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.

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[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

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[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 theresults 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

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[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.

Box 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 first 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

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:

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.

- 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;

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[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

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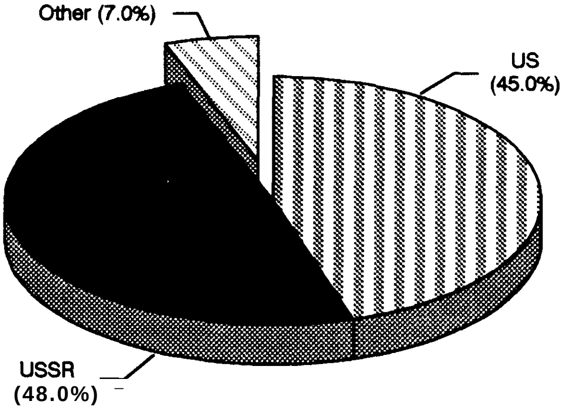
[118] Israel launched its second satellite in April 1990.

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

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[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

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

[129] For example, the amount of fuel necessary to remove satellites above the GEO band varies with respect to the area-to-mass ratio of the abandoned 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,

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

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

[132] Typical 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

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[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.