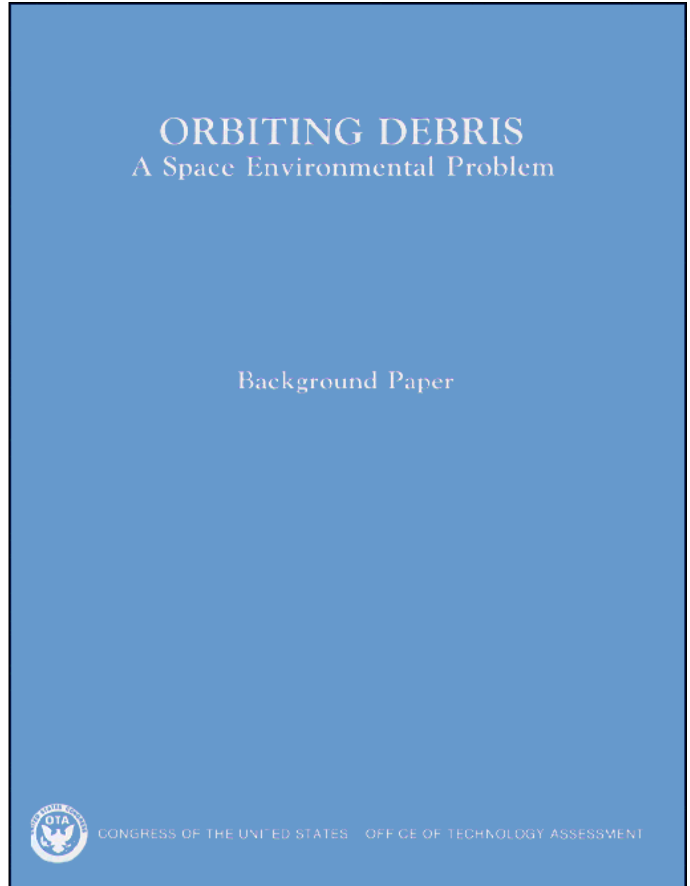
Orbiting Debris: A Space Environmental Problem

October 1990

OTA-BP-ISC-72

NTIS order #PB91-114272



Recommended Citation:

U.S. Congress, Office of Technology Assessment, *Orbiting Debris: A Space Environmental Problem-Background Paper, OTA-BP-ISC-72* (Washington, DC: U.S. Government Printing Office, September 1990).

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Foreword

Man-made debris, now circulating in a multitude of orbits about Earth as the result of the exploration and use of the space environment, poses a growing hazard to future space operations. The 6,000 or so debris objects large enough to be cataloged by the U.S. Space Surveillance Network are only a small percentage of the total debris capable of damaging spacecraft. Unless nations reduce the amount of orbital debris they produce, future space activities could suffer loss of capability, destruction of spacecraft, and perhaps even loss of life as a result of collisions between spacecraft and debris.

Better understanding of the extent and character of "space junk" will be *crucial* for planning future near-Earth missions, especially those projects involving humans in space. This OTA background paper summarizes the current state of knowlege about the causes and distribution of orbiting debris, and examines R&D needs for reducing the problem. As this background paper notes, addressing the problem will require the involvement of all nations active in space. The United States has taken the lead to increase international understanding of the issue but much work lies ahead.

In undertaking this background paper, OTA sought the contributions of abroad spectrum of knowledgeable individuals and organizations. Some provided information, others reviewed drafts. OTA gratefully acknowledges their contributions of time and intellectual effort. As with all OTA studies, the content of this background paper is the sole responsibility of the Office of Technology Assessment and does not necessarily represent the views of our advisors or reviewers.

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NOTE: OTA appreciates and is grateful for the valuable assistance and thoughtful critiques provided by the workshop participants. The Participants do not, however, necessarily approve, disapprove, or endorse this report. OTA assumes full responsibility for the report and the accuracy of its contents.

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Acknowledgments

The following organizations generously provided OTA with information and suggestions:

Aerospace Corporation
Aerojet Corporation
Department of Defense
Department of State
General Dynamics Space Systems Division
Office of Commercial Space Transportation, Department of Transportation
Office of Space Commerce, Department of Commerce
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This report has also benefited from the advice of experts from the government and the private sector. OTA especially would like to thank the following individuals for their assistance and support. The views expressed in this report, however, are the sole responsibility of the Office of Technology Assessment.

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INTRODUCTION

Debris, left in a multitude of orbits about Earth as the result of the exploration and use of the space environment, poses a growing hazard to future space operations. Unless nations reduce the amount of orbital debris they produce each year, future space activities could suffer loss of capability, loss of income, and even loss of life as a result of collisions between spacecraft and debris.

Because of their concerns about the safety of spaceflight, the Senate Committee on Commerce, Science, and Transportation, and the House Committee on Science, Space, and Technology requested an assessment of the future hazard from orbital debris,[1] and an examination of strategies for reducing that threat. This background paper derives primarily from a workshop on orbital debris held at OTA on September 25, 1989. In preparing this paper, OTA also received assistance from other contributors. OTA gathered information from many other sources, including the 1989 U.S. *Report on Orbital Debris*[2] prepared by the Interagency Group (Space), the 1988 European Space Agency (ESA) Report, *Space Debris,*[3] and a workshop convened jointly by OTA and the U.S. Space Foundation in April 1989.[4]

Since the launch of Sputnik 1 by the Soviet Union in 1957, nations and organizations involved in the exploration and exploitation of space have completed over 3,200 launches, which have placed more than 3,800 payloads into orbit around the Earth. About 6,500 artificial objects orbiting Earth, weighing about 2 million kilograms in sum, are now cataloged by the Space Surveillance Network (SSN), operated by the U.S. Space Command (USSPACECOM).[5] However, only 6 percent of the cataloged objects in Earth orbit are functional satellites;[6] the rest fall into the category of "orbital" or "space" debris7 (figure 1). Moreover, analysts believe that the total orbital debris population is much greater, because orbital debris includes a wide variety of *artificial* objects (table 1), which range in size from a millimeter or smaller to the full bulk of a deactivated satellite or spent rocket stage.

Orbital debris travels in the full range of orbits used by Earth-orbiting satellites (box l). Unlike natural meteoroids, which pass through near-Earth space in a matter of a few minutes as the Earth sweeps through space, orbital debris, depending on its altitude, may continue to orbit Earth for periods as long as centuries.[8] It moves in many different orbits

[1]The House Committee on Science, Space, and Technology held a hearingon July 13, 1988 on the subject of orbital debris. Witnesses included representatives from NASA, DOD, the Department of State, and the Department of Transportation, as well as legal and technical experts from the private sector. Witnesses expressed concern about the potential hazards from orbital debris and the need for technical and policy mechanisms to address those hazards.

[2]National Security Council, *Report on Orbital Debris,* Interagency Group (Space), February 1989.

[3]European Space Agency, *Space Debris* (Paris: European Space Agency, November 1988).

[4]U.S. Congress Office of Technology Assessment and U.S. Space Foundation, Joint Workshop on Space Debris and Its Policy Implications, *Proceedings of the Fifth National Space Symposium* (Colorado Springs, CO: U.S. Space Foundation, 1989), pp. 1-24.

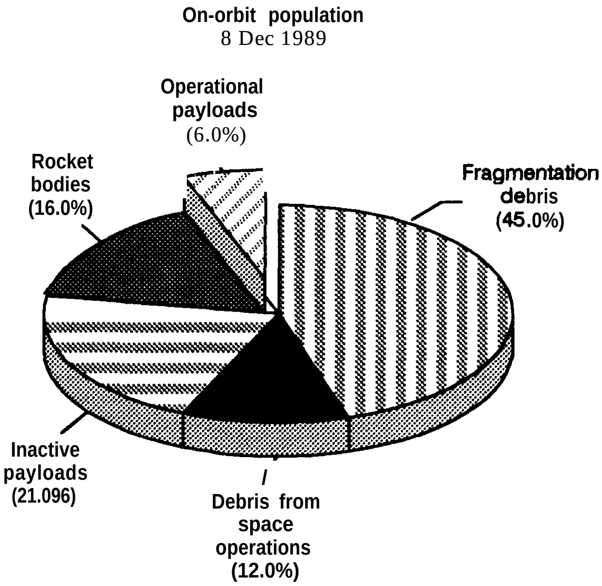
[5]The SSN was earlier operated by the North American Aerospace Defense Command (NORAD). However, in 1988, responsibility for surveillance passed from NORAD to USSPACECOM.

[6]Nicholas L. Johnson and David J. Nauer, *History of On-Orbit Satellite Fragmentations*, 4th ed. (Colorado Springs, CO: Teledyne Brown Engineering, January 1990), NASA Contract NAS 918209.

[7]Both terms are in common use. The term orbital debris will be used throughout this background paper to assist in distinguishing between artifical objects in space, which orbit Earth, and cosmic dust, meteoroids, and other natural objects, which pass by or strike Earth as it travels through the interplanetary medium.

[8]Much debris, however, falls back into the atmosphere within months or years.

Figure 1 -Cataloged On-Orbit Population



SOURCE: Nicholas L Johnson and Davld J. Nauer, *History of On-Orbit Satellite Fragmentatons,* 4th ed. (Colorado Springs: Teledyne Brown Engineering, January 1990), NASA Contract, NAS 18209,

Table 1 -Elements of Orbital Debris

- deactivated Spacecraft
- *spent* rocket stages
- fragments of rockets and spacecraft and their instruments
- paint flakes
- engine exhaust particles
- spacecraft rocket separation devices
- spacecraft coverings
- spent Soviet reactors

SOURCE: Office of Technology Assessment, 1990

Box 1 -Some Categories of Earth Orbits

- ***Low-Earth-Orbit(LEO)-any*** orbit below about 2,000 kilometers (1,250 miles) above Earth's surface,* which correspmds to an orbital period of 127 minutes, or less. Space Station Freedom will reside in LEO at altitudes between 300 and 500 kilometers.
- ***Medium-Earth-Orbit*** (MEO)-orbits between LEO and GSO.
- ***Geosynchrynous Orbit*** (GSO)-orbits at an average altitude of 35,787 kilometers (22,365 miles) in which a satellite has a 24-hr period.
- Geostationary Earth ***Orbit (GEO)-a*** special case of GSO in which a satellite orbits above Earth's Equator at an angular rotation speed equal to the rotation of Earth. It thus appears to remain stationary with respect to a point on the Equator. Positions along the GEO are highly sought for communications satellites because the geostationary vantage point allows one satellite continuous coverage of a large portion of Earth. In addition, GEO satellites can be repositioned along the orbit to change their coverage at reasonable cost.
- ***Supersynchronous Orbit-an*** orbit with a longer period, and greater average altitude than GSO.
- Sun Synchronous Orbit-an orbit synchronized with the sun in such a way that it passes over the Equator the same time each day. Such orbits are therefore highly important for remote sensing satellites that must view Earth's surface at the same time of day on each pass in order to maintain consistent data sets.

* the boundary between LEO and higher orbits is not well defined.

and directions, at velocities ranging from 4 kilometers per second to over 7 kilometers per second, and constitutes a potential hazard to working spacecraft (table 2). In the near-vacuum of outer space, no forces act to slow debris down. Even very small objects, if they have high velocities relative to the objects they hit, may do considerable damage. For example, in 1983, a tiny titanium oxide paint chip, estimated to have been about 0.2 millimeter in diameter, collided with the Shuttle orbiter *Challenger*[9] at very high velocity and damaged a window. Although the damage posed no immediate danger, the window was weakened beyond the allowable safety limits for reflight and was replaced before the orbiter's next launch.

Cataloged objects, some weighing up to several tons, reenter the atmosphere at a rate of two to three per day. Over the past 30 years, some 14,000 trackable objects have fallen to

[9]Nicholas L. Johnson and Darren S. McKnight, *Artificial* Space *Debris* (Malabar, FL: Orbit Books, 1987), p. 4.

Table 2--of Hazardous Interference by Orbital Debris

1. Loss or damage to space assets through collision;
2. Accidental re-entry of space hardware;
3. Contamination by nuclear material of manned or unmanned spacecraft, both in space and on Earth;
4. Interference with astronomical observations, both from the ground and in space;
5. Interference with scientific and military experiments in space;
6. Potential military use.

SOURCE: Space Debris, European Space Agency, and Office of Technology Assessment.

Earth. The largest have attracted worldwide attention.[10] Although the risk to individuals is extremely small, the probability of striking populated areas still finite.[11] For example: 1) the U.S.S.R. Kosmos 954, which contained a nuclear power source,[12] reentered the atmosphere over northwest Canada in 1978, scattering debris over an area the size of Austria; 2) a Japanese ship was hit in 1969 by pieces of space debris that were assumed to be of Soviet origin, injuring five sailors; 3) in October of 1987, a 7-foot strip of metal from a Soviet rocket landed in Lakeport, California, causing no damage; 4) portions of Skylab came down over Australia in 1979. The biggest piece of Skylab that reached the ground weighed over 1,000 pounds.[13]

This background paper treats the issue of artificial debris in space, its causes, and the potential for reducing the hazards that it poses to space activities and the outer space environment. Yet, orbital debris is part of a larger problem of pollution in space that includes radio-frequency interference and interference to scientific observations in all parts of the spectrum. For example, emissions at radio frequencies often interfere with radio astronomy observations. For several years, gamma-ray astronomy data have been corrupted by Soviet intelligence satellites that are powered by unshielded nuclear reactors.[14] The indirect emissions from these satellites spread along the Earth's magnetic field and are virtually impossible for other satellites to escape. The Japanese Ginga satellite, launched in 1987 to study gamma-ray bursters, has been triggered so often by the Soviet reactors that over 40 percent of its available observing time has been spent transmitting unintelligible "data."[15] All of these problem areas will require attention and positive steps to guarantee access to space by all countries in the future.

FINDINGS

Finding 1: If space users fail to act soon to reduce their contribution to debris in space, orbital debris could severely restrict the use of some orbits within a decade or two.

Orbital debris is a growing problem. Continuing steady growth of orbital debris could, by 2000 or 2010, render some well-used low-Earth orbits (LEOs) too risky to use.

[10] Salyut 7, the mothballed Soviet space station, which had beenorbitingin a storage orbit of some 300 kilometers, has slowly slipped to lower altitudes as a result of increased solar activity and is expect to fall to Earth in April 1991. It will be the largest object to reenter Earth's atmosphere since Skylab. Lon Rains, S'News, vol. 1, No. 8, p. 1.

[11] Early in the U.S. space program, rocket launches dropped debris over portions of Africa, which caused considerable concern to U.S. officials. See K H. Meyer and H. H. Hunt, "Investigation of Atlas Booster Fragments Recovered in South Africa," December 1963 (NASA contract NASw-537), General Dynamics Astronautics, San Diego, CA.

[12] See Eilene Galloway, "Nuclear Powered Satellites: The U.S.S.R. Cosmos 954 and the Canadian Claim," *Akron Law Review*, vol. 12, *No.* 3, pp. 401-415, for a comprehensive summary of the legal and political ramifications of this incident.

[13] R. Reinhold, "Space Junk Emits Clatter From Coast to Coast," New *York Times, Oct.* 14, 1987.

[14] M. Waldrop, "Space Reactors Hinder Gamma-Ray Astronomy," Science, vol. 242, November 1988, p. 119. The U.S. Solar Max spacecraft picked up bursts of gamma rays lasting anywhere from a few seconds to almost 2 minutes. The reactors provide power for the Soviet military's Radar Ocean Reconaisssance Satellites (RORSATs), which are used to track Weetern fleet movements, and which have been launched at the rate of two or three per year since the 1980s.

[15] Ibid.

Other orbits, including the economically and strategically important geostationary orbital band (GEO), are vulnerable to the growth of debris. Debris can collide with both active and inactive satellites, damaging the active satellites and producing more debris from both. Pollution in the form of gases and small particles of rocket exhaust may erode and contaminate spacecraft surfaces. Debris may also interfere with inspace and ground-based observations and experiments. International action will be needed to minimize the generation of new orbital debris and to cope with debris already in orbit. The United States and other countries have already taken initial steps to reduce their contributions to orbital debris. Future planning needs to consider the potential long-term effects (50 years and longer) of space debris.

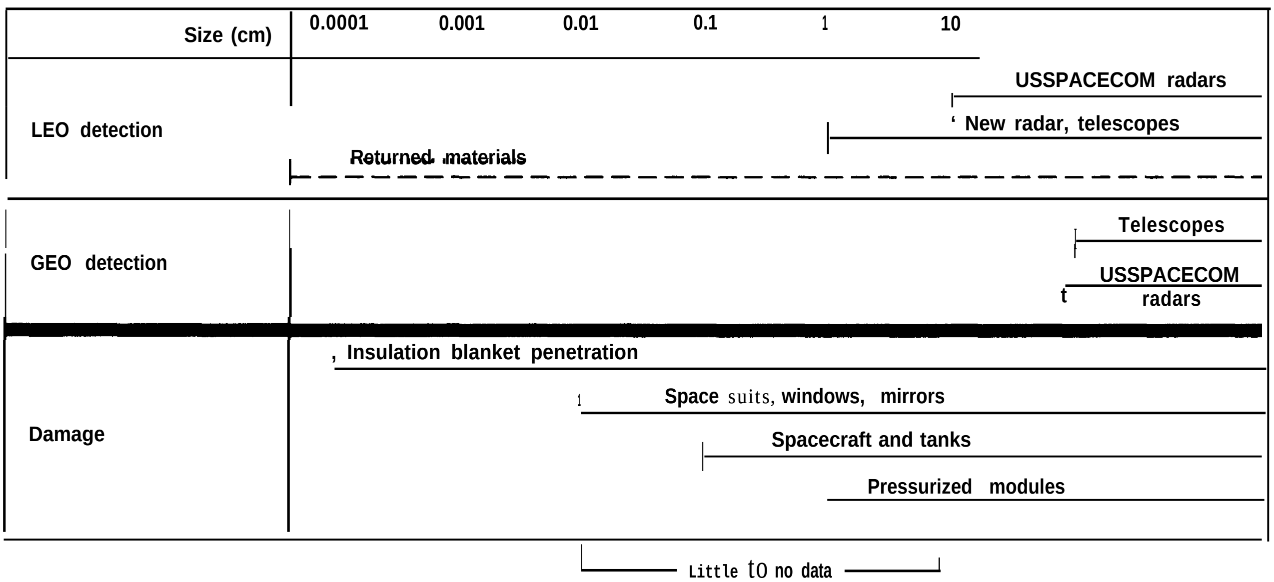
Three critical areas require particular attention:

- developing cost-effective strategies to reduce the contributions to orbital debris;
- encouraging immediate action to minimize debris production by all space-faring nations and organizations; and
- increasing the awareness and involvement of the international community.

Finding 2: Lack of adequate data on the orbital distribution and size of debris will continue to hamper efforts to reduce the threat that debris poses to spacecraft.

The distribution of orbital debris is determined by a variety of means (figure 2), including the use of radar, optical telescopes, and direct observations of damage to items returned from space. Although the Space Surveillance Network (SSN), operated by the U.S. Space Command, currently tracks about 6,500 orbital objects 10 centimeters across and larger (6 percent of which are active spacecraft), smaller debris cannot be followed with current systems. **The nature and extent of the hazard from smaller particles is therefore highly uncertain.** Some analysts estimate

Figure 2-Orbital Debris Relationships



SOURCE: National Aeronautics and Space Administration that some 30,000 to 70,000 bits of debris, one centimeter or greater in diameter, now orbit the Earth. Many more smaller objects are estimated to be in orbit.[16] Other analysts are skeptical of such projections. However, all agree that neither the number nor the distribution of these objects is sufficiently well known to predict which methods of protection would be most cost-effective.

Reducing these uncertainties to acceptable levels will require the development of devices capable of sensing and cataloging smaller objects, and sampling debris in orbit. The Haystack Auxillary Radar, under development by NASA and the Department of Defense (DOD) (operated by USSPACECOM), together with data from the existing Haystack Radar, will assist in characterizing the number and distribution of objects as small as 1 centimeter in diameter. The information supplied by examining the Long Duration Exposure Facility (LDEF),[17] which remained in LEO nearly 6 years, will help in estimating the debris density in LDEF's orbits and in evaluating the long-term effects of the space environment on a wide variety of materials used in spacecraft. Similar future experiments in orbit would continue to assist the accumulation of information on microscopic orbital debris.

To define the space environment adequately, more and better data must also be acquired in the laboratory on the types of explosions that can occur in space and on the effects of impacts, especially hypervelocity impacts (relative velocities of 3 kilometers per second and greater). Impacts occuring at velocities of 5 to 7 kilometers per second and greater lead to great damage because they can cause the impacting materials to liquify and produce many thousands of small particles. The remainder of a satellite may also fragment into hundreds of large pieces capable of causing catastrophic damage to other satellites. However, the details of these mechanisms are not completely understood.

Better orbital debris information will contribute to the development of more accurate predictive models for the evolution of space debris. These data will also support efforts to develop debris reduction and spacecraft protection techniques.

Finding 3: The development of additional debris mitigation techniques could sharply reduce the growth of orbital debris.

A number of relatively simple preventive measures taken by national governments and space organizations would greatly reduce the production of orbital debris. Government-funded research has shown that it is possible to design and operate launch vehicles and spacecraft so they have minimum potential for exploding or breaking up. For example, since 1981 NASA has depleted propellants and pressurants from Delta launch vehicle upper stages after they have completed their mission. NASA has also added electrical protection circuits to spacecraft batteries in order to preclude battery explosions resulting from electrical shorts. Spent upper stages can be removed passively by reducing their altitude to the point where atmospheric drag effects will bring them down. The U.S. Government may implement this technique in the future. Although these and other techniques add a few kilograms to the weight of the spacecraft and the launch vehicle, and therefore increase the cost of a mission, such extra costs maybe necessary to avoid potentially greater costs from failed missions later. In other words, they may well be cost-effective in the long-run.

Further, the use of new materials on spacecraft could reduce the natural degradation

[16] Information regard objects smaller than 0.10 centimeters can only be obtained from materials returned from space. Although these objects might number as much as 3,500,000, objects of this size are not considered a great threat.

[17] See box 5 for findings from LDEF.

and fragmentation that occurs in the harsh environment of outer space. Moreover, nations could avoid deliberately fragmenting satellites. Finally, some experiments can be planned for execution in very low orbit, where the atmospheric drag will bring objects down relatively quickly.[18]

Finding 4: Although it is technically feasible to remove existing debris from low altitudes, the cost of removal is not warranted at this time.

Proposals for debris removal have ranged from developing large balloon-like objects that would "sweep up" debris in certain orbits, to using the Space Shuttle and/or the planned Orbital Maneuvering Vehicle (OMV) to capture inactive satellites and remove them from orbit.

All methods for removing debris exact some economic cost. However, for LEO, the least expensive technique is to remove inactive payloads and spent propulsion stages before they can break up into smaller objects. Removal involves reserving some fuel to send spent propulsion stages or inactive satellites into the atmosphere, where they will break up and bum or fall to Earth.[19] Adding a small device directly to a propulsion stage that would later expand and increase atmospheric drag would also substantially shorten the stage's lifetime on orbit.

The capture and return of space objects is expensive.[20] The present degree of risk does not make debris worthwhile to remove from space. In addition, the potential salvage value of a used satellite, unlike that of an abandoned ship, is extremely small compared to the cost of retrieval at present. Further, unless the launching state were to agree, it is contrary to current international law[21] to interfere with space objects belonging to another state or states. Even inactive satellites, which could threaten the operation of other satellites, remain the property of the states of registry and continue under their jurisdiction. No concomitant duty to dispose safely of inactive satellites exists, and no liability accrues if they substantially interfere with active satellites, though activities generating inactive satellites may be made the subject of consultation pursuant to Article IX of the 1967 Outer Space Treaty.[22]

Finding 5: Protection technologies could reduce the harm that debris can do.

Orbital debris ranges from submillimeter-sized particles to objects several meters long. Although the chances that one of the few large pieces of debris would strike a functioning spacecraft is extremely small, the probability that collisions with objects in the millimeter to centimeter size range would reduce spacecraft performance is growing.

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[18] For example, the Delta 180 experiment for the Strategic Defense Initiative Organization was carried out in low orbit, in compliance with DOD policy on space debris (Department of Defense Space Policy, Mar. 10, 1987).

[19] The U.S. Government is actively considering followingthis practice. Full implementation will require further effort to design the procedures for each specific application.

[20] The recent return of LDEF and its many experiments to Earth demonstrates that such retrieval is possible. However, LDEF was retrieved to recover its valuable experimental results, not for its salvage value, or because it might harm active spacecraft. NASA will charge Intelsat more than $90 million to capture and repair an Intelsat VI communications satellite now stuck in a useless low orbit. James R. Asher, "Astronauts to Catch Stranded Intelsat for $90 Million for Reboost in 1992," *Aviation Week and Space Technology*, June 18, 1990, pp. 26-26.

[21] Article VIII of the *1967 Treaty on Principles Governing Activities ofStates in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*: "A State Party to the Treaty . . . shall retain jurisdiction and control over such object . . . while in outer space . . . ."

[22] Article IX states: "A State Party to the Treaty which has reason to believe that an activity or experiment planned by mother state Partyin outer space, including the Moon and other celestial bodies, would cause potentially harmful interference with activities in the peaceful exploration and use of outer space, including the Moon and other celestial bodies, may request consultation concerning the activity or experiment. "

Efforts to develop protection technologies and methods include materials research, active and passive avoidance techniques, and new shielding designs. Current shield designs make use of an outer wall that causes the striking object to fragment and disperse before hitting the inner wall. A specific dual-wall design is effective for all debris velocities *in excess* of about 5 kilometers per second and particle size of about 0.5 centimeter. Additional research and development will be needed to design more effective, lightweight shields. New materials and techniques will assist that effort. However, some shielding materials could add to the debris hazard. Hence, research on shielding will have to include study of the breakup or degradation of shielding over time.

Finding 6: The presence of debris in low-Earth orbits, where fast moving objects could pierce inhabited spacecraft such as the planned international space station, *Freedom*, and the Soviet space station, *Mir*, is especially troublesome because of the risk to human life.

The tiny paint chip that damaged the Shuttle *Challenger's* windshield in 1983 is evidence of a large population of very small particles. The paint chip would likely have punctured the spacesuit of an astronaut involved in extravehicular activity, had it struck him, though the probability of such an impact is extremely small.[23] Operation of the Space Shuttle could be endangered by orbital debris, especially as Shuttle flights increase in length.[24]

Objects quite a bit larger than the paint chip could pierce the Shuttle and/or space Station *Freedom.* Soviet cosmonauts aboard *Mir* have noted some impacts from small pieces of artificial debris.[25] Although these encounters have not resulted in life-threatening damage, they illustrate the potential threat. Additional data from *Mir* regarding Soviet experience with orbital debris could be very useful in designing appropriate shielding for *Freedom*.

Space station designers will need additional data in order to design effective shielding for *Freedom,* particularly for debris less than 2 centimeters in diameter.[26] The final design requirements for the space station are needed by 1992 in order for them to be incorporated in the hardware. NASA has recently revised its estimates of the debris hazard,[27] which new data shows may have been understated,[28] and continues to refine its understanding of the space environment. Study of the actual experience of debris encounters with LDEF and observations by the Haystack Auxillary Radar, under development by NASA and the Air Force, will play important roles in providing the necessary data.

Freedom will also require tight environmental control to limit generation of orbital debris. Space stations, especially because they are large and have a large surface area also have the potential to produce debris. Over several years, as debris generated by the space station changes orbit slightly and expands into a doughnut-shaped belt, space stations themselves, as well as launch vehicles supplying them, would become targets of space station debris.

[23] L. Parker Temple III, "The Impact of Space Debris on Manned Space Operations" (IAA-86-420), presented at the 37th Congress of the International Astronautical Federation, Innsbruck, Austria, Oct. 4-11, 1988.

[24] U.S. Congress, General Accounting Office, "Space Debris a Potential Threat to Space Station and Shuttle," GAO-CC-90-18 (Washington, DC: General Accounting Office, April 1990), ch. 5.

[25] William Djinis, National Aeronautics and Space Administration, personal communication, 1990.

[26] Shielding for objects greater than 2 centimeters in diameter would be impractically massive. Fortunately, the risk to the Space Station of encountering objects larger than 2 centimeters is much lower than for the smaller ones.

[27] R. Nieder, "Implication of Orbital Debris for Space Station Design" (AIAA 901331). AIM/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Apr. 1619, 1990, Baltimore, MD.

[28] U.S. Congress, General Accounting Office, op. cit., footnote 24, p. 28.

Finding 7: Addressing the orbital debris problem will require the active involvement of all space-capable nations.

Outer space is by nature *and* treaty a global commons. Solving orbital debris problems will require the cooperation of countries capable of reaching orbit. The United States and the Soviet Union are the two largest contributors to the orbital debris population. As other nations increase their space activities, their contribution to the debris population will increase dramatically, unless they also take preventive measures.

The United States has assumed the lead in analyzing the orbital debris distribution and in developing mitigating technologies and methods. The 1989 report of the Interagency Group (Space)[29] has assisted in making the hazards posed by orbital debris more widely appreciated and understood.

Informal discussions among technical representatives of most of the launching nations, convened by the United States, have already proven highly beneficial in developing orbital debris control policies and practices. For example, the Japanese National Aeronautics and Space Development Agency (NASDA) and the European Space Agency (ESA) have both incorporated procedures in their launch sequences to dispense unused propellant after upper stages are used. Discussions between these agencies and NASA have also resulted in the prospect of sharing information on debris tracking, modeling, and hypervelocity testing. In November 1988, ESA released its report on space debris,[30] which reached conclusions similar to those of the later U.S. orbital debris report.

Initial discussions with Soviet officials in December 1989 have proven fruitful to representatives from NASA, who have hitherto had little insight into Soviet efforts to study the problem or to curb its contributions to the orbital debris population.[31] The United States has not yet formally discussed the problems of orbital debris with the People's Republic of China, which has a growing space program.

Finding 8: Existing international treaties and agreements are inadequate for minimizing the generation of orbital debris or controlling its effects. An international treaty or agreement specifically devoted to orbital debris maybe necessary.

One major objective of the international treaties and agreements *on* space activities is to ensure that space activities can be conducted safely, economically, and efficiently. Yet, existing international treaties and agreements do not explicitly refer to orbital debris. As a result, they leave uncertain the legal responsibilities of nations for minimizing the growth of orbital debris.

The economic value of maintaining a safe operational environment for all nations provides strong motivation for nations to take independent action. Yet nations that conduct relatively few launches might consider their contribution to orbital debris to be small. However, as the November 1986 breakup of an Ariane third stage demonstrated,[32] even one breakup can cause a large amount of debris. An international agreement on orbital debris could set the framework for tackling the hazards of orbital debris. To be effective, an international legal regime for debris

[29] National Security Council, Op. Cit., fOOtnOte 2.

[30] European Space Agency, op. cit., *footnote* 3.

[31] Djinis, op cit., footnote 25.

[32] Nicholas L. Johnson, "Preliminary Analysis of the Fragmentation of the Spot 1 Ariane Third Stage," in Joseph P. Loftus (d), *Orbital Debris From Upper-Stage Breakup,* Progress in Astronautics and Aeronautics, vol. 121, 19S9, pp. 41-106.

should address the generation of debris, its removal from orbit, and the possible remedies for damage sustained from debris. However, experience with the development of other treaties suggests that negotiating such an agreement could be arduous and time-consuming.

The United States, and some other governments, are currently reluctant to enter into negotiations over an international agreement on orbital debris, because the uncertainties about debris distribution and potential mitigation methods are still high. In addition, when addressed in a broad multilateral context in which states having no current capability to launch objects into space would participate, the subject has a high potential for becoming the subject of acrimonious debate in which the technical issues and solutions could be lost. However, eventually a formal agreement will probably be necessary in order to encourage all space-faring nations to minimize the production of orbital debris.

It maybe appropriate for the United States to convene a working group limited to space-faring nations that would discuss mitigation strategies and seek to reach agreement on them. The United States is now urging these nations, both informally and formally, to adopt as policy a statement similar to the U.S. policy on orbital debris: "all space sectors[33] will seek to minimize the creation of orbital debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness." This follows U.S. policy, adopted in 1989, that "the United States Government will encourage other space-faring nations to adopt policies and practices aimed at debris minimization."[34]

In the long run, enlightened self-interest is likely to draw most nations with an interest in outer space into such negotiations. Many of the partners in such international organizations as Intelsat, Inmarsat, and Intersputnik, or regional entities such as ESA, Arabsat, and Eutelsat, have an economic interest in maintaining the ability to exploit space, even if they lack the ability to launch spacecraft themselves.

Finding 9: For an international legal regime on orbital debris to be established, several legal issues, including the definition of orbital debris, jurisdiction and control over orbital debris, and the treatment of liability for damage from orbital debris, need to be resolved.

Legal experts do not now agree on a definition of space debris. For example, one major point of debate is whether inactive satellites should be categorized as "debris." Without a common definition, agreements over jurisdiction and control and liability will be extremely difficult to achieve. Hence, if the United States and other nations enter into negotiations over an international agreement on orbital debris, one of the first items of business will be to reach agreement on a definition of orbital debris, and what items are included in or excluded from the category.

It will also be necessary to provide more explicit guidelines concerning the ownership of, and jurisdictional control over orbital debris. Existing legal opinion favors the view that jurisdiction and control of a State over its space objects is permanent, even if the object no longer serves a useful purpose. However, most space debris consists of objects too small to be identified. It maybe necessary for the international community to develop a set of principles regarding the treatment of spent satellites.

Under existing law, launching States cannot beheld liable for the mere presence of orbital debris in outer space. Lack of international agreements on debris is of particular con-

[33] In other words, civilian and military government programs, and the private sector.

[34] White House, President Bush's Space Policy, November 1989, Fact Sheet.

cern because launching States have no legal incentive to avoid generating orbital debris, although they have the practical, self-serving incentive of protecting their own spacecraft. An international agreement on space debris should include provisions dealing with these and other issues.

Reaching agreement will eventually require abroad international approach, supported by individual national efforts. Considerable additional research on the distribution and hazard posed by space debris will be needed to support international legal efforts. Meanwhile, nations and organizations that launch or operate spacecraft can voluntarily take immediate steps to minimize debris.

Finding 10: Private-sector space activities have already benefited from orbital debris research carried out by governments. As private space activities increase, firms will have to bear their share of the burden of mitigating future contributions to the orbital debris population.

The private sector has a major stake in reducing space debris, because an increased debris population could harm private activities. As noted in Findings 3, 4, and 5, Federal investment in debris research has resulted in greater knowledge of the potential harm of space debris and in a variety of measures to mitigate its threat to space operations.

U.S. private-sector space activities are regulated by the U.S. Government in accordance with several U.S. laws. In particular, *The Commercial Space Launch Act of 1984*[35] mandates that all commercial payloads must be reviewed prior to being licensed for launch. The Act gives the Office of Commercial Space Transportation (OCST) in the Department of Transportation the responsibility for licensing commercial launches. This licensing process includes a review of intended safeguards against proliferation of space debris.

Although some safeguards will require additional costs for payload owners and providers of launch services, the Federal Government does not wish to prejudice unnecessarily the international competitiveness of the U.S. launch industry.[36] Hence, to avoid overburdening the private sector, regulation will have to be measured and in concert with reducing the threat of space debris while maintaining U.S. competitiveness with other nations.

Private-sector input to the process of minimizing space debris generation will be extremely important in ensuring that regulations take into account the concerns and needs of private fins, consistent with providing appropriate protection to spacecraft and people in space. Private firms could be especially helpful in comparing the costs of instituting certain debris reduction procedures with the costs of losing spacecraft capability as a result of debris impacts.

Finding 11. Many misconceptions about orbital debris exist. An international educational program about orbital debris would assist in making the hazards of space debris better understood.

Even individuals knowledgeable in other areas of space activities have developed misconceptions about the distribution of space debris and potential hazards (box 2). Continued research and promulgation of results will be needed to improve knowledge of this critical area. The many research reports written by officials at NASA, the Air Force, and industry have alerted the space community to the hazards of space debris. These have been presented over the years at national and international technical symposia sponsored by organizations such as the American Institute for Aeronautics, the American Astronautical Society, the International Astronautical Federation, and the Committee on Space Research. The recent reports by the U.S. Interagency Group (Space) and ESA have reached an even

3549 U.S.C. 2601-2623 (19S4 & supp. 1987).

[36]National Security Council, op. cit., fOOtnOte 2, pp. 49-50.

Box 2-Nine ***Common Misconceptions About Orbital Debris***

One of the major impediments to reducing orbital debris is the lack of knowledge and understanding of the problem. The following paragraphs explore some of the most common misunderstandings about orbital debris.

Misconception 1. Space debris is a larger problem today because the international space launch rate has increased.

On the contrary, **the cataloged debris population has steadily grown while the international launch rate has remained stable.**

Since 1965 the international space launch rate has averaged 117 a year, never dipping below 100,yet the cataloged population has increased sixfold (figure 3 and figure 4) in the same period. There is no clear dependency between the launch rate and catalog growth. Catalogd space objects have increased at an average linear rate of 240 objects per year (including active payloads and debris).

Misconception 2. The hazard from orbital debris is well defined.

***On the contrary,* there is significant uncertainty (orders of magnitude) in the probability of collisions and the effect of the impact of debris.**

The hazard to a functioning satellite is determinedby the probability of collision and the lethality of impact. Because the number of debris objects in various orbits is uncertain, the probability of collision calculated from the density and velocities of cataloged objects (app. A) is also uncertain. Hence, estimates of future hazard reflect, or should reflect, that uncertainty. Because the number of small objects in each orbital regime is thought to be much greater than those that can be tracked by the SSN, the hazard is likely to be much greater than that estimated from cataloged data.

The actual effects of collision on an active spacecraft are also uncertain. A collision might destroy an active spacecraft or it might only damage part of it. For example, although a 100 gram debris fragment traveling at 10 kilometers per second (the average relative velocity in LEO) possesses the destructive energy of one kilogram of TNT, it may strike the satellite in an area that would damage, but not destroy, the satellite.

In addition, the nature of the debris environment is very dynamic; both the sources and sinks of debris will change over time, adding to the difficulties of defining the debris environment.

Misconception 3. The cessation of satellite breakups will solve the orbital debris problem.

On the contrary, **the hazard from debris already residing in space, coupled with other sources of new debris, such as debris resulting from space operations, will still create a concern for many years to come even if no more satellites were to fragment in the future.**

About 45 percent of the cataloged population is the result of nearly 100 satellite fragmentations (figure 1).[1] Elimination of spacecraft explosions is more effective than any other method of controlling space debris growth. Yet, there are still other significant sources that must be controlled. The remnants of successful space missions, spent rocket bodies, and inactive payloads account for one third of the catalog. These objects are large and maybe the source of future debris. Satellite deterioration as the result of reaction with atomic oxygen and thermal cycling could produce fragments that range in size from micron-size paint chips to large solar panels. These payloads and rocket bodies may also remain in orbit a longer time than fragmentation debris.

The last category, operational debris, makes up 12 percent of the trackable objects in orbit.[2] This debris is released during normal operations of satellites: lens covers, explosive bolts, springs, shrouds, spin-up mechanisms, empty propellant tanks, etc. Crews have even accidently released items during extravehicular activities and been unable to retrieve them. However, at altitudes in which the Shuttle operates, objects reenter relatively frequently.

Misconception 4. International laws and treaties help to control the growth of the orbital debris population.

***On the contrary,* no formal laws or treaties have any impact on the control of orbital debris.**

There is at present no international law or treaty that specifically calls for the control, reduction, or elimination of "space debris." Some feel that an international legal agreement formulated now may unnecessarily restrict future space operations. Yet, if the spacefaring nations do not act soon on an international level, the effects of continued debris growth may make future space activities more dangerous. The next 10 years are pivotal for the future of debris growth and control treaties and regulations.

Informal discussions among technical representatives of the European Space Agency, France, Germany, Japan, and the United States, have already proven to be useful in developing technical policies and practices for controlling orbital debris. Discussions with the Soviet Union have begun and may prove fruitful in the future.

Misconception 6. The danger of satellite collision is greater in GEO than in LEO.

***On the contrary,* the current collision hazard in GEO is estimated to be hundreds of times less than in *LEO*.**

[1] Nicholas L. Johnson and D. Nauer, History *of On-Orbit Satellite Fragmentations*, 4th ed. (Colorado Springs, CO: Teledyne Brown Engineering, January 1990), NASA Contract NAS 9-18209.

[2] Ibid.

Continued on next page

The probability of collision between a satellite and the debris population is a function of:

- the spatial density of objects in space;
- the relative velocity between debris and a satellite;
- the effective cross-section of the satellite; and
- the duration of the satellite on orbit.

The estimated probability of collision is a factor of 100 to 10,000 less in the GEO band than in LEO because there are fewer objects in the former and they would cross paths at lower relative velocities. Further, because relative velocities are lower, the consequences of a collision are significantly less. However, even though the hazard to satellites in GEO is much less than it is today in LEO, there are concerns for the future. For one thing, we have less data about potential GEO hazards. GEO likely contains other orbiting objects too small to be tracked by current methods (less than about 1 meter at GEO altitude), which could increase the hazard. In addition, more satellites are being launched into GEO and there is no natural cleansing effect such as atmospheric drag to control debris growth in these orbits. A series of satellite breakup events (i.e., a chain reaction) could have catastrophic effects on the GEO satellite population.

Misconception 6. The Soviet Union, which has been responsible for more than 70 percent of all space launches and satellite breakups during the past 25 years, has historically been the source for the majority of Earth's debris population.

***On the contrary,* the United States and the Soviet Union are about equally responsible for the present cataloged population.**

Up until the mid-1980s, the United States was responsible for a larger percentage of debris in orbit. The debris produced by Soviet breakups is usually shortlived since it has historically been produced at lower altitudes. Thus even though the Soviets have produced more debris over time, at present they have less in orbit than the United States (figure 5), but more cataloged objects as a result of a larger number of inactive payloads and rocket bodies.

The rate at which Soviet satellites fragment has actually been increasing while the cataloged population has been decreasing Since 1961 the number of non-Soviet satellite breakups has consistently averaged less than one per year. The Soviet breakup rate has increased steadily from one per year in the 1960s to four per year in the 1980s. However, recently, the Soviet Union has fragmented its satellites in very low orbits, where the resulting debris falls back into the atmosphere relatively quickly.

Misconception 7. Debris from weapons tests in space is a major component of Earth's satellite population.

***On the contrary,* the 12 breakup events associated with space weapons tests are responsible for less than 7 percent of the cataloged population.**

Despite the attention given to weapons tests in space, they have contributed very little to cataloged debris, in large part because they have decayed from orbit relatively quickly. However, such tests may have added smaller debris that cannot be detected with existing methods. Weapons tests could contribute substantially to the debris environment if they were carried out in higher orbits where the effects of atmospheric drag are extremely small.

Misconception 8. Bumper shielding can easily protect a space system from the debris environment.

***On the contrary,* a bumper system can protect a satellite from only a portion of the debris environment.**

Although bumper shielding can protect a spacecraft from impact by some classes of objects, this shielding must be "tuned" to specific types and velocities of debris threats. Hence it will only partially protect satellites. One that would be effective for all sizes and velocities would be prohibitively costly in weight, complexity, and cost. Additional research will be required to protect spacecraft from the most likely collision events. However, shielding will not provide absolute protection. Debris minimization by all parties will also be required to reduce the hazard to acceptable levels. For some large systems, collision avoidance may be necessary.

Misconception 9. People are likely to be killed by fragments of reentering debris.

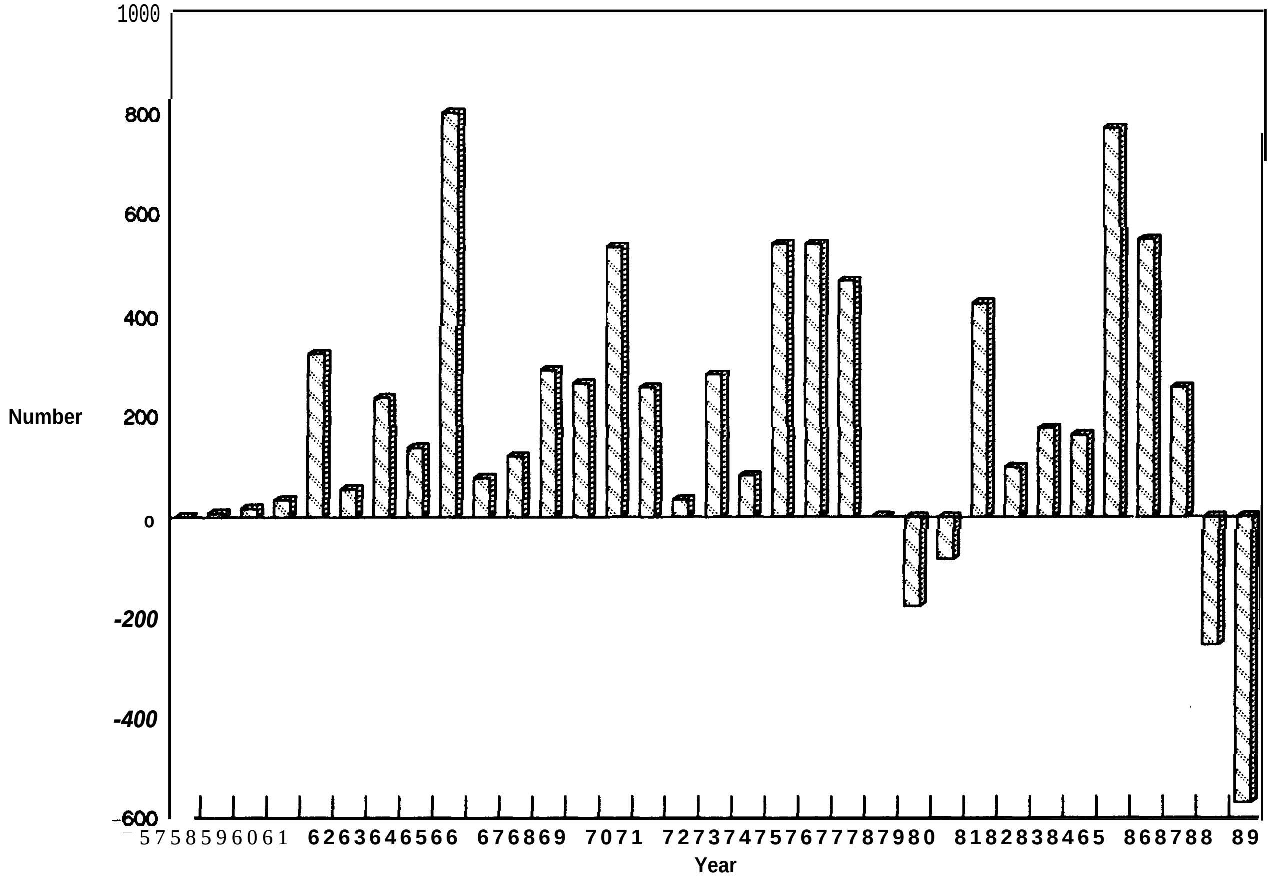
***On the contrary,* the chances of being struck by debris fragments are extremely small.**

Thousands of debris fragments of all sizes reenter the atmosphere each year. Most disintegrate in the atmosphere and are converted to gases and ash, or breakup into extremely small pieces. Very few actually reach Earth's surface intact. The chances of harm from reentering space debris is much smaller than the chances of being hit by one of the 500 or so meteorites that strike Earth each year. Nevertheless, the uncertainty associated with our inability to predict precisely, in advance,[3] when large objects such as the U.S. Skylab or Soviet Cosmos spacecraft will enter the atmosphere and where they may fall to Earth, coupled with considerable press attention, has led to unwarranted public alarm.

SOURCE: Darren S. McKnight, 1990.

[3]The closer in time an object is to enteringthe atmosphere the more precisely can its entry be predicted by the Space Surveillance Network.

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

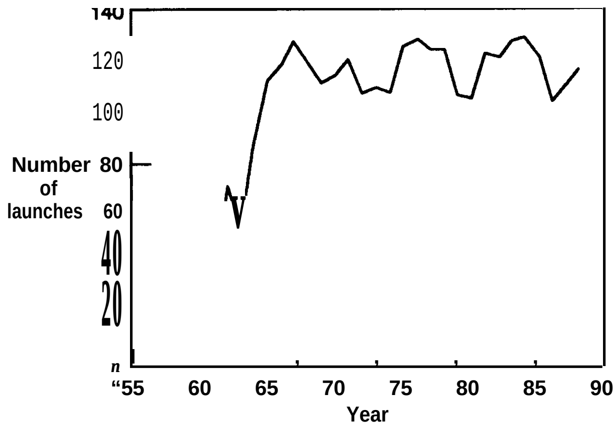
Space debris can interfere with scientific, commercial, and military space activities. In some orbits, debris deposited today may affeet these activities far in the future. This section describes the hazards posed by orbital debris and summarizes how they are generated.

Hazards to Space Operations From Orbital Debris

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

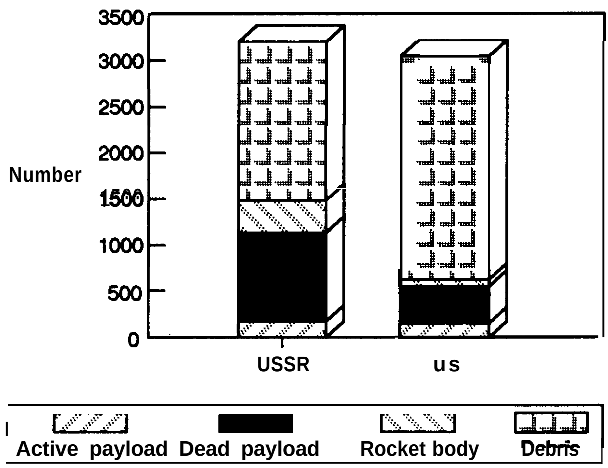
- *Collisions* of space debris with functional satellites could result in damage that could significantly impair the perform-

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."
- ***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.

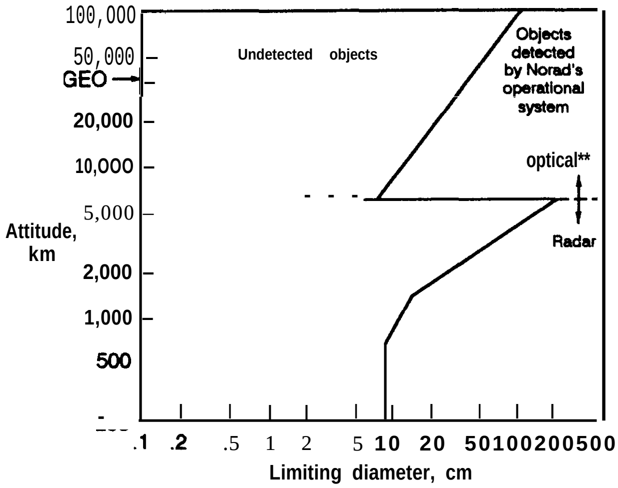
rently the SSN follows about 6,500 cataloged objects. However, in LEO the SSN is limited to tracking objects 10 centimeters in diameter or larger (figure 6). Some analysts estimate that some 30,000 to 70,000 additional debris fragments ranging in size from 1 to 10 centimeters are also in orbit around 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.

- *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.

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.

[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 t. 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.

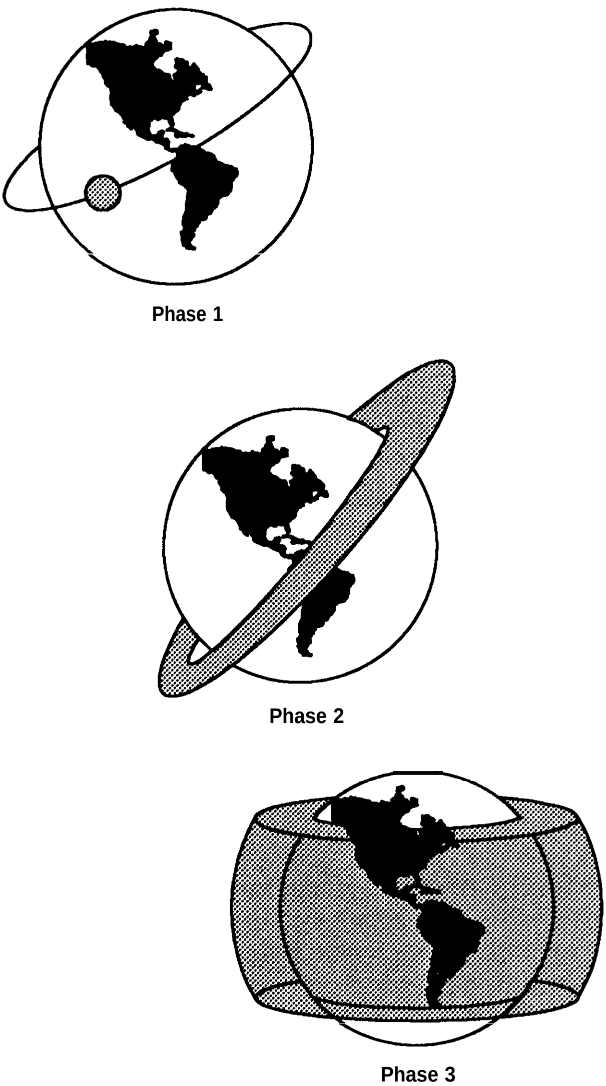
SOURCE: Darren S. McKnight, 1990.

[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

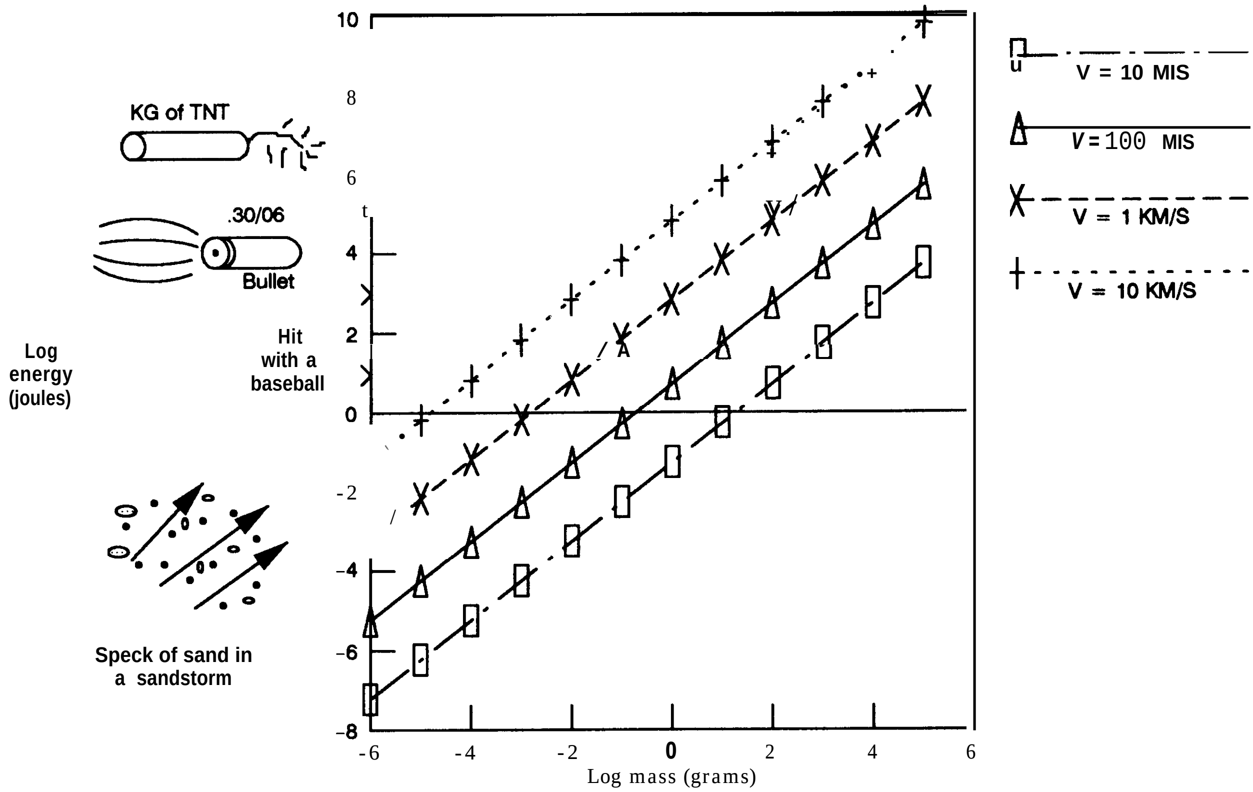
Class of breakups	No. of events	No. debris cataloged	No. debris in orbit
Phase 1:			
Soviet ASAT	7	545	296
Phase 2:			
Soviet ASAT	3	189	154
P-78 Breakup	1		
D-180 Test	1	18	0
	12	1,037	488

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. Cour-Palais, "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.

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.

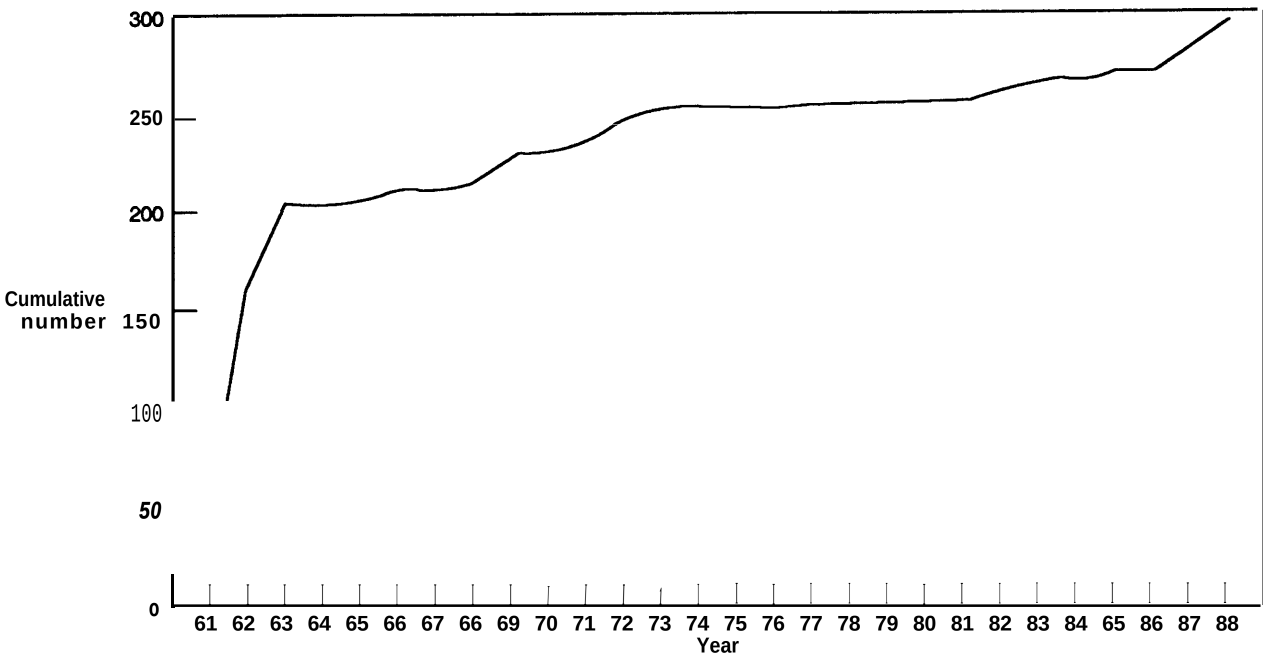
[67] Richard S. Hujsak, Applied Technology Associates, Inc., personal communication, July 1990.

[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.

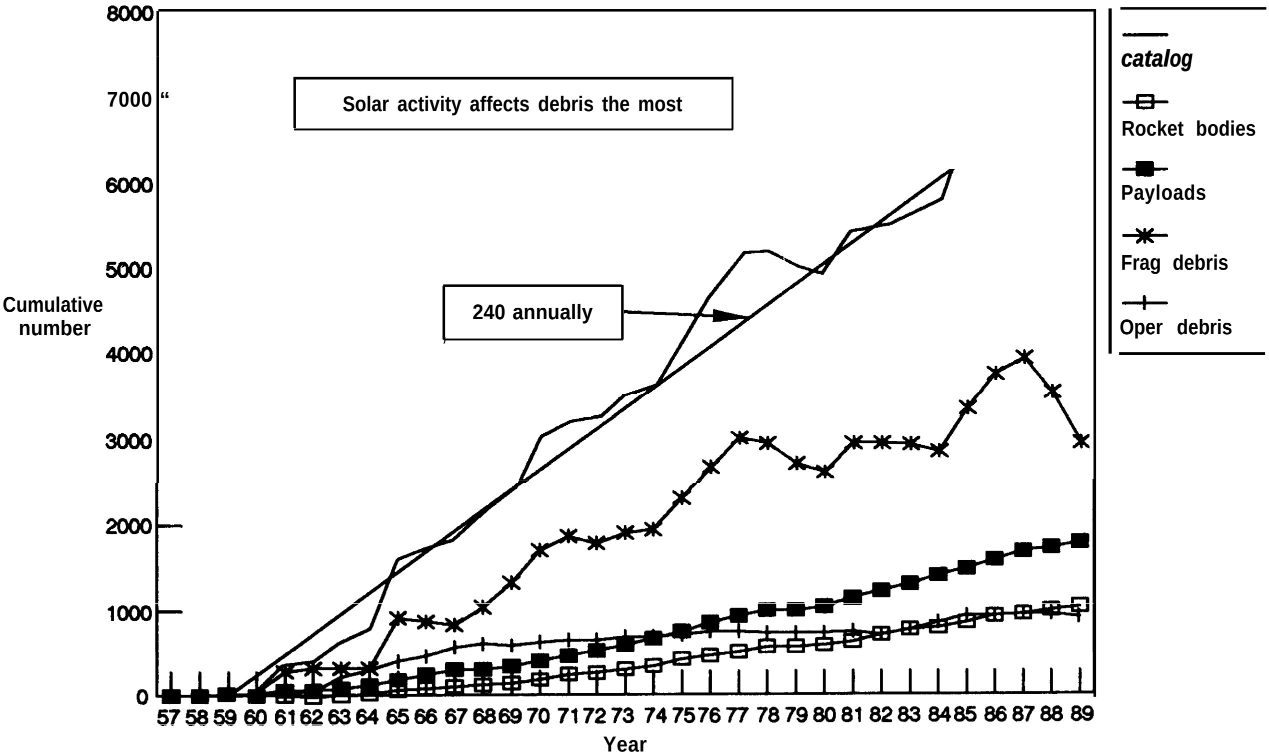
[77] Solar Max had been orbiting at about 570 kilometers above Earth's surface after being redeployed following repairs in 1984, an orbital altitude that would normally leave it in orbit for much longer than 5 years.

[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

[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 tw₀ 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.

to make redundant systems. Making solar panels and antennas some 10 to 20 percent larger would compensate for losses from collisions with small debris.[88]

Providing shielding, redundant systems, and extra large systems adds considerable extra weight to payloads and therefore increases overall operating costs. Hence, more accurate characterization of the space environment that would allow spacecraft designers to determine more precisely the protection needs of particular spacecraft could reduce costs accordingly.

Geostationary Orbit

GEO represents a special case because objects placed there remain for millions of years, and because certain segments of the orbit are used more intensively than others.[89] To reduce the chances of accidental collisions between inactive and active satellites, some organizations, including agencies of the U.S. Government, just prior to retiring a satellite from service have used a satellite's last remaining fuel to place it in a higher orbit beyond GEO. Just how effective this practice will prove to be is currently under study. Analysts do not yet know the minimum safe distance necessary to prevent objects drifting back through GEO years afterward, but believe that inactive satellites should be boosted into a circular orbit at least 300 kilometers farther outgo If a satellite in an orbit less than 160 kilometers beyond GEO were to breakup, roughly half of its fragments would eventually drift back through GEO, posing a greater hazard to active satellites along the orbital band than if the satellite had remained in GEO.[91] However, because boosting satellites out of GEO reduces their potential lifetime on orbit, and therefore their economic value, operators are reluctant to spend more fuel than necessary on this procedure. Additional theoretical modeling analysis would assist in determining the most economical removal orbit.

Other hazards may pose greater threats. For example, the explosion of a single upper stage (orbital transfer stage), used to carry a communication satellite to GEO, could create more pieces of fragmentation debris passing through GEO than would be removed by hundreds of end-of-life maneuvers.[92] Yet, because orbital transfer stages follow a highly elliptical orbit that takes them between LEO and GEO altitudes after they have deposited their satellites in GEO, it may be possible to control the stage's perigee and place it low enough that the upper reaches of the atmosphere will slow it down every time it cycles through perigee. Eventually, the upper stage would tumble back into the atmosphere and bum up.

LEGAL IMPLICATIONS

Domestic and international law regulating space activities began to develop in the late 1950s and early 1960s. Yet only recently have managers of space systems recognized that the hazards of space debris might require some sort of regulatory regime. Earlier law, including the international treaties and agreements on space, failed to address orbital debris explicitly. Any domestic and international legal regimes for debris should address the generation of debris, its removal from or-

[88] If appropriately design the solar panels could suffer losses of individual cells without causing total loss of the Panel'scalability.

[89] In orbital arcs serving the United States, trans-Atlantic traffic, and Europe, where the volume of digital, video, and voice traffic is particularly high and of high economic value, the density of communications satellites is particularly high.

[90] V.A. Chobotov, "Disposal of Spacecraft at End-of-Life in Geosynchronous orbit,'" AAS/AIAA Astrodynamic Specialist Conference, StOwe, Vermont, Aug. 7-10, 1989 (paper No. AAS 89-378).

[91] Kessler, op. cit., footnote 56.

[92] Ibid.

bit, the question of jurisdiction and control over space debris, detection and identification of space debris, international responsibility for space debris, and possible remedies for damage caused by debris. This section explores the legal implications of orbital debris and suggests areas where new international agreements may eventually be needed.

The Definition of Orbital Debris

One of the impediments to developing new laws to address the problems posed by space debris is the lack of an adequate definition of space debris. Existing national laws and international space treaties and agreements (box 5) contain neither a definition nor a description of orbital debris. While orbital debris maybe divided into four classes for descriptive purposes (table 4), legal experts disagree whether the legal scope of orbital debris includes all technical classes.

The seriousness of the debris problem for space operations, the possible confusion over the literal meaning of "debris," and the need to define the scope of debris all suggest the need for a legal term of art. Such a term would provide a starting point for discussing the legal issues arising from the orbital debris problem.

An explicit definition of orbital debris might not be necessary, however, if that term were subsumed under an existing space law treaty definition. Although the term "contamination," found in Article IX of the *Outer Space Treaty,* might be thought to serve this purpose, it refers only to harmful microbiological organisms of terrestrial origin, which might be accidentally released in the aftermath of a collision or explosion in outer space.[93] The term "space object" is more promising. The *Liability Convention* provides that "space object" includes a spacecraft, the launch vehicle, and the component parts of both. The *Registration Convention also* contains this description. However, existing international law does not define space object.

During the debates over the terms of the *Liability Convention,* negotiators could not agree on a description for "space object," nor was the question of whether orbital debris is included in "space object" specifically addressed. Negotiators were primarily concerned with which artificial objects should be considered "space objects," not with the effects of those objects following their active lives. During these debates, legal experts put forward two definitions of "space object."[94] The narrow definition included the object itself and its component parts, as well as the means of delivery and its component parts. Although some delegates offered a much broader definition, which would have included articles on board the space object and articles detached, thrown or launched from the space object, the narrower interpretation was adopted. Consequently, it is unclear which classes of space debris, if any, are included implicitly in "space object." Consider, for example, inactive payloads. The *Liability Convention* is silent on whether a payload must be active to qualify as a "space object" capable of causing damage. If inactive payloads are included, then they are space debris, with liability for compensation attaching to the launching state.

Orbital debris may also be considered a "space object" if it falls under the term "component parts." Yet what exactly constitutes "component parts" is not settled. According to the description of space object in *the Liability Convention, all* operational debris except

*Howard Baker, *Space Debris:* h@/ *and Policy Implications* (Dordrecht: Martinus Nijhoff Publishers, 1989), P. 103.

[94]The history of relevant U.S. national positions, and the negotiation of relevant UN treaties involving issues related to debris, pollution, and contamination can be found in Carl Christol, *The Modem International Law of Outer Space (New* York, NY: Pergamon Press, 1982), chap. IV, pp. 129-151; For a detailed discussion of this issue, see Baker, op. cit., footnote 92, pp. 83-85.

Box 6 – Internatwnal Space Treaties and Agreements

1. The ***Outer Space*** Treaty of 1967,1 to which the United States and more than 100 countries are signatories, provides that a State party assumes international responsibility for space activities conducted by its government agencies and non-government entities.[2] The Treaty establishes that State parties are internationally liable for damages to the persons or property of other State parties, if the damage is caused either by an object launched into outer space or its component parts, whether the damage occurs on the ground, in air space or in outer space. This liability applies to States launching and procuring launches, and to States whose territory or facilities are used for launches.[3] Of great importance to environmental considerations is the treaty's statement obligating States to engage in appropriate international consultation in circumstances where it can be established that there is a reasonable belief that a space activity of one State party would cause potentially harmful interference with space activities of other State parties.[4]

2. ***The Liability Convention of 1972***[5] provides that both intergovernmental organizations and State parties are liable on the basis of fault for damage of their space objects, launch vehicles, or component parts thereof may cause in outer space.[6] States collaborating in launch activities are also jointly and severally liable for damages.[7] The standard of compensation is to be in accordance with international law and principles of justice and equity.[8] Because the ***Liability Convention*** defines a "space object" as "including component parts of a space object as well as its launch vehicle and parts thereof, "[9] the launching State's liability would continue whether its "space object" was functional or had reached the non-functional status of "space debris. "[10]

3. ***The Registration Convention of 1976***[11] provides a system whereby any space object launched into Earth orbit or beyond is to be registered with the United Nations.[12] In the case of two or more launching States, an agreement among or between those States will determine who registers the object.[13] Where identification of debris causing damage cannot be obtained from the registration information, the Convention requires other parties with space monitoring and tracking facilities to assist to the greatest extent feasible in identifying the space object.[14]

4. ***The Rescue and Return Agreement of 1968***[15] establishes State party obligations regarding the return to Earth and recovery of space objects or their component parts.[16] A State party discovering such material must notify the launching authority and the United Nations.[17] The discovering State shall take practical steps to recover returned material in its territory if the launching authority so requests. If a discovering State reasonably believes that the returned material is dangerous or hazardous, the launching authority, under the direction and control of the discovering State, is to take immediate effective action to eliminate possible danger or harm.[18]

I Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 18 U.S.T. 2410, T. I.A.S. No. 6347,610 U. N.T.S. (Apr. 22, 1968).

[2] Article VI.

[3] Article VII.

[4] Article IX.

[5] Convention on International Liability for Damages Caused by Space Objects, 24 U.S.T. 2389, T. I.A.S. No. 7762 (Mar. 29,1972, effective Oct. 9, 1973).

[6] Articles I, III, IV, and XXII.

[7] Article V.

[8] Article XII.

'Article I.

[10] There is no retirement i either the Liability Convention or the Outer Space Treaty that space objects, launch vehicles, or any components must be functional when damages occur in order for liability of the launching State/State of Registry to attain.

[11] Convention on Registration of Objects Launched into Outer Space, 28 U.S.T. 695, T. I.A.S. No. 8480, U. N.T.S. 15 (Oct. 9, 1973.)

[12] Articles I-IV.

[13] Article II, paragraph 2.

[14] Article VI.

Continued on next page

5. The Moon *Agreement of 1979*[19] entered into force on July 11, 1984. However, none of the major spacefaring nations, including the United States, is party to the Agreement. The Agreement establishes obligations of States parties and international organizations regarding environmental protection.[20] Measures must be taken to prevent the disruption of the existing balance of the environment of the Moon, other celestial bodies in our solar system, and orbits around or other trajectories to or around them, and to avoid harmfully affecting the environment of Earth.[21] Notice is to be given to the Secretary-General of the United Nations of the placement and purpose of radioactive materials.[22] Mandatory consultation procedures and subsequent means for settling disputes are provided.[23]

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[15]*Agreement on the Rescue and Return of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space*, 19 U.S.T. 7570, T.I.A.S. No. 6599,672 U. N.T.S. (Apr. 22, 1968).

[16]Article V.

[17]Article V, paragraph 1.

[18]Article V, paragraph 4.

[19]*The Agreement Governing Activities of S&&,on the Moon and Other Celestial Bodies*, United Nations General Assembly, Resolution 34/6S (Dec. 5, 1979).

[20]Article VII and Article XVI.

[21]Articles I, paragraphs 1 and 2; and Article VII, paragraph 1.

[22]Article VII, paragraph 2.

[23]Article xv, paragraphs 2 and 3.

Table 4- Classes of Space Debris

- Payloads that can no longer be controlled by their operators;
- Operational debris (objects produced as a *result* of normal space activities, remaining in outer space);
- Fragmentation debris (products o fexplosions and collisions); and
- MicroParticulate matter (micron-size objects such as solid-propellant rocket motor effluent, paint flakes, and thermal coatings).

SOURCE: Office of Technology Assessment, 1990.

litter appears to be "component parts," although jurists do not agree on this point. Whether all fragmentation debris and microparticulate matter are included is even more problematic, even if the broader interpretation of "space object" is invoked. This fuzziness is unfortunate because fragmentation debris represents about half of the orbital debris population.

Summarizing, the only classes of orbital debris included in current treaty law, with any degree of certainty, are operational debris, to the exclusion of inactive payloads, fragmentation debris, microparticulate matter, and litter. The degree of difficulty already manifest in attempting to obtain international agreement on the definition of debris clearly suggests that early voluntary national action to limit and reduce debris may be far more effective than attempting to obtain any international agreement on debris reduction procedures in the near term.

Jurisdiction and Control

Who has jurisdiction and control over space debris? If remedial action is to be included in any regulatory scheme for orbital debris, consideration should be given to the issue of who is authorized to remove orbital debris. Article VIII of the *Outer Space Treaty* provides that the State of registry of "an object launched into outer space" has the right to make and enforce domestic law in relation to that object and "any personnel thereof," and that ownership of a space object is not affected by its presence in outer space. Two legal issues raised by this provision are whether orbital debris falls within the scope of Article VIII and the extent to which jurisdiction and control over space objects is permanent.

Legal analysts agree that both active and inactive payloads fall under Article VIII. They do not agree, however, on an appropriate method for distinguishing active payloads from inactive ones. Although a test of "effective physical control" has been proposed, successfully applying this test is hampered by several obstacles. First, legal opinion favors the view that jurisdiction and control of a State over its space objects is permanent.[95] Moreover, because ownership of a space object also is permanent, regardless of its use and condition, and because the owner retains the rights of possession, use, and disposal, states or other legal entities would require the consent of the State of registration in order to interfere in any way with that space object.

Applying a doctrine of permanency to debris objects appears to impede attempts to minimize the quantity of orbital debris as it only accounts for inactive payloads, and it applies only to identifiable space objects. There may be two possible exceptions to this doctrine, however: the analogy to abandonment, and sentence 1 of Article IX of the *Outer Space Treaty.*[96]

In maritime law, abandonment arises where no personnel remain on board a vessel and there is no intent to return and reactivate it. Then the vessel becomes a derelict subject to salvage. It is not yet clear, however, whether the hazard posed by orbital debris is sufficient justification for its removal without the consent of the State of registration. Sentence 1 of Article IX of the *Outer Space Treaty* provides in part that State parties to the Treaty have obligations to cooperate, to provide mutual assistance, and to have due regard for the corresponding interests of other State parties. Although some have suggested that these legal obligations fetter the absolute nature of jurisdiction and control and ownership, application of sentence 1 may be limited. First, some have argued that corresponding interests exclude threats posed by orbital debris.[97] Second, the *Outer Space Treaty* provides for competing interests among states, but does not lay down any rules for designating priority among these interests, which include a right to hazard-free space navigation as well as a right to leave an inactive payload in orbit.

Suggestions providing for timely removal of hazardous space objects, without consent of the State of registration, are limited in their effectiveness. They refer at best to inactive payloads and other identifiable space objects, and offer no preventive measures, but only compensation after the fact. Given the inchoate nature of the law regarding orbital debris, a rigorous analysis of analogous provisions in other legal regimes would probably be quite useful.

Detection and Identification

To remove orbital debris from outer space and to hold States accountable for damage caused by their orbital debris entails a method of identifying the State responsible for the debris. Identification of space objects is addressed in the *Registration Convention.*

Identification of space objects involves two phases: detection of the object and identification of its State of registry. The *Registration Convention* contains no provisions for detection and does little to establish a system that

[95] See, for example, I. Diederiks-Verschoor, "Legal Aspects of Environmental Protection in Outer Space Regarding Debris," 30th *Colloquium on the Law of Outer Space,* 1987, p. 131.

[96] In the exploration and use of outer space, including the Moon and other celestial bodies, States Parties to the treaty shall be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space, including the Moon and other celestial bodies, with due regard to the corresponding interests of all other States Parties to the Treaty.

[97] Carl Q. Cristol, *The Modern International Law of Outer Space* (New York, NY: Pergamon Press, 1982), p. 139.

would identify the States of registry of space objects that do not appear in the registration lists.[98] Consequently, this treaty is of little use in identifying orbital debris, especially in its untraceable manifestations. Without proper identification, the *Liability Convention* cannot be invoked because the State of registry cannot be ascertained. Another possible weakness of this treaty is the absence of a provision for compulsory markings, although markings must be registered if they are used. Therefore, what would be the most obvious and convenient method for identifying space objects is voluntary. Large components could be identified relatively easily. Very small components and microparticulate debris cannot readily be marked.

Liability for Damage Caused in Outer Space

The *Liability Convention* sets out a legal regime to provide compensation for damage caused in outer space by space objects. In outer space, liability is based on fault. It is significant to note that negotiations for the *Liability Convention* did not consider the question of the risks posed by orbital debris. As a result, the negotiators did not address several liability issues of extreme importance related to damage caused by orbital debris. These issues include the meaning of "damage" and the reasonableness of a fault-based liability[99] regime for damage caused in outer space by orbital debris.

Experts generally agree that damage to the outer space environment per se is not within the scope of the *Liability Convention*. Consequently, launching States cannot be held liable for the mere presence of orbital debris in outer space. In this regard, microparticulate matter and very small pieces of fragmentation debris are of particular concern because launching States have no legal incentive to avoid generating these types of orbital debris, although they have enormous operational incentives to do so. It would be possible to amend the *Liability Convention so* as to include damage to the outer space environment per se, based on the fact that outer space is a global commons. Yet, even if accepted, resolution of three significant legal issues beyond the scope of space law would still remain: legal standing for claimant States (who is going to speak for mankind?), assessment of damages, and the nature of the liability.

The principle of fault-based liability is a further impediment to compensation for damage caused in outer space by orbital debris. Application of the fault-based outer space liability regime of the *Liability Convention* to orbital debris is doubtful because the Convention "appears to be primarily concerned with a possible collision between [active] space objects."[100] Even if damage caused by orbital debris were within the scope of this regime, several other important legal issues, such as proof of negligence, and contributory negligence, among others, would remain unresolved.

Article III of the *Liability Convention* does not specify whether the damage caused must be reasonably foreseeable, that is, whether the damage caused by orbital debris is of a kind that specialists in the field would expect to occur. It has been argued that, as a result of the impossibility of foreseeing all the different situations that could lead to damage in outer space, only two factors need to be established –the damage, and a cause-and-effect rela-

[98] As long as an object is intact, and has been registered by the launching State, as required by the convention, the State of registry can be established by observing its orbital parameters. However, the State of registry of most space debris, especially debris that cannot be tracked by existing technology, is uncertain.

[99] Fault-based liability is liability based on the ability to establish direct or indirect fault for damage.

[100] United States Congress, Staff of Senate Committee on Aeronautical and Space Sciences, 92d Cong., 2d Sess., ***Report on the Convention on International Liability for Damage Caused by Space Objects: Analysis and Background Data*** (Comm. Print 1972), p. 27.

tionship between the damage and the incident giving rise to the damage.

The terms of the *Liability Convention* place restrictions on who may seek compensation for damage caused in outer space by orbital debris. For example, compensation is unavailable for any damage resulting from a collision between two space objects, each owned by a different private entity, if both entities are under the jurisdiction of the same launching state.[101] The same result would follow if one of the space objects were a piece of identifiable orbital debris. Nor is compensation available under the convention to injured parties who are either nationals of a launching State or foreign nationals participating in any phase of a space activity. This restriction extends to nationals of all States participating in any one launch activity, and to nationals of all States entering into joint ventures with any State participating in any launch activity. Additionally, certain provisions of NASA launch agreements that allocate risk among the participating parties further limit eligible claimants by arranging reciprocal cross-waivers of claims among participants.

One serious shortcoming of the decision to base damage in outer space on fault has been that the rationale for fault-based liability must be applied to damage caused in outer space by orbital debris. This rationale, ostensibly based on the equality of States in undertaking space activities, makes three fundamental assumptions: States participating in space activities accept the risks involved; States are free to conduct any space activity as long as fault-based damage does not result; and absolute liability[102] for damage to space objects in outer space would lead to absurdities and inequities.

Although the fault rationale may well be justified in the event of collisions between two active, and therefore controlled, satellites, its application seems unreasonable where damage in outer space is caused by orbital debris. In this situation, application of the rationale for absolute liability may be more appropriate. First, space flight and space activities may be considered ultrahazardous or abnormally dangerous activities for which "responsibility [should be] imputed to the person or entity making the initial decision to engage in the activity which exposes others to risks where possibly no amount of foresight or feasible protective measures may avert injuries."[103] Therefore, in cases where orbital debris causes damage, those who create the risk should bear the cost of not only compensating for damage done to persons and property in outer space, but also protecting the space environment itself. Second, absolute liability is considered necessary when it is unlikely that fault can be established. In the outer space context, and particularly when orbital debris is being considered, problems of establishing the proof of fault necessary for satisfying the courts are magnified. The problems encountered with making the case under existing or even strengthened liability provisions make it essential to concentrate on establishing a preventive set of measures and enforcement mechanisms.

The Kosmos 954 incident illustrates how a claim may be based upon the *Liability Convention* and principles of international law. Canada's claim consisted of compensation for search, recovery, testing, and clean-up. Under principles of international law, Canada had a duty to take the necessary measures to prevent and reduce the harmful consequences of the damage (mitigation).[104] The settlement procedures of the *Liability Convention* were

[101] In that case, an injured party would have to seek redress under national laws of the State concerned.

[102] In other words, where liability is incurred by a party regardless of fault.

[103] U.S. Senate Report on Liability Convention, op. cit., footnote 99, p. 26.

[104] See Canada: Claim Against the Union of Soviet Socialist Republics for Damage Caused by Soviet Kosmos 954, reprinted in *International Legal Materials*, vol. 18, 899, par. 15 & 17, 1979.

never actually applied to the matter, however, as the dispute was resolved without invoking them. Officially the Soviet Union did not admit liability for the damage,[105] but agreed to pay Canada $3 million (Canadian) "in full and final settlement of all matters connected with the disintegration" of Kosmos 954.[106]

FUTURE DIRECTIONS FOR REDUCING ORBITAL DEBRIS

The effect of orbital debris on future space activities depends in part on the success nations have in instituting procedures to reduce their future contributions to orbital debris. The first spacecraft was launched into space in October 1957; the first serious fragmentation of a satellite occurred in June 1961.[107] Yet nearly two decades passed before the potential hazard from orbital debris began to be widely appreciated. Although the technical community had developed concern about the debris hazard,[108] several additional years of observation and experimentation passed before the United States adopted a formal policy on space debris. The first formal policy step was the adoption by the DOD in February 1987 of a space debris policy as part of its overall space policy.[109] Prior to 1987, NASA and the Air Force had already begun to adopt informal operational strategies to minimize space debris. For example, as noted earlier, shortly after the last explosion of a Delta upper stage in 1981, NASA instituted the practice of eliminating excess fuel from these upper stages after placing payloads in orbit.

Administration policy on orbital debris was first publicly articulated in February 1988 as part of a comprehensive statement of space policy: "all space sectors will seek to minimize the creation of orbital debris. Design and operations of space tests, experiments, and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness."[110] The Bush Administration has continued that same policy, but has extended it to include outreach to other nations: "The United States government will encourage other space-faring nations to adopt policies and practices aimed at debris minimization."[111]

One of the important frost results of the 1988 policy was the *Report on Orbital Debris,* which was developed and published by the Interagency Group (Space) for the National Security Council in February 1989. That report, and the earlier ESA report on orbital debris,[112] along with a number of technical workshops and briefings, have made substantial contributions to a wider understanding of the debris problem. These efforts have assisted in garnering support for further study of the increasing threat, and the development of possible mitigation strategies.

[105] L.H. Legault and A. Farand, "Canada's Claim for Damage Caused by the Soviet Cosmos 954 Satellite," Ottawa, 1984, pp. 19-23.

[106] "Canada-Union of Soviet Socialist Republics: Protocol on Settlement of Canada's Claim for Damage Caused by 'Cosmos 954'," *International Legal Materials,* vol. 20, p. 689.

[107] This was a Transit 4A rocket body, which "unexpectedly blew itself apart only a few hours after launch": Johnson and McKnight, op. cit., footnote 9.

[108] For example, the American Institute of Aeronautics and Astronautics issued a position Paper on space debris in 1981 that warned of the hazard and urged action to reduce it: AIAA Technical Committee on Space Systems, Space Debris, An *AIAA Position Paper, American* Institute of Aeronautics and Astronautics, New York, 19S1.

[109] The DOD policy stated, "DOD will seek to minimize the impact of space debris on its military operations. Design and operations of DOD space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements." Office of the Secretary of Defense, Department of Defense Space Policy Statement, Mar. 10, 19S7 (unclassified).

[110] White House Fact Sheet, "Presidential Directive on National Space Policy," Feb. 11, 1988, p. 4.

[111] Space Policy, op. cit., footnote 34.

[112] European Space Agency, Op. cit., footnote 3.

Characterization of the Debris Environment

The limited data available on the extent and character of the orbital debris environment inhibits the development of mitigation strategies. In the United States, both NASA and the Air Force have modest programs to expand our understanding of the space environment.

As noted in box 2, the orbital debris catalog baseline for extrapolation into the future is a growth rate of 240 objects per year. Yet, some experts expect the growth rate to increase as the number of space activities increases. The increasing numbers of spacecraft placed in high, long-lived orbits are particularly worrisome. If launch and breakup rates[113] increase during the coming period of low solar activity, when the "wash out" effect will below, the debris growth rate may approach 5 or 10 percent per year. For example, preliminary analysis has shown that deterioration of certain types of satellites may produce numerous trackable objects over time. This type of breakup may prove to be a significant source of debris as more satellites linger in orbit after their operational lifetime.[114]

Determining which rate to use for future projections is very important for future planning. For example, at a 10 percent debris growth rate, the cataloged debris population would double in only 7 years. At a 5 percent growth rate, the period needed to double the debris population is 14 years, and for a linear growth of only 240 cataloged objects per year, the doubling rate would be 29 years. Knowing the number and mass of objects capable of being included in the SSN catalog helps to quantify the hazard from debris, but derelict pieces of hardware too small to be cataloged still pose a more significant hazard to space systems than do cataloged items.

Table 5-Key Program Needs for Characterizing the Debris Environment

Concern/Uncertainty	Program Needs
Nontrackable debris	Improved sensing capabilities, in situ experiments and database
Debris creation	Analytic models based on empirical data
Trigger for breakups	Experiments (explosion/collision)
Population trends	Analytical studies
Improve database and ability to moniter debris	Expand number of radar sites and add more optical and infrared observations
Enhance data management capacity	Improve communications between data sources and database
Long term evolution	Traffic models and propagation techniques
Define mass of debris	Correlate radar, optical, and infrared observations

SOURCE: Darren S. McKnight end the Office of Technology Assessment, 1990.

Table 5 lists some of the key needs for improving the characterization of the space debris environment. In order to establish the necessary information base on which to build strategies for effective future management of orbital debris, the United States and other countries will have to develop sustained programs to characterize the existing space environment and to model potential future growth of space debris.

Data from spacecraft surfaces exposed to the outer space environment and returned to Earth for analysis (table 6) have provided the United States with information on direct impact damage from natural and artificial space debris.[115] These surfaces show that, compared to natural objects, artificial debris causes a larger number of impact craters less than 20

[113] Note that launch rates could increase and the debris population stay constant or even decrease if the breakup rate decreased accordingly.

[114] Nicholas L. Johnson, Preliminary in-house analysis for Teledyne Brown Engineering, 1989.

[115] H.A. Zook, D.S. McKay, and R. P. Bernhard, "Results from Returned Spacecraft Surface%" AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, April 16-19, 1990, Baltimore, MD, p. 1.

Table 6-Spacecraft Surfaces Returned From Space Analyzed for Debris Impacts

- windows from Mercury, Gemini, Apollo, Skylab, and Shuttle;
- meteroid experiments exposed on Gemini, Skylab, and Shuttle flights;
- parts of Surveyor III spacecraft returned from the Moon;
- Palapa and Westar satellites; and
- Solar Max surfaces.

SOURCE: H.A. Zook, DS. McKay, and R. P. Bernhard, "Results From Returned Spacecraft Surfaces," AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Apr. l&19, 1990, Baltimore, MD.

microns in diameter, and may cause a greater number of impacts larger than a few millimeters; but the data on this finding are inconclusive. Natural micrometers cause the greatest number of impact craters in size ranges between 100 microns and a few millimeters. These data support the conclusion that debris densities in LEO have increased since the 1970s when Skylab was orbited and that particles from solid rocket motors and surface paints clearly contribute to the debris population.

The LDEF– (box 6), which NASA retrieved from orbit in January 1990, provided an unparalleled opportunity to gather data on the debris environment of LDEF's orbits. Because the planned Space Station will be located in similar orbits, this information will be invaluable in designing the means to help protect the Space Station from orbital debris impact.

The existing Haystack Radar and the future Haystack Auxiliary Radar, which USSPACECOM will operate for NASA (box 7), will provide the most cost-effective means to study the general distribution of space debris at LEO altitudes (below 500 kilometers). Eventually, a space-based system maybe required (table 7). It maybe important to place optical and infrared systems on space station *Freedom* to characterize and monitor its particulate environment. Otherwise, *Freedom's* use as a scientific observing platform may be degraded.

Box 6-The *Long Duration Exposure Facility (LDEF)*

LDEF, a spacecraft the size of a small school bus, was designed to measure the effects of atomic oxygen, space radiation, micrometeroids, orbital debris, vacuum, and other space-related phenomena on a variety of materials. It carried more than 10,000 test specimens in 57 experiments. More than 200 investigators from 9 countries were involved in these experiments.

On April 7,1984, NASA deployed LDEF from the Shuttle orbiter ***Challenger.*** It had been scheduled for retrieval in the fall of 1966. However, the failure of ***Challenger*** in January 1966 and the necessity to launch more critical payloads in 1966 and 1969 after the Shuttle returned to service, kept LDEF in orbit for nearly 6 years. As a result, LDEF represents an unexpected opportunity to observe there-sults of long-term exposure to the space environment, including the effects of orbital debris.

The orbiter ***Columbia*** retrieved LDEF in January 1990. Although some experiments aboard LDEF had been degraded by the unexpected length of time the satellite was in orbit, the extra exposure to the space environment has produced results that are of great interest to spacecraft designers. Detailed examination of LDEF and interpretation of the results will take months. Initial observations revealed the following

Thin films-Some thin-film test specimens appear to have degraded or completely eroded.

Kapton-Thermal covers on two trays for experiments on heavy ions in space were partially peeled back. In addition, the thermal cover strips around the detectors of a space plasma high voltage drainage experiment eroded away.

Debris damage-The thermal cover of a cosmic ray nuclei experiment, located at the leading edge of the spacecraft, sustained damage from either artificial or natural debris.

Cosmic **dust** impacts-the first year of LDEF's operation revealed 15,000 impacts from interplanetary dust, from six directions.[1] The experimental surface facing the direction of flight experienced 4,500 dust impacts.

SOURCE: National Aeronautics and Space Administration

[1]S. F. Singer et al., paper presented at the 21st Meeting of the Division on Dynamical Astronomy, American Astronomical Society, Austin, TX, April 1990.

Bo x 7– ***Orbital Debris Radar Observations***

In 1989 NASA and USSPACECOM completed an agreement to develop aground-based radar program that will be capable of examining the debris population density of objects of 1 centimeter or greater diameter at altitudes up to 500 kilometers. It will provide much needed data for:

- extended duration Shuttle orbiter;
- long-duration extravehicular activity by astronauts;
- future modifications to Space Station Freedom shielding,
- determination of sources of debris;
- effectiveness of operations designed to minimize debris.

USSPACECOM will make near-term observations (through 1991) of space debris from the existing Haystack antenna in Massachusetts. Haystack is a high-power, X-band radar. Haystack provided frst test results in May 1990, and demonstrated that it could observe orbital debris with diameters smaller than 10 centimeters. Full calibration of the antenna to determine the sizes of objects it is observing will require more tests. By September 21, 1990 NASA expects to have data from about 400 hours of observations.

NASA will be responsible for the costs of developing a Haystack Auxiliary (HAX) Radar at Millstone Hill, Massachusetts, and a copy on Ascension Island. The USSPACECOM will operate HAX, which will gather data in the Ku-band, after the new facility becomes operational in late 1991, and continue to provide debris information for NASA and Air Force needs. The HAX Radar will have a broader beam. Its data will supplement data from Haystack and, when correlated with Haystack observations, w-ill provide additional information on the size of observed particles.

SOURCES: National Aeronautics and Space Administration; U.S. Air Force; and J. Beusch and I Kupiec, "NASA Debris Environment Characterization with the Haystack Radar" (AIAA 90-1346). Presented at the AMA/ NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Baltimore, MD, Apr. 16-19, 1990.

Table 7-Radar Performance Requirements

Near-Term for Space Station Freedom

- **50 percent probability of detection of 1 centimeter diameter debris at 500 kilometer altitude;**
- **irregular debris objects;**
- **attitude determined to +/- 25 kilometers over altitude range of 300-600 kilometers;**
- **100 detections in 3 months to reach accuracy of +/- 30 percent;**
- **radar operational by 1 October 1991 to support Freedom critical design review.**

Long-Term Monitoring

- detect **debris** at **inclinations of 7° or greater with an accuracy of +/- 5°;**
- **determine altitide to +/- 1 kilometer over range of 300-2,000 kilometers;**
- **90 percent detection probability of 1 centimeter diameter particles at 500 kilometers altitude.**

SOURCE: National Aeronautics and Space Administration and U.S. Air Force.

Mitigation and Protection Techniques

Mitigation

If the space-faring nations are to reduce the hazards posed by orbital debris, research on debris mitigation techniques must continue, and nations must continue to assess their ability to reduce the growth of orbital debris (table 8). In particular, work is still needed on reducing the amount of debris from space operations, in reducing the risk of breakup as a result of collisions, and in limiting the erosion of spacecraft parts and other space objects because of materials degradation. The research conducted on LDEF will provide critical information on the performance of various materials used on spacecraft. As yet, no government or industry studies on alternative spacecraft design have been carried out.

Table 8-Key Program Needs for Debris Mitigation

Concern/Uncertainty	Program Needs
Debris mitigation policies	Develop laws/regulations Assign national points of contact
Derelict rocket bodies	Vent excess propellants and pressurants
Derelict payloads	Design for removal by propulsion and/or drag enhancement
Reduce number of GEO derelicts	Propulsion and hazard analysis
Operational debris	Redesign and use degradable material
Reduce secondary debris	Advanced materials
Minimize debris production	All of the above

SOURCE: Damn S. McKnight and the Office of Technology Asseesment, 1990

Table 9-Key Program Needs for Protection From Debris

Concern/Uncertainty	Program Needs
Response to large debris impact	System level interactions, materials
Passive avoidance	Redesign mission profile
Active avoidance	Prediction, propulsion, structures, sensors
Response to small debris impact	Shielding, materials

SOURCE: Darren S. McKnight end the Office of Technology Assessment, 1990.

Protection

Additional means to protect against debris impacts will be important. The conventional dual wall system, designed to protect spacecraft from meteoroids, has also been used to defend against small pieces of artificial debris. Yet, there is still no cost-effective way to shield against debris impacts from fragments larger than 0.5 centimeters in diameter. Equally as uncertain are the effects of collisions with these larger objects.

Work is underway within NASA and the Air Force on means to provide spacecraft with greater protection from small space debris (table 9). However, work on protecting from impacts of larger objects, and on debris avoidance, is needed.

U.S. Research *Plans*

The U.S. Interagency Group report on orbital debris recommended that NASA, DOD, and DOT develop a research plan to improve orbital debris monitoring and modeling, and management of accumulated data; and develop "generic technologies and procedures for debris minimization and spacecraft survivability."[116] This plan was completed and disseminated in early June, 1990.117 The three agencies envision preceding in two phases. Phase I (near-term, fiscal year 1990-92) would:

- assess the orbital debris environment;
- develop space station *Freedom* protection design criteria;
- develop new (and document existing) debris minimization practices and procedures;
- develop new breakup models for spacecraft and techniques for assessing survivability against debris; and
- collect data to support future development of regulations, standards, nation-d policy, and international understanding.

Table 10 summarizes projected expenditures for Phase I studies.

Phase II would build on the information developed in Phase I; hence, specific activities cannot be planned today. However, the agencies are likely to pursue the following types of activities:

- monitor the debris environment;

[116] National Security Council, op. cit., fbOtnOte 2, p. 52.

[117] DOD/N ASA/DOT, "Orbital Debris Research Plans," May 1990.

Table 10-Phase I Summary of Projected Expenditures for the NASA/DOD/DOT Research Plan

	Fiscal year '90			Fiscal year '91			Fiscal year '92		
Program includes:	DOD	NASA	DOT	DOD	NASA	DOT	DOD	NASA	DOT
Debris environment assessment									
● Measurements/data analysis									
. Modeling									
● Data management									
Space Station *Freedom* Criteria									
Debris Minimization									
● Commercial regulatory options and economic impacts									
Spacecraft Survivability									
● Commercial regulatory options and economic impacts									
Total budgeted ($K)	(1,000)	14,986	80	(1,500)	12,121	110	(1,500)	7,578	180

NOTE: DoD ( ) = unfunded requirements.

SOURCE: National Aeronautics and Space Administration.

- update debris characterization models;
- improve hazard assessment capabilities;
- improve protection techniques;
- minimize debris generation; and
- review commercial regulatory options.

International Cooperation

The United States has taken the lead in studying the orbital debris environment, providing a debris database for the rest of the world, and in developing strategies to reduce the potential for generating new orbital debris. However, even if the United States were able to eliminate completely its future contribution to the orbital debris environment, little effect on the overall debris environment would result unless similar practices were adopted in other countries. At present, the United States, the Soviet Union, Europe, China, and Japan are capable of launching payloads into the full range of Earth orbits. India is developing its own independent launch capability and should be able to place objects routinely in low-Earth orbits in a few years. In addition, Brazil, Iraq, and Israel are also working toward independent launch capabilities.[116]

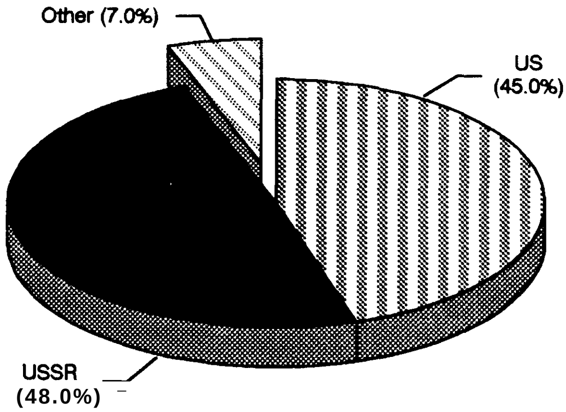
The existing debris population poses a small, but finite, hazard today. Despite cleansing effects during periods of high solar activity, most experts agree that fragmentations and collisions of existing debris will continue to add objects to this population. Hence, it is in the best interest of the United States and other space faring nations to tackle these problems in concert. Working with the Department of State and other agencies, NASA has briefed space officials in Australia, Canada, the European Space Agency (ESA), France, India, Japan, the Soviet Union, and West Germany. Officials from NASA and ESA have met several times to discuss concerns of mutual interest on orbital debris and to identify specific areas for future cooperation. In 1987 NASA convened a conference on orbital

[118] Israel launched its second satellite in April 1990.

debris from upper stage breakups,[119] which included participants from ESA, France, and Japan, and has sponsored other meetings on orbital debris issues. European and Japanese participants contributed papers to the orbital debris conference held by the American Institute of Aeronautics and Astronautics, NASA, and DOD in Baltimore in April 1990.[120]

The United States and the Soviet Union are the two major contributors to orbital debris (figure 11). However, to date, any efforts the Soviet Union might have taken to characterize and reduce the hazard posed by orbital debris are poorly understood in the United States. Although "Glasnost" has made working with Soviet officials much easier than in the past, access to Soviet policy thoughts or to reliable Soviet data on debris has been difficult to obtain. In December, 1989, NASA officials traveled to Moscow to brief Soviet space officials on U.S. progress and to learn about the efforts the U.S.S.R. has made toward understanding the orbital debris environment. Although U.S. officials failed to reach a thorough understanding of any Soviet efforts to study the orbital debris problem, the meeting furthered prospects for cooperating with the Soviet Union on limiting the production of orbital debris. Soviet officials showed concern about the problem and expressed interest in cooperating to limit the future growth of debris.[121] Independent indications, derived from Space Surveillance Network data, suggest that the Soviet Union has stopped its practice of fragmenting its own satellites in the higher altitudes of LEO. Recent fragmentations were carried out at altitudes where the debris would enter Earth's atmosphere within 90 days.

Figure 11 -Total Number of Orbital Objects in the Space Surveillance Network Catalog by Nationality



The United States and U.S.S.R are about equally responsible for the total cataloged population.

SOURCE: Darren S. McKnight, 1990.

These efforts, though extremely important first steps, do not go far enough. Some sort of concerted international action to reduce the threat of orbital debris is needed. It may therefore be appropriate for the United States to convene a working group of spacefaring nations that would discuss mitigation strategies and seek to reach agreement on them. As soon as feasible, other nations that have an interest in space activities, even though they cannot yet launch spacecraft into orbit, should also be brought into such discussions on the ground that their investment in space systems is at risk. For example, the International Telecommunications Satellite Organization (Intelsat) and the International Maritime Satellite Organization (Inmarsat) purchase launch services on the international market to place their communications satellites in GEO. Both organizations are owned by nations only a few of which have the capability to place satellites in orbit. Yet the communications satellites they own are threatened by space debris. Likewise, regional organizations such as Arabsat (Middle East) and Eutelsat (Europe), as well as individual countries, own assets in GEO. In the future, when more nations make use of

[119] Loftus (cd.), op. cit., footnote 80, pp. 41-106.

[120] AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Baltimore, MD, Apr. 1619, 1990.

[121] Joseph Loftus, NASA, personal communication, 1990.

LEO for remote sensing satellites and other uses, their satellites will be placed at risk in these orbits.

Crews in Space

The destructive consequences of orbital debris are of special concern when considering human spaceflight, especially long-term stays. Crews in space require habitats of much larger cross section than are required for automated spacecraft. For a given orbital debris flux, the larger cross section substantially raises the probability that such spacecraft would experience a destructive impact during a given period of time. Human crews currently operate in LEO, where the debris flux is already relatively high and where the relative velocities between debris and spacecraft are also high. Cosmonauts aboard the Soviet station, *Mir,* experience small hits from artificial and natural debris, which they hear as "pings" against the exterior shell.[122] Although none of these encounters have caused serious damage, some have broken the exterior light bulbs on *Mir,* which as a result are now protected.

As the aftermath of the 1986 *Challenger* failure demonstrated, our society places great importance on the personal safety of humans in space. Hence, in planning space station *Freedom* and in operating the long-duration Shuttle orbiter,[123] it will be extremely important to understand fully the risks that debris poses to their operation. The overall costs to the space program of losing human lives from debris encounters could far outweigh the simple cost of repair of *Freedom* or replacement of a long-duration orbiter.[124] In building the Shuttle, designers took into account the risk of collision from natural debris, but did not consider the risks of orbital debris. Even though the yearly probability of encounters with orbital debris may be extremely low, impact with a large debris object could cause significant damage. *Freedom* is being designed to last 30 years on orbit, and should be capable of shielding against small objects (less than about 2 centimeters) and, infeasible, avoiding larger ones.

NASA plans to provide shielding for critical elements of the space station, such as the habitation modules.[125] It is studying possible collision avoidance maneuvers for Shuttle and *Freedom.*[126] However, before completing the station's shield design, NASA will have to provide an up-to-date model for characterizing the orbital debris environment.[127]

A probabilistic risk analysis of space station *Freedom* should take into account both the probability of a significant impact event (the estimation of the hazard) and its consequences (the total cost to NASA to the nation, and to the other participating countries of such an event). A risk analysis also should examine the proposed use of *Freedom* as a transportation node and service depot for launching cargo and crews to the Moon and Mars. How would fuel and other volatile substances be handled, for example? Although NASA may be able to reduce the probability of a fuel tank explosion to extremely small levels, some small chance of explosion, as a result

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[122] Djinis, op. cit., footnote 25.

[123] NASA is now developing the means to allow the Shuttle orbiters to remain in space for up to 28 days, which is more than twice as long as the longest Shuttle mission to date.

[124] Public reaction to losses of life is difficult to predict but could result in a much more conservative approach than now exists to placing humans in space.

[125] Neider, op. cit., footnote 27.

[126] Faith Vilas, Michael F. Collins, Paul C. Kramer, G. Dickey Arndt, and Jerry H. Suddath, "Collision Warning and Avoidance Considerations for the Space Shuttle and Space Station *Freedom*," AIAA-90-1337, AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Baltimore, MD, Apr. 18-19, 1990.

[127] U.S. Congress, General Accounting Office, op. cit., footnote 24, p. 28.

either of structural failure or human error, would remain. Even if a fuel depot were located several hundred kilometers from the Space Station, such an explosion would cause debris to spread rapidly to *Freedom,* placing at risk the entire facility and the crews in it (figure 7). The debris cloud formed may decay only slowly with time, forcing NASA to make difficult decisions about the safety of crew and equipment. In addition, the debris cloud could threaten other spacecraft in nearby orbits, including the Shuttle orbiters, future escape vehicles, and perhaps, the successor to the Soviet ***Mir*** and crew-carrying launch vehicles and habitats of other nations.

Space stations, especially because they are large, complicated structures and have a large surface area, may also produce debris. Over several years, as debris objects generated by space station operations change orbits slightly and expand into a toroidal belt (figure 7), space stations, as well as launch vehicles supplying them, become targets of their own debris. *Freedom* will therefore require tight environmental control to limit generation of space debris.

NASA is developing shielding for *Freedom* and is weighing the risks of carrying out other space activities in *Freedom's* orbits. Most objects resulting from activities in or near its orbital range will generally have small relative velocities with respect to the space station,[128] hence the protection necessary from such debris will be relatively lightweight. However, other debris, in orbits that would intersect the plane of *Freedom's* orbits, could have much higher relative velocities and cause considerable damage. Fortunately, the probability of damaging encounters with this debris is extremely small.

Special Concerns About Geostationary Orbit

As noted in Section IV, experts do not yet agree about the minimum safe distance to remove spacecraft from GEO in end-of-life maneuvers. Considerable additional study will be necessary to characterize the existing debris environment in GEO and to predict the long-term results of potential mitigation strategies.[129] As satellite owners need to plan for disposal of their satellites when they are being designed, the relevant technical committees of the International Telecommunication Union, as well as international organizations such as Intelsat and Inmarsat, should be involved in such studies.

Raising satellites to a level beyond the GEO altitude currently recognized as the minimum required for efficient protection (200 - 300 kilometers) can require the same amount of fuel required as keeping a satellite on orbit for an additional year. Hence, boosting satellites beyond GEO may exact a significant cost from the operator.[130] For example, the loss of a year's revenue for an Intelsat VI satellite is estimated to be more than $20 million.[131] However, for many satellites, lost revenue will be considerably less; satellite designers are investigating ways to measure residual fuel more accurately. Removing spacecraft to supersynchronous orbits 300 to 600 kilometers above GEO could reduce the collision hazard by factors of as much as 1,000.[132] However, the

128A]ong as they do not result from explosions or hypervelocity collisions with large debris objects.

129For example, the amount of fuel necessary to remove satellites above the GEO band varies with respect to the area-to-mass ratio oftheabandoned satellite. See A. G. Bird, "Special Considerations for GEOESA," AIAA/NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions, Baltimore, MD, Apr. 18-19, 1990,

130One of the problems operators face is gauging correctly the amount of fuel they have left in an operational satellite. See A.G. Bird, ibid.

131National Security Council, op. cit., footnote 2, p. 33.

132Typical propellant requirements for this maneuver are estimated to be less than 10 kilograms of fuel. See Chobotov, op. cit., footnote 89.

value of such procedures must be balanced against the probability of experiencing other harm from them. For example, firing a satellite thruster may result in an explosive failure of the thruster. Although the probability of such an event maybe very small, it should be weighed against the probability of collision if the satellite is not removed.[133]

National Security Concerns

Military activities involving sensitive instruments used to gather information from space could be adversely affected by orbital debris that damages sensors or disrupts communications.[134] Impact of space debris with a crucial national security satellite, such as one used to verify international treaty compliance, could heighten tension at times when international tension was already high, as such damage may be extremely difficult to separate from intentional attack.

Some commentators have noted that orbital debris could actually be used to military advantage.[135] If a non-functioning satellite is considered to be debris, there maybe a military advantage to leaving it in orbit. An adversary might not be able to distinguish it from a spare. On the other hand, the deliberate introduction of debris into outer space either to deny access to a particular orbital region or to interfere with surveillance activities is certainly antithetical to existing international treaties and agreements. Deliberately introducing debris into an orbit would also harm the perpetrator, as it would deny *all* users the use of it and nearby orbits. Nevertheless, either clouds of debris or individual, larger objects could be used to inflict damage on the spacecraft of other nations. The United States may well wish to place these and other related considerations on the table in discussions of international approaches to minimizing orbital debris.

The Private Sector

According to the *Outer Space Treaty of 1967,* to which the United States is party, each nation is responsible for regulating the activities of its nationals in outer space. The private sector, including the launch vehicle industry and the spacecraft industry, will be affected by any international agreements entered into by the U.S. Government.

Several U.S. Government agencies regulate private sector space activities in accordance with several U.S. laws (app. C). Whatever policies the United States adopts for regulating private sector activities should take into account the needs and concerns of the private sector. In particular, government agencies charged with regulating space activities should not unnecessarily prejudice the ability of the U.S. private sector to compete with firms in other countries. However, the government should also assure itself that private firms are instituting appropriate controls on the generation of orbital debris.

Firms that own space assets have already benefited from government-sponsored research on the extent of orbital debris, mitigation strategies, and protective technologies. In the long run, privately owned space assets will experience a safer environment as a result of this research. However, some debris-reduction strategies that could be required by the government may be costly. The Department

[133] J.J. Butts and W. G. Bagnuolo, "Satellite Collisions in the Geosynchronous Belt," contract no. F04701-81-C-0082, The Aerospace Corp., Jan. 15, 19S2.

[134] N. Jasentuliyana, "Environmental Impact of Space Activities: An International Law Perspective," American Institute of Aeronautics and Astronautics, *27th Colloquium on the Law of Outer Space,* 19S4, p. 391.

[135] See Baker, op. cit., footnote 92, pp. 21.22; R Bridge, "International Law and Military Activities in Outer Space," vol. 13, *Akron Law Review, 1980,* p. 649.

of Transportation is investigating the costs and benefits of controlling debris generation.

The expertise on detailed vehicle and spacecraft design in the United States is shared between highly specialized government research facilities, the universities, and the aerospace industry. A national appraisal of the problem of space debris should draw upon all of the best talent available. As commercial space activities grow in importance, government should continue to involve the private sector in developing debris reduction strategies and in determining which ones are most cost-effective.

Appendixes

Appendix A
Collision Probabilities for Satellites

The probability of collision (PC) between a satellite and debris during a mission of duration T is represented by

$$PC = 1 - e^{(-SPD * VREL * AC * T)} \qquad (1)$$

where SPD = spatial density, objects per km^3
VREL = relative velocity, km/s
AC = cross-sectional area, km^2
T = mission duration, sec

When the probability of collision is very small, less than 0.190, the equation above may be approximated by

$$PC = SPD * VREL * AC * T. \qquad (2)$$

Table A-1 summarizes typical values of the *terms* in the PC equation for LEO and GEO orbits over a mission period of 1 year.

Table A-1 - Probability of Collision

	LEO	GEO
SPD	10^{-10} to 10^{-7}	10^{-11} to 10^{-7}
VREL	6 to 14 km/s	0.1 to 0.8 km/s
AC	10 m^2	10 m^2
T	year	1 year
PC	10^{-7} to 10^{-4} per year	10^{-12} to 10^{-7} per year

NOTES: For the GEO calculations the maximum values for SPD and VREL cannot be used simultaneously to arrive at a maximum PC.
The PC for a GEO satellite is clearly orders of magnitude smaller than for a LEO satellite

SOURCE: Darren S McKnight

Appendix B
U.S. Statutes Governing Outer Space

The National Aeronautics and Space Act[1] does not refer specifically to "space debris;" rather its provisions for environmental protection are based upon the National Environmental Policy Act (NEPA)[2] and its pertinent regulations.[3] This means that whenever NASA's actions may affect the quality of the environment it must either have an environmental assessment (EA)[4] or submit an environmental impact statement (EIS).[5] Both U.S. and ESA reports rely upon the international legal definition of '(global commons," which are those territories outside the jurisdiction of any states. This definition provides the broadest, most general basis for including outer space within those "global commons, " and would provide a mandate for protection of the space environment. Such a mandate would necessitate recognition and prioritization of some of the legal issues which involve mitigation and control of space debris.[6] This definition is also the basis for the Outer Space Treaty's provision that no state shall claim sovereignty over outer space, the Moon, or other celestial bodies.[7] However, NASA regulations that provide for environmental protection appear to characterize the global commons much more narrowly, and it is argued that NASA regulations do not mandate protection of the outer space environment, per sea For example, NASA regulation 14 CFR 1216.321(a) (1988) states that the analysis by the Headquarters Official of actions under his/her supervision shall include consideration of the environmental effects abroad as well as potential effects upon the global commons (i.e., "oceans and the upper atmosphere") (emphasis added). That argument might be stronger if the agency created by the Act was simply the "National Aeronautics Administration," but the title includes SPACE; therefore the regulations appear to have been constructed in ways to leave U.S. obligations to the outer space environment in the internatational forum, rather than expanding domestic regulations. Consequently, an environmental assessment or environmental impact statement is not a legal requirement for space activities in outer space, which could produce space debris.

The application of the *National Environmental Protection Act.* according to the U.S. report, has been stated by various government agencies as legally inappropriate for application to space debris problems because neither civil nor military regulatory law provide standards SPECIFIC to space law.[9] Such agencies may choose to conduct environmental assessments for their activities involving space transportation and communication as a matter of policy, but do not consider such

[1] National Aeronautics and Space Act, 72 Stat. 426 (1958) (codified at 42 U.S.C. 2451 [1978 & supp. 19871).

[2] 42 U.S.C. 4321-4370 (1978& supp. 1987). NEPA states that all Federal agencies must comply with its requirements. (42 U.S.C. 4321).

[3] 40 CFR 1500-1517 (1987). The NASA regulations implement the directives of NEPA to "protect and enhance the quality of the environment . . . (from) actions which may have an impact on it." 14 CFR 1216.102(a) (d) (1984).

[4] EAs are generally required 'or'. "specific spacecraft development and flight projects in space and terrestrial applications; reimbursable launches of nonNASA spacecraft or payload;. . . and actions to alter ongoing operations at a NASA installation which could lead either directly or indirectly to natural or physical environmental effects. " 14 CFR 1216.306(c)(2) (1984).

[5] A type of specific action that would require NASA to do a more formal EIS would be. ". . . development and operation of space vehicles likely to release substantial amounts of foreign materials into the Earth's atmosphere, or into space. " Ibid. (c)(2).

[6] National Security Council, *Report on Orbital* Debris by Interagency Group (Space), February 1989, p. 43.

[7] Outer Space Treaty, Article II.

[8] Howard Baker, Space Debris: Legal and Policy Implications (Dordrecht: Martinus Nijhoff Publishers, 1989), p. 70.

[9] National Security Council, op. cit., footnote 6, p. 43.

assessments to be required, under essentially the same argument as that stated above for the NASA environmental protection regulations. A similar decision has been made with regard to Executive Order 12114 for certain Federal actions that may affect the "global commons outside the jurisdiction of any nation (e.g., the oceans or Antarctica)": the specification of examples is interpreted as an intention to narrow the environmental considerations.[10]

The Commercial Space Launch Act ***of 1984, as*** *amended*[11] establishes a licensing process that addresses hazards from space debris generated by commercial launch activities.[12] In addition, for certain payloads, the Office of Commercial Space Transportation must determine whether the launch of these payloads would jeopardize public health and safety, safety of property, and U.S. national security and foreign policy interests.[13]

The Lund Remote Sensing Commercialization Act ***of 1984***[14] provides that licensed entities must dispose of any satellites in space when the license terminates, and disposal must be made "... in a manner satisfactory to the President."[15] Presumably this would mean that a defunct spacecraft would not be left where it would contribute to the creation of more space debris.

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[10]Ibid.

[11]49 U.S.C. app. 2601-2623, Public Law 96-575, 100-657, (1984 and Supp. 1988).

[12]14 CFR, Ch. III.

[13]Ibid. (14 CFR 415.27).

[14]Public Law 96-366, 98 Stat. 451, July 17, 1984.

[15]National Securit, Council, op. cit., footnote 6.

Appendix C
U.S. Commercial Regulatory Programs

The three U.S. governmental agencies most involved in the regulation of commercial activities in outer space are the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce[1], the Federal Communications Commission (FCC)[2], and the Department of Transportation (DOT).[3] Each of these agencies is involved in promulgating regulations that fulfill three principal regulatory aims of the Federal Government: direct control of commerce and trade; protection of public health and the environment; and proper management and control of Federal funds and property.[4] National Space Policy recommends a certain amount of regulatory restraint, in order not to ". . . unnecessarily prejudice the development and international competitiveness of the U.S. commercial space industry."[5]

Federal Communications Commission. The role of FCC in regulating commercial space activities is connected to its authority to allocate radio frequencies and to manage their use.[6] Because FCC authorizes construction, launch, and operations of U.S. commercial communications satellites, it is necessarily involved in activities to promote orbital safety for the purposes of maintaining communications capabilities in GEO as well as to promote general safety of life and property. President Bush's National Space Policy (November, 1989) includes a mandate to all governmental and private-sector entities involved in outer space activities to reduce and control space debris. By implication, FCC licensing of communication satellite activities should address debris control and prevention through both design and operational stages. The U.S. report, *Orbital Debris* suggests that in the same way the FCC coordinates its regulations with the Federal Aviation Administration, so it should coordinate with DOT to address on-orbit safety and space debris issues.[7]

National Oceanic and Atmospheric Ministation. NOAA is responsible for licensing private land remote sensing systems[8] in order to phase-in commercial land remote sensing while providing up-to-date information to the Federal Government and advancing its commitment to international obligations and national security. The U.S. *Report on Orbital Debris* states that NOAA has the specific authority to control the disposition of the entire spacecraft, and this authority should include directing reasonable conditions for keeping a spacecraft in one piece during its operations. NOAA's authority does not extend to activities of the launch itself.

Department of Transportation. The DOT involvement in space debris issues is by far the most comprehensive, as it attempts to address the orbital debris problem in commercial space launch activities through licensing and enforcement, research and standards

[1] NOAA's authority with respect to commercial space activities derives from Title IV of the Land Remote-Sensing Commercialization Act of 1984.

[2] The authority of the FCC is derived from the Communications Act of 1934.

[3] DOT's authority is granted to the Secretary of Transportation under the Commercial Space Launch Act of 1984.

[4] National Security Council, ***Report on Orbital Debris by Interagency Group(Space)*** (Washington, DC: National Security Council, February 19s9).

[5] National Security Co w@ P. 49.

[6] National Security Council, p. 47.

[7] Ibid.

[8] The Land Remote-Sensing Commercialization Act of 19S4, Title IV, 402(b)(3).

development, and setting financial responsibility and risk allocation requirements.[9] Under the Commercial Space Launch Act of 1984,10 DOT's authority as a safety and regulatory agency covers all nongovernmental launches made by U.S. citizens or from U.S. territory, including the safety at prelaunch, launch, and in-space transportation stages of these operations. The U.S. *Report on Orbital Debris* suggests that Federal regulations toreduce and control space debris should be a direct result of DOT's Safety Review and Mission Review procedures.11 As part of the launch license application evaluation, DOT examines proposed commercial launches to ensure no other activities in space are directly at risk. The interagency review of the application, which includes input from NASA and DOD, assists in this process.

9DOT's focus as t. safety and transportation for remote-sensin, systems is combined with the economic focus of NOAA and the regulatory focus of the FCC.

1049 U.S.C. 2601-2623 (19S4 & supp. 1988)

11National Security Council, op. cit., footnote 4, pp. 48-49.

U.S. GOVERNMENT PRINTING OFFICE : 1990 0 - 21-701 : QL 3