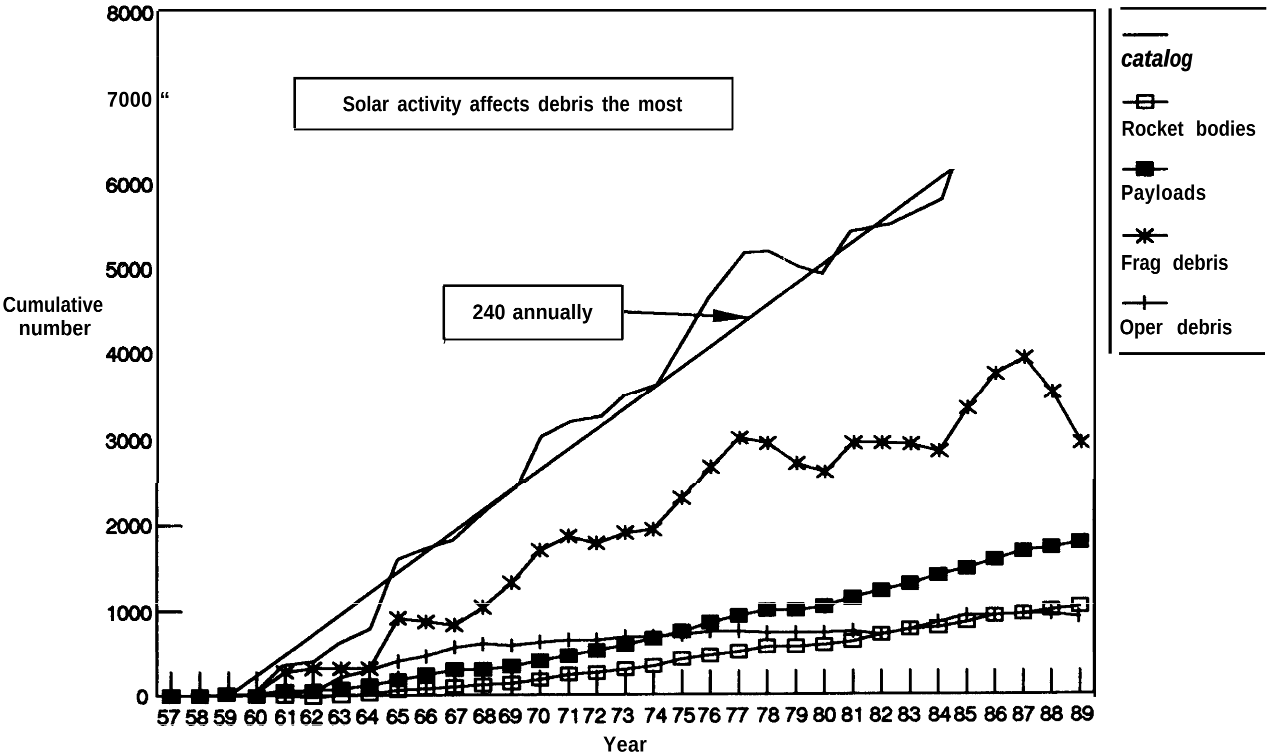
[77] Solar Max had been orbiting at about 570 kilometers above Earth's surface after being redeployed following repairs in 1984, an orbital altitude that would normally leave it in orbit for much longer than 5 years.

[78] Department of Defense Strategic Defense Initiative Office/Kinetic Energy Office, "Delta 180 Final Report," vol. 5, March 1987.

[79] Some proposed methods for removing existing space debris could inadvertently add more debris to the space environment than they remove.

[80] A.J. Petro and D. L. Talent, "Removal of Orbital Debris. " See Joseph P. Loftus, Jr. (cd.), in *Orbital Debris From Upper-Stage Breakup, Progress in Astronautics and Aeronautics,* vol. 121, 1989, pp. 169-182.

Figure 10- Spatial Densities In LEO for Various Sizes of Debris



SOURCE: Darren S. McKnight, 1990.

For deorbiting large objects, an Orbital Manuevering Vehicle (OMV) similar to that which NASA had under developmental might be effective in LEO. The OMV would attach itself to the space object and propel it to a lower altitude.[82] The use of space tethers has also been suggested. This technique would require attaching a tether between the debris object and a "remover" spacecraft and letting the tether out, causing the remover spacecraft to move higher in orbit, and the debris to move lower. Eventually the debris object moves close enough to the upper atmosphere that after release from the tether it spirals in and burns UP.[83]

Spacecraft launched in the future to orbits between about 250 and 750 kilometers could be brought down within a few years by deploying a balloon-like device-at the end of their useful lives-to increase atmospheric drag. Spacecraft in low and medium orbits could be sent back into the atmosphere at the end of their useful life by reserving some fuel for the purpose, or by adding a propulsive device specifically designed to deorbit the spacecraft. Launch vehicle upper stages can also be designed to be brought back to Earth after delivering their spacecraft to orbit. High costs will limit the use of many such procedures. If possible, reserving some fuel is the most eco-

[81] As a result of severe cost overruns, NASA recently canceled the OMV development program – "OrbitalManeuveringVehicle Program is Terminated," *NASA News,* Release *90-78,* June 7, 1990.

[82] Ibid.

[83] P. Eichler and A. Bade, "Removal of Debris From Orbit," AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Apr. 18-19, 1990, Baltimore, MD.

nomical means of deorbiting spacecraft and upper stages.[84] Adding a deorbiting device to satellites and rocket stages appears to be the next most economical method.* Some cases might call for using a combination of these two methods.

On several occasions, NASA demonstrated that the Space Shuttle could be used to capture and repair,[86] or return to Earth,[87] nonfictional satellites. However, at the present time the cost of retrieving them far outweighs any benefit that could be derived strictly from salvage. In addition, because they may involve extravehicular activity (EVA), such operations may be dangerous to the crew.

Shielding and Other Protective Measures

Designers have included various shielding devices on spacecraft. In the 1960s Astronomer Fred Whipple suggested using a dual-wall system to protect space systems from micrometeoroid impacts. Such a design was employed on the U.S. Skylab space station and on the European Giotto spacecraft, which flew through the tail of Comet Halley. In this design the outer wall (bumper) sacrifices itself to breakup the impacting projectile. As a result, the inner wall is subjected only to the impact of many smaller fragments, traveling at lower velocities. This inner wall is often a pressure vessel for the primary satellite structure.

The key to the effectiveness of most protective bumper systems is that they are "tuned" to a specific hazard: mass, velocity, size, and density of impacting object. For example, a shield designed to protect against an 8 millimeter diameter aluminum fragment traveling at 6 to 10 kilometers per second, is not necessarily effective against slower moving fragments. That is to say, the bumper will not cause a comparable-sized projectile moving at a lower 3 kilometers per second to fragment because the latter does not carry enough kinetic energy. Thus, the slower projectile pierces the outer wall and moves onto strike the inner wall with greater impulse per unit area than a comparable object initially moving much faster.

In summary, a bumper shield is effective for a specific hazard within some margin of tolerance. However, the bumper system will not adequately protect the satellite from all impacts of lesser or greater energy. The debris environment in LEO contains hazards from objects ranging from milligrams to kilograms, with relative velocities ranging from O to 14 kilometers per second. Thus, bumper shielding can only shield spacecraft from a portion of the debris hazard.

Areas in which shielding research is being pursued include methods to shield astronauts engaged in extravehicular activity (EVA), coatings on optics and windows, the use of several intermediate shielding layers, the use of nonmetallic and composite materials for shields, and stronger insulation between bumpers and spacecraft.

Providing redundancy for critical spacecraft systems would allow the backup system to function even if the primary system fails as a result of collision with space debris. Some critical spacecraft elements, like solar panels or antennas, cannot be shielded without destroying their effectiveness and are too heavy

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[84] In addition, the operational]ife of some stages may have to be extended to position it for ocean disposal. Both measures will generally exact some penalty in spacecraft performance, as the stage must carry extra propellant, and therefore additional weight.

[85] A.J. Petro and H. Ashley, "Cost Estimates for Removal of Orbital Debris. " Loftus, Op. cit., footnote 80, pp. 183-186.

[86] In April 1984, NASA retrieved the Solar Maximum Satellite from an orbit about 500 kilometers above Earth and repaired it after the satellite's attitude control system had failed. The repaired Solar Max continued to function until Dec. 2, 19S9.

[87] NASA retrieved two communications satellites whose upper stages had failed after being launched from the Shuttle. Although this was an important demonstration of the Shuttle's ability to retrieve space objects, from an economic point of view, it was not cost effective, as the cost of retrieval and refurbishment of the payloads outweighed the cost of building a replacement satellite.