A Study of International Compliance with Current Space Debris Mitigation Initiatives

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Is it possible for man-made space debris and/or micrometeoroids to hit a spacecraft and destroy or significantly reduce its functionality? Absolutely!

SYNOPSIS

The likelihood of debris or micrometeoroids colliding with a spacecraft and causing the loss or significant damage to that spacecraft is no longer a theoretical issue. The Russian *Kosmos*-1275 is believed to have been destroyed by space debris [Wilson 1996]. The French *Cerise* spacecraft lost its stabilizing boom due to a debris impact in July of 1996 [AP 1997]. The U.S. Space Shuttle has spent $5Million on replacing windows damaged by debris [Wilson 1996]. This is why the major spacefarers (US, Japan, France, Europe, China, and Russia/Ukraine) have largely adopted independent (national in most cases and regional for ESA) regulations for debris mitigation. While this is a start, it is questionable whether this is efficient or globally effective. Therefore this paper will review the current policies, positions, and regulations on space debris mitigation and establish whether they are effectual along with whether they are being adhered to. It will then examine what options could be exercised in the future.

BACKGROUND

On April 12, 1961, Yuri Gagarin began mankind's exploration and exploitation of space. In the subsequent 41 years we have seen quantum leaps in technology and the accumulation of debris in space. The space industry's goals over this time period were focused on technological advances, not the preservation of the space environment for future use. The result is approximately 40,000,000* objects in near-Earth space and growing. Out of the total objects occupying near-Earth space there are approximately 350 operational spacecraft [Bates 1997], while the rest are debris or garbage.

*Projected from 1995 35,117,000 quantity [NSTCC 1995] & growth rate of 2% per year [NRC 1995]

The types of debris that exist fall into the following categories: [AIAA 1992 & Flury 1999]

(1) Exhaust and Spacecraft Aging Products – Spacecraft surface degradation material, leakage matter, and solid rocket ejecta (6%);
(2) Discarded Rocket Bodies/Stages - Launch vehicle upper stages (18%);
(3) Inactive Payloads/Spacecraft - Spacecraft that have had a catastrophic system failure or have past their functional lifetime due to propellant depletion or programmatic decision (21%);
(4) Operational Debris - Spacecraft or launch vehicle parts released as part of operations, deployment, or anomaly (e.g. lens covers, payload shrouds, bolts, pyrotechnic material, and biological remains) (12%);
(5) Collision and Explosion Fragments - Debris resultant from debris and space vehicle (spacecraft or launch vehicle) collision or any combination of the two and that debris which is the result of an intentional or unintentional explosion of a space vehicle or space vehicle part (i.e.; the recently recorded fragmentations of a Titan upper stage and the EKRAN satellite [Flury 1999]) (43%).

All types of debris are potentially very dangerous to space operations. The magnitude of the risk to space operations depends on the velocity, size/mass, and proximity of space debris to operational assets. Debris size and effect on spacecraft can be grouped into the following categories: [NSTCC 1995]

(1) Debris less than 0.01cm - Causes surface pitting and erosion, which may have significant effect on the spacecraft after long exposures.
(2) Debris 0.01cm to 1cm - Causes significant impact damage, which can be serious depending on spacecraft system design.
(3) Debris larger than 1cm - Causes significant damage and may cause the catastrophic loss of the spacecraft.

Evidence of such debris damage to space assets has been seen on returning spacecraft and spacecraft parts: *SolarMax, LDEF, EURECA,* and *HST*-solar arrays. Therefore major spacefarers (US, Japan, France, Europe, China, and Russia/Ukraine) have largely adopted independent national initiatives for debris mitigation to ensure the safe and reliable availability of space for the future. However, the space debris population is still growing at 2% per year [NRC 1995]. Currently the spatial density of the debris population is large enough at some altitudes to require evasive maneuvers by space assets and cause erroneous trailing in astronomical observations [Vovchyk 1999]. Specifically, the Space Transportation System (STS) and spacecrafts, ERS-1 and SPOT-2, have completed such maneuvers recently [Flury 1999].

MITIGATION INITIATIVES

Since debris damage is a reality and simulations have forecast of the debris population growing exponential if the spacefarers continue business-as-usual, the future of space operations will be severely threatened without increased debris mitigation [Anselmo 2001]. Historical practices of abandoning spacecraft and upper stages at the end-of-life (EOL) have to change. If not, collisions between space objects, debris and assets, will generate an irrepressible major source of small debris in the next 50 years [NOSMA 1995]. Therefore independent (national in most cases and regional for ESA) and global efforts have been started to mitigate debris formation or begin spacekeeping.

International:

The original five international space treaties and conventions do not specifically deal with space debris, since they were created before the ramifications of space debris were well understood. However, The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies or the Outer Space Treaty can be applied since it states that states/governments are responsible for the activities of their nationals and themselves and are not allowed to cause “potentially harmful interference with the activities of other parties” [NSTCC 1995]. This statement when evaluated in terms of debris would mean that collisions between spacecraft and debris or debris generation would be considered potentially harmful interference.

In addition, The Liability Convention (Article XXII) indicates that states have jurisdiction/ responsibility over launched space objects and their actions as well as defines a space object to include “component parts of a space object as well as its launch vehicle and thereof” [Verschoor 1993]. Using the naturalist point-of-view, with reasoning based on the scientific fact that matter is neither created nor destroyed, it can be inferred from this article that the debris/artifacts generated by any space operation would be under the jurisdiction of the launching state (or states based on Article V and the Registration Convention) because such debris/artifacts would the component part(s) of a space object. Thereby states would be liable for the damage caused by their debris since this convention states that states are liable for damage "caused elsewhere than on the surface of the Earth to a space object of one launching state or to persons or property on board such a space object of another launching state" [NRC 1995]. Thus from this point-of-view this convention would extend a state's space operations liability to include its debris' interchanges of any kind that cause damage.

In 1993, with a better understanding of the debris population and debris beginning to impact space operations the international community formed a coordination committee, Inter-Agency Space Debris Coordination Committee (IADC), to organize and unify the independent agencies' debris mitigation and research initiatives that had taken shape since their was no international explicitly defined position on debris [Flury 1999]. This establishment of the IADC prompted the International Telecommunications Union (ITU) to recommend debris mitigation to its commercial spacecraft members. Specifically, in ITU-R S.1003 (4/1993) it was recommended that: "1) as little debris as possible should be released into geo-stationary orbit (GSO) during the placement of a satellite in orbit; 2) that every reasonable effort should be made to shorten the lifetime of debris in the transfer orbit; 3) that a geo-stationary satellite at the end of its life should be transferred before complete exhaustion of its propellant, to a super-synchronous graveyard orbit that does not intersect GSO; 4) that the transfer to the graveyard orbit should be carried out with particular caution in order to avoid RF interference with active satellites" [ITU 1993].

Research on debris effects and mitigation options by multiple agencies has since been presented to the IADC indicating that mitigation guidelines need to be "applied uniformly and consistently by the entire international spacefaring community" to be effective [Perek 1999]. Accordingly the IADC is now working on global debris guidelines, to be released to the UN in the next year, to establish a global spacekeeping strategy versus the diverse efforts, at the common goals of 1) prevention of on-orbit breakups; 2) removal of mission terminated spacecraft from the useful regions; 3) limiting the objects released during normal operations; currently recommended by each individual agency/entity [Kato

2001]. It is expected that global spacekeeping strategy will be in place and self-reporting on compliance with that strategy will begin no later than February 2005 [Johnson 2002].

United States of America:

The United States as an IADC member is involved in all aspects of debris research and mitigation initiatives. Currently, the United States has several organizations developing debris mitigation initiatives, which allows each organization to control its own activities. These organizations are: [Kato 2001]

I. National Aeronautics and Space Administration (NASA),
II. Department of Defense (DOD),

COMMERCIAL

III. Department of Transportation: Federal Aviation Administration (FAA),
IV. Department of Commerce: National Oceanic Atmospheric Administration (NOAA),
V. Federal Communications Commission (FCC).

This separation is primarily due to historical spacecraft and/or organization purpose while actions are based on the following Presidential Directives:

> *1989 Presidential Directive*: "…All space sectors will seek to minimize the creation of space 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…" [AIAA 1992]
>
> *1996 Presidential Directive (PDD-NSC-49/NSTC-8 Section 7)*: "(a) The United States will seek to minimize the creation of space debris. NASA, the Intelligence Community, and the DOD, in cooperation with the private sector, will develop design guidelines for future government procurements of spacecraft, launch vehicles, and services. The design and operation of space tests, experiments, and systems will minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness.
>
> (b) It is in the interest of the US Government to ensure that space debris minimization practices are applied by other spacefaring nations and international organizations. The US Government will take a leadership role in international fora to adopt policies and practices aimed at debris minimization and will cooperate internationally in the exchange of information on

> debris research and the identification of debris mitigation options." [FAS 2001]

These several organizations, although responsible for developing their own debris initiatives, did attempt to coordinate their individual responses to these directives by initiating an inter-agency working group process. This process produced an unofficial orbital debris strategy paper, which included a list of agreed upon US Government Orbital Debris Mitigation Standard Practices. However, each organization remains free to implement these practices in its own way [Johnson 2002].

NASA: To comply with the 1989 Presidential Directive NASA began with its NASA Management Instruction (NMI) 1700.8, Policy to Limit Orbital Debris Generation, in April 1993. With the instigation of this policy each NASA space-bound program began to take a serious look at debris generation and mitigation. Specifically, to comply with this policy each space-bound program had to conduct a formal assessment of the potential to generate orbital debris from nominal and anomalous operations and post-mission disposal. NMI 1700.8 also became the cornerstone for all follow-on NASA debris initiatives since it set NASA's policy, which is still in place today, to that of employing "design and operations practices that limit the generation of orbital debris, consistent with mission requirements and cost-effectiveness" [NOSMA 1995]. Today, NASA Safety Standard, Guidelines and Assessment Procedures for Limiting Orbital Debris (NSS 1740.14) in conjunction with NASA Policy Directive 8710.3 (the revised version of 1700.18) detail the debris mitigation actions to be performed [NSTCC 1995 & Kato 2001]. Thereby NASA requires its programs to: 1) limit the number, size, altitude, and orbit lifetime of debris in GEO and LEO; 2) limit to very low the probability of accidental explosions during or after the mission life; 3) limit the debris quantity, size, and risk to other assets generated by intentional breakups above 90 km; 4) limit to very low the probability of a collision and the collision's potential for mission modifying damage; 5) remove space systems from useful regions via reentry (atmospheric or retrieval) or orbital storage; 6) limit the number and size of debris that survives reentry (See Table 1 for detailed initiative data) [Kato 2001]. However, the NASA initiatives only require compliance if mission and/or cost effective to the program in question, which can potentially lead to a self-controlled versus a unified approach. NASA therefore minimizes this potential by having each program address any non-compliances in its NMI 1700.8 formal debris assessment with a justification for approval.

DOD: To comply with the 1996 Presidential Directive and to be responsive to the changing political environment, on 9 July 1999 the DOD issued the Department of Defense Space Policy Directive, 3100.10, to supersede its Defense Space Council directive. Thereby setting the current DOD policy on debris, as well as other space-related activities, to one of debris generation minimization, end-of-life (EOL) spacecraft disposal, and preservation of human and technological space-based assets in accordance with mission requirements, cost effectiveness, and national security [DTIC 2001]. However, more specific direction was needed for DOD spacefarers to be able to utilize the policy in their individual programs therefore as is the common DOD practice instructions were issued to meet this need. These instructions were the Department of Defense Space Support Instruction (3100.12), and subordinate instructions (Air Force Instruction 91-202, Air Force Space command Instruction 10-1024, National Reconnaissance Office Instructions 82-2 82-3 & 82-6, and US Space Command Instruction 13-4) which require that DOD programs to: 1) minimize debris generation during normal operations; 2) justify 5mm or larger debris generation with extended lifetimes; 3) minimize the debris generated from accidental explosions; 4) limit to very low the probability collision with known objects during launch and orbital life; 5) dispose of spacecrafts or upper stages by reentry (atmospheric or retrieval) or orbital storage; (See Table 1 for detailed initiative data) [DTIC 2001]. However, the DOD initiatives only require compliance if mission, national security, and/or cost effective to the program in question, which can potentially lead to a self-controlled versus a unified approach. The DOD, like NASA, minimizes this potential by having each program justify any non-compliances to obtain approval for their mission during the course of the mission preparation process.

Commercial: In 1997, to comply with the 1996 Presidential Directive the following commercial space commerce control and licensing agencies:

- Federal Aviation Administration (FAA) - licensor for commercial space launches

- National Oceanic and Atmospheric Administration (NOAA) - licensor for remote sensing spacecraft
- Federal Communications Commission (FCC) - licensor for communications spacecraft

began integrating orbital debris considerations into their licensing process. Specifically, new FAA rules (Title 14 Code of Federal Regulations Part 415.39) were adopted on 21 June 1999 based on their March 1997 Notice of Proposed Rulemaking (47). The FAA rules require commercial satellites to prevent unplanned collisions of their launch vehicle and satellite components and debris generation from energy sources. The FCC rules, although still in work, are directly derived from the unofficial orbital debris strategy paper's list of US Government Orbital Debris Mitigation Standard Practices [Loftus 1999]. Thereby the FCC is attempting to require communication satellites to: 1) limit the number, size, and orbital lifetime of operational debris generated; 2) limit the risk of accidental explosions during or after the mission life; 3) limit the risk of a collisions with debris; (See Table 1 for detailed initiative data) much like the NASA does with its initiatives for civil programs [JSC 2002]. This would mean that commercial communication satellite programs would need to adhere to the FAA as well as the FCC rules on these mitigation practices. Whereas all commercial spacecraft are or will be required, in various degrees by are the FAA, NOAA (Title 15 Code of Federal Regulation Part 960.6g) and FCC, to follow the mitigation practice of safely disposing of their post-mission commercial space assets. Acceptable disposals are: [Loftus 1999]

- Reentry without significant debris or public safety risk for NOAA.
- Passivation (i.e., propellant depletion, battery discharging, and venting of pressurized systems) for the FAA.
- Removal of space systems from useful regions via reentry (atmospheric or retrieval) or orbital storage for the FCC.

Commercial initiatives currently vary greatly but they are still under development. Coordination can be expected since all commercial licensors were party to the inter-agency working group process that produced the unofficial orbital debris strategy paper, which included the list of agreed upon US Government Orbital Debris Mitigation Standard Practices.

Although the United States has several organizations developing debris mitigation initiatives, each organization is guided by inter-agency as well as IADC research and inputs, which facilitates frequent similarity in approaches.

Japan:

Since October 1969, under the National Space Development Agency Law, the National Space Development Agency of Japan (NASDA) has been responsible for the Japanese usage of space. Specifically, NASDA is task by the Japanese Prime Minister's space development plan to: [NASDA 2002]

- Develop satellites (including space experiments and the space station) and launch vehicles as well as launching and tracking of craft.
- Develop of methods, facilities and equipment required for the above.

As an active IADC member and as one of the world's spacefarers interested in preserving space accessibility, in 1996 Japan implemented its own debris mitigation initiative, NASDA Standard NASDA-STD-18. This standard seeks to control debris generation through the program elements of management, design, and operations. It specifies requirements (See Table 1 for detailed initiative data) for each element as applicable to each program phase addressing five globally accepted debris mitigation principles of: 1) preventing on-orbit breakups; 2) transferring post-mission GEO spacecraft to higher storage orbit; 3) reducing GEO-Transfer-Orbit (GTO) lifetime of components; 4) minimizing operational debris releases; 5) reducing lifetime of post-mission components can interfere with useful orbits [Kato 2001].

France:

Currently, the French regulate their space activities through their space agency, Centre National d'Etudes Spatiales (CNES). CNES conducts space policy in two complementary fashions:

- "by participating in the programs of the European Space Agency (ESA) in which it plays a major role,
- by carrying out a dynamic national program, to guarantee strong industrial competitiveness worldwide." [CNES 2000]

In 1997, in responding to IADC and in-house research France as an IADC member began to actively control its space activities in regard to debris mitigation. Specifically, the CNES drafted standard MPM-50-00-12 (Safety Requirement Pertaining to Space Debris. The draft was then implemented as a standard in April 1999 and regulates French debris mitigation today. This standard requires that all French space programs to: 1) limit the number inert objects released to one; 2) avoid the production of operational debris; 3) minimize the debris from propellant motors, pyrotechnic devices, fragmentations, and material aging; 4) limit to very low the probability of a collision; 5) passivize post-mission spacecraft; 6) remove space systems from useful regions via reentry (atmospheric or retrieval) or orbital storage; 7) avoid public safety hazards from debris that survives reentry (See Table 1 for detailed initiative data) [Kato 2001].

Europe:

The European Space Agency (ESA) coordinates a vision for Europe's future in space. It also develops the strategies needed to fulfill that vision. In 1993, ESA became one of the founding members of the IADC based on its 1989 position:

> "…Recognizing that space debris constitutes an unacceptable (man-made) risk to man and materials in space and on ground, the objective for the future must be to minimize the consequences of the existence of space debris and minimize the creation of additional space debris…" [AIAA 1992]

Since then has been deeply involved and continues to be involved in debris environmental modeling and hypervelocity impacts. However, ESA did not develop any specific debris guidelines until 1999 when it issued its Space Debris Mitigation Handbook and began drafting the European Space Debris Mitigation and Safety Standard. The handbook provides the following information to users:

1. “description of the current space debris and meteoroid environment
2. risk assessment due to debris and meteoroid impacts
3. future evolution of the space debris population
4. hyper-velocity impacts and shielding
5. cost-efficient debris mitigation measures.” [ESA 2000]

The European Standard is ESA’s attempt at coordinating the debris mitigation initiatives of ESA, CNES, Italian Space Agency (ASI), British National Space Center (BNSC), and German Aerospace Center (DLR). It requires that all European space projects to: 1) limit the number launch related objects released to one or two orbital objects depending on payload and no sub-orbital objects; 2) trap operational debris and avoid its production; 3) prevent intentional fragmentations; 4) limit to very low the probability accidental fragmentation; 5) passivize post-mission spacecraft; 6) remove space systems from useful regions via reentry or orbital storage while limiting orbital lifetimes; 7) avoid public safety hazards from debris that survives reentry (See Table 1 for detailed initiative data) [Baccini 2002]. The European Standard is currently in draft form but is intended to be part of the European Co-operative for Space Standardization (ECSS) standards. The next revision to the current draft is expected to be released this summer.

China:

Currently, the Chinese regulate their space activities through their space agency, China National Space Administration (CNSA). CNSA has not established any independent debris initiatives to date for Chinese activities although it has joined the IADC. In joining the IADC, CNSA has involved the Chinese in the ongoing global exchange of data on space debris and international mitigation guidelines.

Russia/Ukraine:

The many changes since the fall of the Union of Soviet Socialist Republics have meant that Rosaviakomos or the Russian Aviation and Space Agency (RASA) has become the controlling force of Russian space activities and the National Space Agency of Ukraine (NSAU) has become the controlling force of Ukrainian space activities.

RASA as an IADC member involved in all aspects of debris research and mitigation initiatives, RASA has put in force a Mitigation of Space Debris Population Standard (OST-134-1023-2000; 7-01-2000). This standard requires that all Russian space programs except defense spacecraft to: 1) minimize debris produced by spacecraft self-destruction; 2) minimize the production of operational debris; 3) minimize the debris from propellant motors, pyrotechnic devices, fragmentations, and material aging; 4) minimize the risk of spacecraft and space debris collisions; 5) passivize post-mission spacecraft and launch vehicle/missile upper stages including pulling in of long tethers; 6) remove GEO space systems from useful regions via orbital storage; (See Table 1 for detailed initiative data) [RASA 2000]. Much like the NASA initiatives, the RASA standard allows economic impact to be factored in on the observance of required measures.

To date, NSAU has not established any independent debris standards to assure mitigation in Ukrainian space activities. NSAU has joined the IADC and as an IADC member has concurred with the current draft of the IADC global debris guidelines [Johnson 2002]. Ukrainian space activity debris mitigation guidance therefore should primarily be based on IADC initiatives although its activities are also directly supported by Russian Federation [Pike 2001].

INITIATIVE EFFECTIVENESS

Initiatives on debris mitigation must have long-term effectiveness and compliance to significantly stabilize and/or improve the debris environment and keep space accessible. Using the existing initiatives (major examples cited above) and global (IADC) debris mitigation philosophies simulation research has been conducted to evaluate and modify debris mitigation positions over time. Recently, simulations were conducted on the effectiveness of current debris mitigation strategies for Low-Earth Orbit (LEO) debris control, although their results can also be extrapolated to all orbital environments. One such simulation was a century long (1999-2098) simulation with the following scenarios: [Anselmo 2001]

1. business-as-usual (voluntary mitigation if any);
2. suppression of operational debris production after 2005 and explosion prevention by passivation after 2010 (known as full mitigation);
3. explosion prevention by passivation after 2010;
4. full mitigation and de-orbiting of spacecraft at <2000km high after 2015 immediately;
5. full mitigation with de-orbiting of spacecraft at <1400km high, and re-orbiting of GEO crafts after 2015;
6. full mitigation with de-orbiting of spacecraft at <1400km high in 25 years, and re-orbiting of GEO crafts after 2015;
7. full mitigation with de-orbiting of spacecraft at <1400km high in 50 years, and re-orbiting of GEO crafts after 2015.

Results (See sample in Figure 1a & 1b) of this simulation study and others show that although all the current mitigation philosophies impact the stability of the debris population some are more effective than others. Business-as-usual or operational debris suppression alone for example will lead to an exponential growth in the mm/cm debris population and create a condition for increased collision rates producing even greater amounts of LEO debris [Walker 2001 & Anselmo 2001]. But full mitigation with either immediate or eventual de-orbiting of space objects will be able to stabilize the LEO debris environment [Anselmo 2001]. Extrapolating these LEO simulation findings to GEO indicates that end-of-life spacecraft management (post-mission disposal) will stabilize debris population growth in GEO and avoid the LEO like debris level issues for decades [Anselmo 2001]. Therefore full mitigation with either immediate or eventual post-mission disposal of space objects for all space environments will serve to assure the long-long-term accessibility and usability of space. At this time current mitigation initiatives are the mechanisms the global space community is utilizing to facilitate its mitigation aspirations.

Accordingly only those initiatives that are requiring or recommending full mitigation with either immediate or eventual post-mission disposal are effectively meeting the global space community's goal of debris control. The majority of the major spacefarers, as shown above, are attempting to have their space activities comply, with full mitigation and either immediate or eventual post-mission disposal, via their initiatives. However, explosion or fragmentation avoidance is part of full mitigation and both NASA and RASA allow intentional fragmentation or self-destructions. Post-mission disposal initiatives also vary greatly (See Table 1) which complicates collision avoidance and compromises disposal effectualness.

However initiatives are only as effective as their space users' adherence to them. Compliance with debris initiatives today remains mostly voluntary and is still often overlooked during the design process for a space system (i.e., no propulsion system for post-mission disposal/collision avoidance, no pressure system venting for passivation). Overlooking debris mitigation initiatives at an early stage in a space program can either make eventual debris mitigation compliance impossible, mission objective(s) compromising, and/or very costly. Making voluntary compliance, starting at the earliest possible stage in space system development, the limiting factor to all current and future initiatives' effectiveness until the space community either independently or globally mandates consequences for space environment degradation.

Table 1: Independent Initiative Detailed Comparison

	International (IADC* & ITU)	United States	Japan	France	Europe*	Russia
Fragmentation Minimization	Prevention of on-orbit breakups recommended.	Minimize probability of accidental explosion (NRO) (0.0001 for NASA). No credible failure modes shall exist to cause accidental explosions unless probability of failure mode is limited through design or operational procedures (DOD). Passivation of all on-board energy sources (i.e., batteries, propellant, and pressurized systems) (NASA, USSPACECOM, DOD, FAA/FCC & DOT).	Intentional destruction shall not be a nominal process. Passivation of potential fragmentation causes: • residual propellant • high pressure systems • batteries	Intentional destruction is prohibited. The probability of accidental explosion shall be kept to less than or equal to 0.0001. Passivation shall be accomplished within one year of end-of-mission.	Intentional destruction of a space vehicle or any of its parts is prohibited. The probability of accidental explosion from internal origin shall be kept to less than or equal to 10^{-4} for the operational phase of the space vehicle. All space vehicles shall be passivated and remain passivated after its operational phase (specific waivers are permitted).	Prevention of accidental explosion of space assets upon their active life ending by passivation of: • residual propellant • liquid and gas of the high pressure systems • explosive devices • flying wheels/ gyroscopes • batteries except for those craft that are disposed of by controlled reentry or destruction.
Fragmentation Debris Minimization	Not Addressed since prevention is guideline.	Generation of debris by accidental explosion shall be minimized (DOD). Limit the long-term risk to other space systems from intention break-ups by conducting such break-ups at an altitude (i.e., 90km for reentry process) such that: a) debris larger than 1mm does not exceed 0.1m^2-yr or 100 objects-yr. b) no debris larger than 1mm will remain in orbit longer than a year. c) the probability of debris larger than 1mm colliding with other assets does not exceed 10^{-6} (NASA).	Not Addressed since prevention is standard.	Not Addressed since prevention is standard.	Not Addressed since prevention is standard.	Mitigate debris generation from spacecraft self-destruction by: • limiting the number of self-destructed device fragments in near-earth space • self-destruct space vehicles just before reentry.

* Note IADC Guidelines and ESA Standard are still in work

	International (IADC* & ITU)	United States	Japan	France	Europe*	Russia
Post-Mission Disposal	Remove mission terminated spacecraft from the useful regions. GEO: raise perigee by 300km (ITU) and 245 – 435 km (IADC) and apogee by 250 km (ITU) GTO: shorten lifetime of objects left in GTO (ITU)	Dispose of post-mission assets from high value regions (FAA/NOAA/FCC) by: a) maneuvering LEO assets to an orbit (i.e., < 650km) in which atmospheric reentry will occur in 25 years due to natural causes (NASA, DOD, & USSPACECOM), b) maneuvering LEO or GEO assets to a storage orbit with perigee above 2500km and apogee below 35,288 km (above LEO and below GEO) (NASA), c) directly retrieving LEO assets within 10 years (NASA & DOD), d) maneuvering GEO assets to a storage orbit 300km above GEO (NASA & USSPACECOM) or 36,100km orbit (DOD) e) maneuvering semi-synchronous assets with perigee above 19,900km and apogee below 20,500 km to a storage orbit with perigee above 2500km and apogee below 19,900km or to one with a perigee above 20,500km and apogee below 35,288 km (NASA), f) maneuvering semi-synchronous assets \to a storage orbit above 500km higher (USSPACECOM), g) maneuvering assets to a heliocentric orbit (DOD) h) maneuvering assets to a storage orbit with perigee above 2000km and apogee below 19,700km or to one with a perigee above 20,700km and apogee below 35,300 km (DOD).	Remove post-mission spacecraft from high value regions by requiring that: a) atmospheric reentry will occur in 25 years due to natural causes, b) assets be maneuvered to a storage orbit above 1700 km (2500km if possible) and below 19,700km or to one above 20,500km and below 35,288 km, c) assets be directly retrieved by STS, d) spacecraft be maneuvered to a storage orbit above 200km above GEO.	Remove post-mission spacecraft from high value regions by: a) atmospheric reentry will occur in 25 years due to natural causes, b) maneuvering space systems to a storage orbit above 2000km and below 35,500 km, c) maneuvering space systems to a storage orbit 235km above GEO.	Each project shall have a debris mitigation plan including a disposal plan for removal of post-mission space vehicles in accordance with the following: a) The operator of a space vehicle shall perform maneuvers to limit orbital lifetime (periodic or permanent) to 25 years maximum via direct reentry, natural reentry, or disposal orbit placement, b) GEO vehicles shall be re-orbited into a disposal orbit 235km above GEO.	Remove launch vehicles, ballistic missiles, and spacecraft upon service life termination by re-orbiting them to a burial region 200km above GEO or reducing their orbital lifetime.

* Note IADC Guidelines and ESA Standard are still in work

	International (IADC* & ITU)	United States	Japan	France	Europe*	Russia
Operational Debris Suppression	Limit the objects released during normal operations	Minimize size, quantity (FCC, NRO & DOD), and lifetime of LEO debris to: a) a total area-time product of no larger than 0.1m2-yr and a object time product of no larger than 100 objects-yr for debris < 1mm (NASA) b) an orbital lifetime of ≤ 25 years for debris > 5mm in any dimension (DOD) Minimize size, quantity (FCC, NRO & DOD), and lifetime of GEO debris to: a) an orbital lifetime of ≤ 25 with total area-time product of no larger than 0.1m2-yr and a object time product of no larger than 100 objects-yr for debris < 5cm (NASA) b) an orbital lifetime of ≤ 25 years for debris > 5mm in any dimension (DOD).	Minimize debris releases during normal operations.	Limit debris injected into orbit to 1 inert object per payload. Minimize the production of debris and releases from: • Solid propellant motors • Pyrotechnical devices • Explosions • Aging materials	Limit debris injected into orbit by launch operations based on number of payloads per mission: a) one element of debris for a single payload mission, b) two (at most) elements of debris for a multiple payload mission. Payloads shall limit debris generation by (although waivers are permitted): a) retaining released parts (i.e., deployment related devices), b) released objects (even from material aging) are to be avoided (pyrotechnic release size limit is 10 microns). Any sub-orbital space object shall not generate debris.	Limit fragment generation during partition and separation of payloads as well as the release of safety covers and springs. Minimize the number of dangerous fragments from engines. Material erosion shall be minimized. Long spacecraft tethers shall retracted.
Collision Avoidance	Not addressed specifically yet.	Mitigate/minimize the potential for in-space collisions with other known objects (FAA/FCC, DOD & NRO) to: a) < 0.001 probability for large objects (NASA) b) < 0.01 probability for small (1 cm - DOD) but with sufficient size to prevent mission disposal objects (NASA) c) no physical contact between a launch vehicle or its components and its payload (DOT)	Avoid interference with spacecraft in the same orbital scheme.	Collision risk limit is program allocated. Avoidance maneuvers are to be performed as necessary.	Not specifically addressed.	Collision risk of a space vehicle shall be known and orbital maneuvering provided for avoiding collisions.
Sources:	[KATO 2001] & [ITU 1993]	[NOSMA 1995] & [Loftus 1999] & [DTIC 2001]	[KATO 2001]	[KATO 2001]	[Baccini 2002]	[RASA 2000]

* Note IADC Guidelines and ESA Standard are still in work

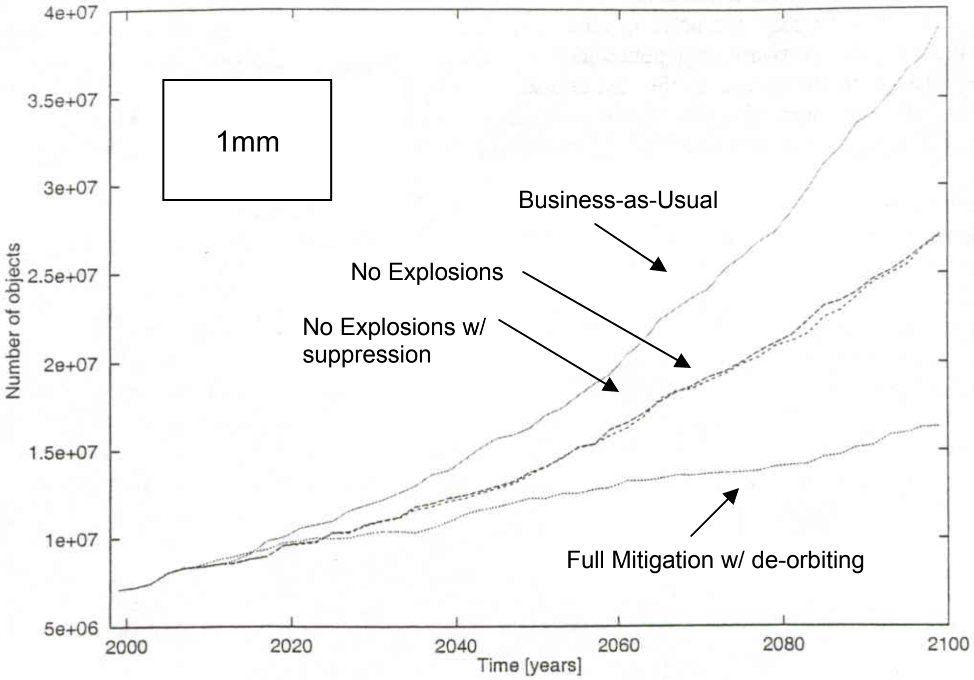

Figure 1a: LEO Debris Growth Simulation 1mm Results [Anselmo 2001]

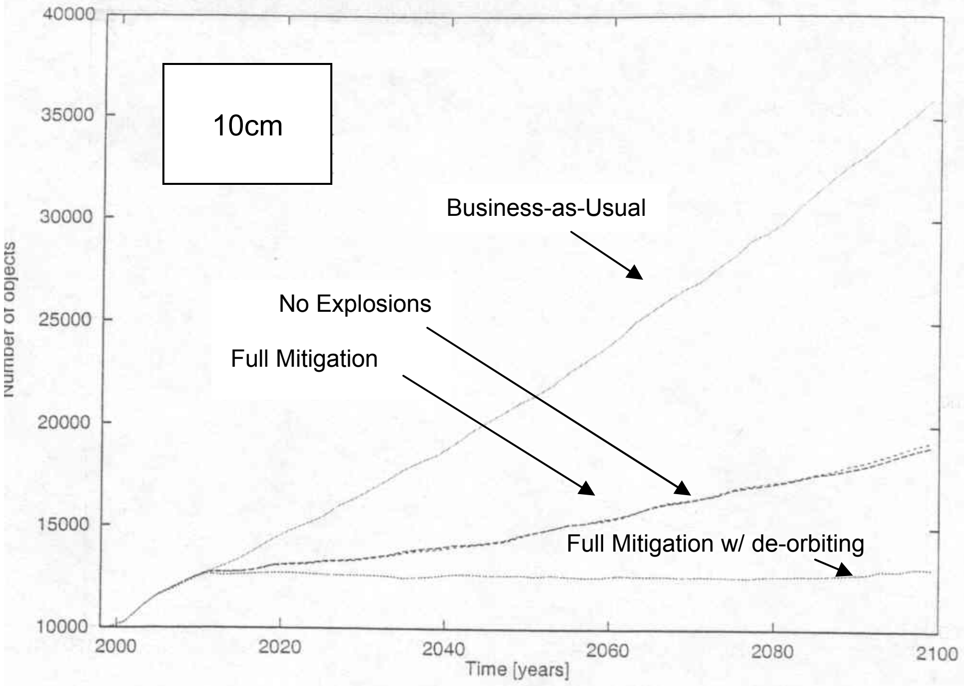

Figure 1b: LEO Debris Growth Simulation 10cm Results [Anselmo 2001]

INITIATIVE ADHERENCE

The global understanding of debris issues and the desire to keep space accessible is evident from the similarity between each nation's and region's (ESA) debris initiatives and/or IADC participation. However initiative compliance, while essential to any initiative's effectiveness, varies greatly depending on the area of debris mitigation (i.e., fragmentation/ fragmentation debris minimization, post-mission disposal, operational debris suppression, and collision avoidance) being considered but is having a fairly positive impact on the debris environment as shown in Figure 2.

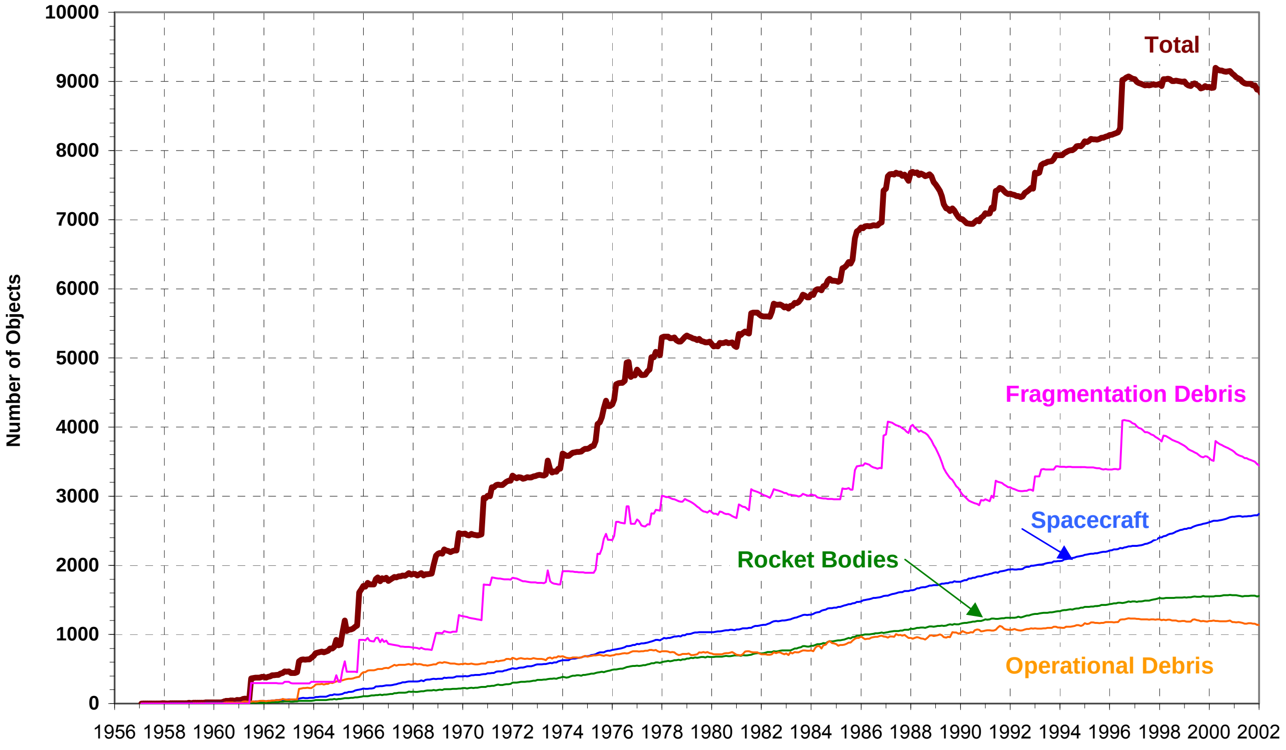

Figure 2: Space Object Population [Johnson 2002]

Fragmentation/Fragmentation Debris Minimization:

Since “the vast majority of fragmentations appear to have arisen from explosions involving residual propellants or pressurants, battery malfunctions, self-destruction charges, or space defense activities,” operational changes as suggested by the current initiatives are required [JSC 2002]. These operational changes are passivation of upper stages/retired spacecraft and avoidance of intentional space object destructions. However, debris initiatives and the enlightenment of the space community, that spacekeeping would be beneficial, only started in the late 1980s and early 1990s. If compliance with the initiatives exists a decline in fragmentations and/or debris produce by fragmentations of spacecraft launched after that time should be evident. As shown in Figures 3 and 4, fragmentations and the debris produce by fragmentations of spacecraft launched after the late 1980s and early 1990s tend to be on the decline. Which suggests that there is compliance with fragmentation/ fragmentation debris minimization initiatives, but the sporadic spikes and troughs in the fragmentation data also reveals that this compliance varies considerably.

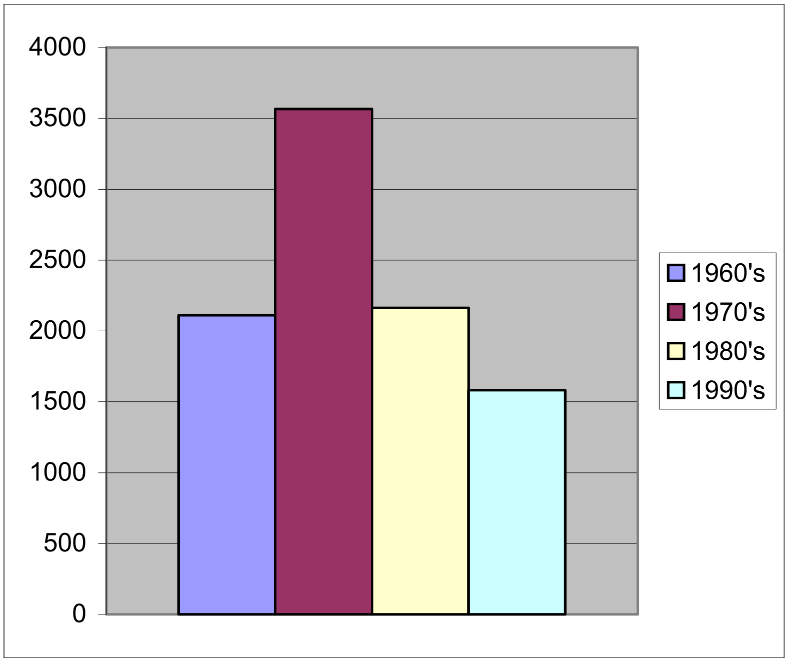

Figure 3: Fragmentation Debris Trend
Data Source is [Anz-Meador 2001]

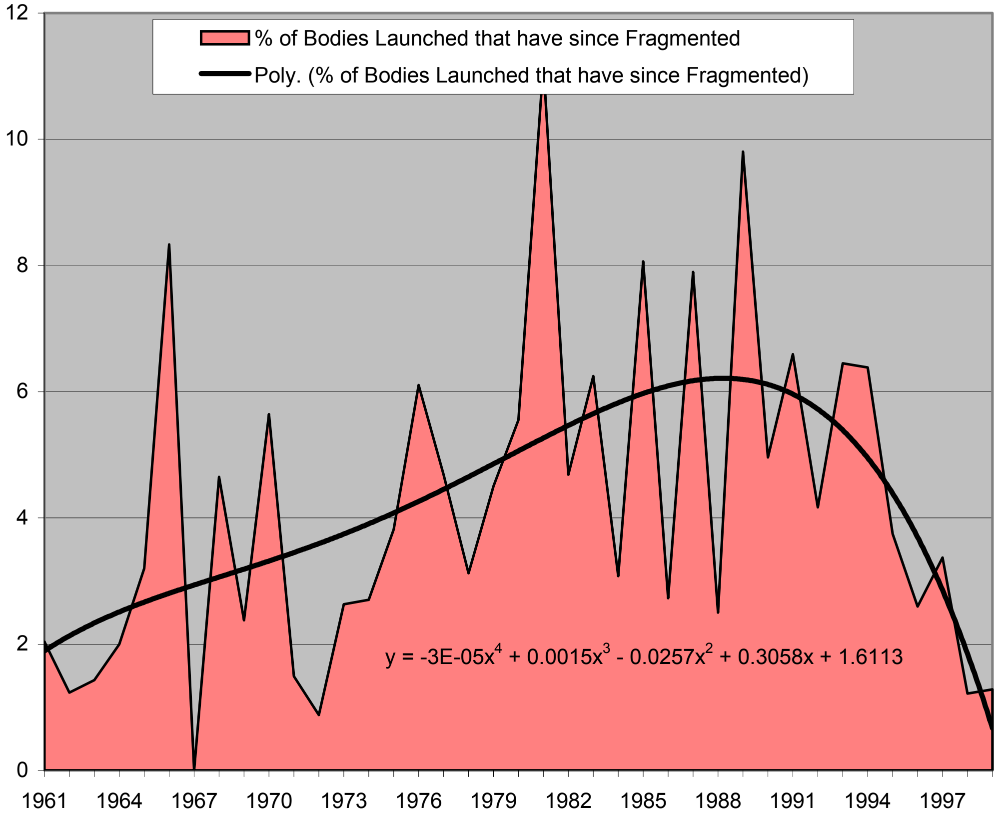

Figure 4: Fragmentation Trends as a Percentage of Launched Bodies
Data Sources are [Anz-Meador 2001], [Gunter 2002] & [NASA-OSF 2002]
(Note: Data truncated at 1998 since aging bodies tend to take 3–5 years to begin to self-fragment or have EOL self-destruction (i.e., *Kosmos* series) making 1999-2002 data misleading [ODPO 2002].)

The evident variations in compliance are best shown through specific actions (positive and negative) of spacefarers with major impacts to the debris population. Typical negative types of incidences are exemplified by the following specific events (Refer to Appendix A for all events since 1961): [Anz-Meador 2001 & ODPO 2002]

- *Fengyun 1-2* rocket body fragmentation 4-Oct-90:
    - Launched 3-Sep-90
    - 83 debris pieces generated
    - Propulsion system not passivated

- *NIMBUS 6* rocket body (*Delta-156*) fragmentation 1-May-91:
    - Launched 12-Jun-75
    - 240 debris pieces generated
    - Propulsion system not passivated

- *Cosmos 2225* fragmentation 18-Feb-93:
    - Launched 22-Dec-92
    - 6 debris pieces generated
    - Deliberate self-destruction

- *Pegasus HAPS Step-II* rocket body fragmentation 3-Jun-96:
    - Launched 19-May-94
    - 704 debris pieces generated
    - Propulsion system not passivated

- *Long March 4* rocket stage fragmentation 11-Mar-00:
    - Launched 14-Oct-99
    - > 300 debris pieces generated
    - Propulsion system not passivated

- *Proton-K Block DM* SOZ ullage motor fragmentation 14-Ju1-01:
    - Launched 19-May-94
    - >14 debris pieces generated
    - Propulsion system not passivated
    - 25th event for this type of vehicle

- *Molniya 3-35* fragmentation 14-Dec-01:
    - Launched 08-Jun-89
    - 24 debris pieces generated
    - Aerodynamic loading during orbital decay

Typical positive types of incidences are exemplified by the following specific events or practices: [ODPO 2002]

- Boeing adopted formal upper stage passivation in 1981 beginning with *Delta-156* 2nd stage.
- ESA/Ariane adopted passivation of their launch vehicles in 1993.
- Orbital adopted passivation of *Pegasus* launch vehicles following 1996 event.
- Proton's SOZ ullage motors are not ejected from vehicle following their ullage burn in newer version of *Proton DM.*
- *Cosmos* end-of-mission disposal has been revised from the apparent self-destruct methodology to a de-orbit methodology begin with *Cosmos-1172* in late1997.

Therefore compliance with the current initiatives for fragmentation/fragmentation debris minimization does exist and is on the rise, making the current initiatives more effective at mitigating debris. However, RASA is not consistently using the redesigned *Proton DM* and passivation is not apparent in Long March launch processes indicating that additional efforts are needed to ensure that the entire space community has the same enlightened view on how to keep space safe and useable [ODPO 2002].

Post-Mission Disposal:

Simulations have clearly shown that fragmentation/fragmentation debris minimization, although necessary for full debris mitigation, will not be able to decrease or stabilize the debris population in the long-term unless supported by the other mitigation techniques associated with full mitigation and post-mission space asset removal [Anselmo 2001]. The most important support is the disposal of post-mission assets by de-orbiting or re-orbiting, since defunct spacecraft left in operational orbits significantly increase the potential for debris generating collisions and operational asset damage. However, initiatives for this technique vary greatly in their requirements/recommendations for the execution of compliant disposals (See Table 1). Therefore compliance with post-mission initiatives must be evaluated in terms of concept adherence, governing (as defined by the Registration Convention) initiative execution criteria observance and international guideline achievement based on specific actions (positive and negative) of spacefarers. However recalling that debris initiatives originated only in the late 1980s and early 1990s compliant actions can only be expected for space activities after that time.

Various launch service providers have begun disposal of orbital upper stages, as shown by the following deployment results of the *Iridium, Orbcomm* and *Globalstar* commercial constellations.

> *Iridium* constellation deployment 1997-1999: Utilizing three launch service provider vehicles, *Delta-II, Long March 2C* and *Proton,* 88 satellites were deployed. This introduced twenty-six orbital upper stages to the environment, all with the potential to become debris if abandoned. *Iridium* required initiative compliance and 25 out 26 upper stages were de-orbited via very short-lived orbits. The remaining one stage was stranded in orbit due to a malfunction not non-compliance. [Johnson 2001]
>
> *Globalstar* constellation deployment 1998-2000: Utilizing *Soyuz–IKAR* and *Delta-II* launch services 52 satellites were deployed, thereby introducing nineteen orbital upper stages to the environment, all with the potential to become debris if abandoned. *Globalstar* required initiative compliance and 15 out 19 upper stages were de-orbited. All the de-orbited stages were *Soyuz-IKAR* upper stages, which de-orbited within 2 days of launch. [Johnson 2001]
>
> *Orbcomm* constellation deployment 1997-1999: Utilizing *Pegasus* launch services 31 satellites were deployed, introducing eight orbital upper stages to the environment, all with the potential to become debris if abandoned. Due to

> voluntary compliance by Orbital, 5 of the 8 stages were de-orbited by 2001, 2 more will de-orbit well within the 25 year lifetime recommendation of current initiatives, while 1 stage will have an extended orbital lifetime due to an early mission failure. [Johnson 2001]

Although these accomplishments are outstanding in terms of compliance, overall launch service provider compliance remains low as shown by the continuing accumulation of upper stages in Earth orbit (See Figure 5) and recent global launch service accomplishments (See Table 2). The lack of compliance in this mitigation area is routinely justified by the cost penalties associated with disposal.

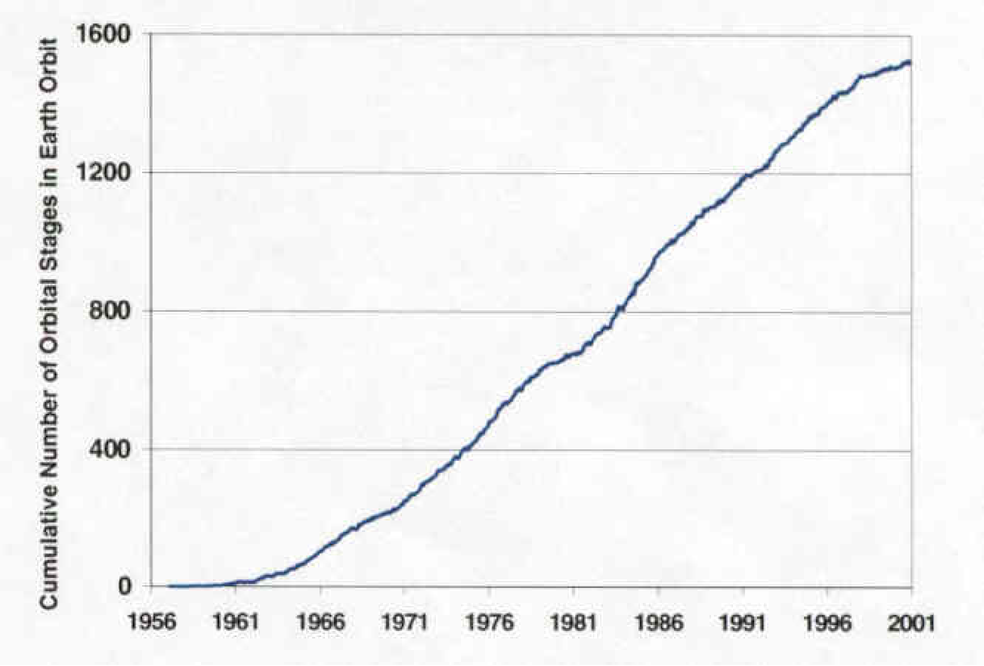

Figure 5: Orbital Stage Accumulation Rate [Johnson 2001]
(Note: rate of increase has decreased post-initiative development.)

Table 2: Overall Launch Service Compliance in 2000 [Johnson 2001]

Launch Service	**Compliance Record for 2000**	**Origin**
Atlas (8 Launches)	• 3 out of 7 GEO orbital stage will comply with 25-year decay initiative, 1 has already decayed. • 3 GEO Transfer Orbit (GTO) stages abandoned in orbit. • 2 Integrated Apogee Boost System (IABS) stages abandoned in orbit.	US
Delta-II (6 launches)	• 5 out of 6 2nd stages decayed in 4 months and comply with initiatives, 1 will be long-lived. • 3 out of 4 3rd stages will comply with 25-year decay initiative.	US
Minotaur (2 launches)	• 1 out of 2 upper stages will comply with 25-year initiative.	US
Pegasus (2 launches)	• 1 out of 2 upper stages will comply with 25-year initiative.	US
Taurus (1 launches)	• all upper stages will comply with 25-year initiative.	US
Titan 4 (2 launches)	• both upper stages will comply with 25-year initiative, 1 re-entered in 3 months.	US
Dnepr (1 launches)	• upper stages will remain in orbit failing to comply with RASA initiative.	Russia
Kosmos (3 launches)	• 1 upper stage will reenter within 25-years complying with RASA removal initiative. • 1 launch failure re-entered in 1:15 hours. • 1 will remain in orbit with no lifetime reduction failing to comply with RASA removal initiative.	Russia
Proton (14 launches)	• 12 out of 14 3rd stages re-entered in 5 days complying with RASA removal initiative. • 2 3rd stages remain sub-orbital with no lifetime reduction failing to comply with RASA removal initiative. • 12 4th stages were abandoned near LEO and GEO failing to comply with RASA removal initiative. • 1 Breeze upper stage was abandoned in a GEO traversing orbit failing to comply with RASA removal initiative.	Russia
Rokot (1 launches)	• 1 Breeze upper stage re-entered in a month complying with RASA removal initiative.	Russia

Launch Service	**Compliance Record for 2000**	**Origin**
Soyuz (13 launches)	• 9 upper stages re-entered in a few days complying with RASA removal initiative. • 3 out of 4 Fregat upper stages were maneuvered and will re-enter complying with RASA removal initiative.	Russia
Start (1 Launch)	• upper stage will re-enter complying with RASA removal initiative.	Russia
Zenit (2 Launches)	• 1 upper stages re-entered in 3 weeks complying with RASA removal initiative. • 1 upper stage left in-orbit failing to comply with RASA removal initiative.	Russia
Ariane-4 (8 Launches)	• 5 out 8 upper stages will re-enter in 25-years complying with ESA initiative.	Europe
Ariane-5 (4 Launches)	• 4 out 4 upper stages will remain in orbit > 25-years failing to comply with ESA initiative.	Europe
Long March 3 (4 Launches)	• 2 out of 4 upper stages decayed by early 2001. • 1 out of the 4 upper stages will decay in 25 years. • 1 out of the 4 upper stages will not decay in 25 years.	China
Long March 4 (1 Launches)	• upper stage will decay in a few years.	China
SeaLaunch (2 Launches)	• 1 out of 2 upper stages was short-lived complying with international goal of orbital lifetime shortening. • 1 was abandoned near LEO.	International

Although the first GEO satellite disposal boost maneuver was executed in 1977 (*Intelsat*), between 1997 and 1998 only ¼ of the retired GEO spacecraft were maneuvered in this manner since satellite operators have been slow to comply fully with disposal initiatives based on the added cost or mission life lost in performing a disposal maneuvers. More recently, between 1999 and 2001, 38 GEO satellites reached their end-of-mission but only 22 (58%) conducted the disposal boost maneuvers [Johnson 2002]. Furthermore only 10 of those 22 reached their associated initiative specified disposal orbit altitude (See Figure 6). Indicating that GEO operators' are able to comply with disposal initiatives when proper planning is done and are beginning to do so.

Non-GEO operators' compliance with disposal initiatives is often restricted by design features such limited or non-existent maneuvering capability (i.e., *NOAA-17*) due to operational altitude requirements [Johnson 2002]. Enlightenment of the space community to debris issues has prompted design changes in some new non-GEO vehicles to include disposal provisions, namely maneuvering capability and propellant reserves. Examples of this are the NOAA-M series being replaced with the maneuverable NPOES series as well as *Iridium* commercial communication satellites and NASA's *AquaSat* carrying reserves sufficient for disposal. Still non-GEO operator compliance, like GEO operator compliance, is not yet uniform since new commercial[Ŧ] and non-commercial[ǂ] vehicles (i.e., *Globalstar, Orbcomm, JasonSat*) are making it to orbit without a maneuvering capability to facilitate disposal [Johnson 2002]. Compliance today therefore appears to be predominantly design related versus profit motivation dependant. However, reassurance that non-GEO compliance will continue to increase is gained with the recent disposal efforts successfully made amongst the older designs on-orbit (i.e., NASA's Compton Gamma Ray Observatory, CNES's SPOT vehicles, *Landsat-4*) [Johnson 2002].

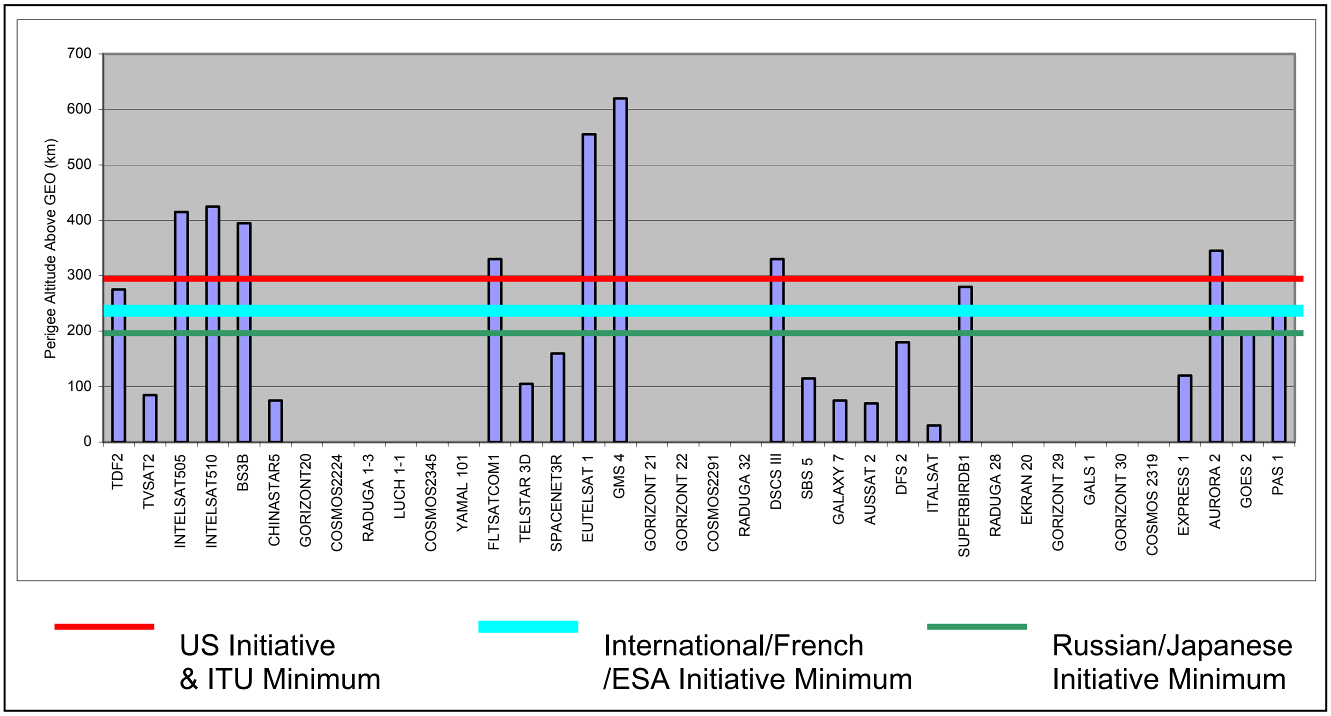

Figure 6: 1999 –2001 GEO Disposals [Johnson 2002]

[Ŧ] - No financial incentive exists for commercial operators to voluntarily comply and often EOL demands for continued profitable operations depletes disposal reserves.

- Non-commercial operators are often budget restricted and use heritage designs (often non-compliant) or allocate their budget to mission instrumentation versus disposal designs/reserves and also have EOL demands from the scientific community to deplete disposal reserves to continue science (i.e., TRMM). [Johnson 2002]

Operational Debris Suppression:

Although not as significant as fragmentation/fragmentation debris minimization and post-mission disposal to debris population control operational debris suppression is still a necessary part of full debris mitigation, which simulations have clearly shown when combined with de-orbiting is the only way to stabilize and/or reduce the debris population [Anselmo 2001]. Since although most operational debris is generated at a rate of a few pieces at a time there have been single incidences generating $\geq$200 pieces (*Salyut 7*) [Anz-Meador 2001]. Incidences of operational debris generation include those events which involve very low velocity debris separations predominantly generated from material degradation, system leakages, small particle impacts, deployments, and Extra-Vehicular Activities (EVAs) although the exact lineage is not always clear [ODPO 2002 & JSC 2002]. This lack of clarity makes compliance evaluation less quantitative and more subjective for this mitigation area. Specifically, the sporadic versus routine nature of operational debris events subjectively indicates that compliance with operational debris mitigation initiatives exists among spacefarers. The level of that compliance can also be said to be increasing with spacefarer experience or lessons-learned (i.e., material selections, EVA procedures, etc.). A good example of the later is that there are magnitudes of difference in debris quantities generated during *MIR* and *Salyut* mission EVAs (100s of objects) and ISS EVAs (under 10 objects) [ODPO 2002]. However that is not to say that all spacefarers have learned all their lessons or that all lessons are known since new (*Ariane-40*) and old (*Nimbus-2 & SeaSat*) crafts alike still sporadically generate operational debris, specifically 3 pieces in 2001[ODPO 2002].

Collision Avoidance:

Although not specifically included in the simulation research completed to date collisions are known to produce debris, damage, and/or fragmentation unless avoided but are not considered a debris population driver unless other mitigation initiatives are ignored [Anselmo 2001]. Therefore many current initiatives include provisions to avoid collisions. Recent acts of compliance include:

> *International Space Station (ISS)* 26 Oct 1999 maneuver:
> This ISS maneuver was a collision avoidance maneuver to avoid a derelict *Pegasus* upper stage. [ODPO 2002]

> *ERS-1* June 1997 maneuver: This ERS-1 maneuver was a collision avoidance maneuver to avoid a near miss predicted by US Space Surveillance. [ODPO 2002]

However many impacts are not always avoided and have damaged as well as permanently changed the orbits of spacecraft (i.e., *Cosmos-539* (21 April 2002) & *NOAA-7* (August 1997)) [Johnson 2002]. Therefore compliance is presumed to be very high in regard to avoiding large body impacts and less so in regard to smaller body impacts (See Table 3 for recorded STS Damage).

Table 3: Recorded STS Debris Damage [ODPO 2002]
(Note: 6/92 thru ISS Missions diameter of damage between 0.55mm and 17mm)

Mission	Window Impacts	Radiator Impacts	Other Areas
STS-50	1	1	0
STS-55	0	0	1
STS-59	1	0	0
STS-73	0	1	1
STS-75	0	0	1
STS-79	0	1	0
STS-80	0	1	0
STS-81	0	1	0
STS-84	0	1	1
STS-85	0	1	0
STS-86	0	2	0
STS-92	38	3	0
STS-94	1	0	1
STS-97	30	12	0

Overall compliance exists and is on the rise for the current initiatives on debris mitigation however as seen in each mitigation area evaluated above compliance levels are not globally consistent. The IADC attempted to quantify this variation based on a survey of commercial space companies and found the following: [Kato 2001]

a. Almost all organizations deny the generation of operational debris;

b. Almost all organizations acknowledged that they perform propellant passivation but do not perform battery passsivation yet.

c. Many GEO spacecraft operators plan to re-orbit post-mission, but distances above GEO vary from150km to 300km.

d. Most organizations affirmed that collision avoidance requires data and analysis tools not available to the common space user yet.

e. Some companies want “some kind of international regulation to enforce debris mitigation measures and assure a fair competitive environment.”

Thus mitigation compliance as well as initiatives currently vary, which unconstructively effects the global debris mitigation. Therefore both need to be made globally consistent to truly stabilize and reduce the global debris environment.

FUTURE MITIGATION GOALS

The future usability of space depends on global and consistent mitigation, which will only happen if a worldwide consensus on debris mitigation requirements and their acceptable implementation is reached. The IADC is striving for such a consensus via its IADC Mitigation Guidelines document, which is to be finalized October 2002 [Johnson 2002]. In doing so thought must be given to establishing equilibrium between re-entries, disposal, and launches in any orbit so as not to create a traffic congestion or collision problem for operational or retired assets [Anselmo 2001].

IADC plans also include the submission of the finalized IADC Mitigation Guidelines to the United Nations for deliberation by February 2003 [Johnson 2002]. Since compliance with current initiatives has not been uniform, as shown in detail above, the current version of these guidelines requests self-reporting of compliance by all spacefarers in hopes of inspiring compliance. If the approval process goes as planned self-reporting will begin February 2005 [Johnson 2002]. The effectiveness of this type of compliance inspiration should be evident some 3-5* years after that.

CONCLUSIONS

Debris pollution of our near-Earth space environment must be stopped otherwise eventually space, the province of all mankind, will no longer be accessible. However, “recent voluntary measures for debris mitigation applied by space operators have not stemmed the increase” in debris [Flury 1999]. There are sporadic increases in voluntary

* Based on routine LEO spacecraft lifetimes.

compliance when a significant debris event occurs (i.e., *INDIAN PSLV* Fragmentation 12/19/01(See Appendix A)) but overall compliance is still relatively subdued.

Historically it has been difficult for multiple sovereign nations to agree on any common regulations. Therefore when a global consensus on debris mitigation (IADC Mitigation Guidelines) is reached, current initiatives will have to not only be voluntarily revised to be consistent with that consensus but also inspire compliance to improve the debris environment for future space activities. Inspiration techniques will remain at the discretion of the responsible nation or agency but non-compliance ramifications and compliance incentives whether financial or logistical (or any form) could be potential candidates.

However, space has often been an arena of international coordination (i.e., Apollo-Soyuz, International Space Station, International Solar Terrestrial Physics Program, etc.) with the most prominent policy coordinator being the Committee on the Peaceful Uses of Outer Space (COPUOS). For debris mitigation the IADC efforts will produce internationally accepted guidelines but COPUOS efforts will be essential to establishing debris mitigation as a global standard practice. Without direction from COPUOS, in a concrete form such as a convention, IADC guidelines may or may not motivate each nation or region (ESA) to change their current initiatives, as they should to align their initiatives with the international consensus. COPUOS direction will take time to formulate though since any COPUOS action requires the consensus of all its member nations. Therefore debris mitigation is likely to remain voluntarily controlled for many years to come.

Dealing with near-Earth debris issues does not excuse the space community in regard to debris in the exploration and use of space in its entirety. Near-Earth lessons learned in debris accumulation/mitigation must be applied to all space operations. Therefore any debris mitigation convention or initiative crafted to control near-Earth operations must also be binding to all celestial operations (i.e., flights, landers, colonies, etc) as well.

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Appendix A

History of Satellite Breakups by Event Date
[Anz-Meador 2001 & ODPO 2002]

Satellite Name	Event Date	Quantity of Debris Catalogued	Assessed Cause
TRANSIT 4A R/B	29 June 1961	296	Propulsion: ABLESTAR Stage
SPUTNIK 29	29 Oct. 1962	24	Propulsion: MOLNIYA Final Stage
ATLAS CENTAUR 2	27 Nov. 1963	19	Propulsion: Centaur Stage
COSMOS 50	05 Nov. 1964	96	Deliberate Self Destruct
COSMOS 57	22 Feb. 1965	167	Deliberate Self Destruct
COSMOS 61-63 R/B	15 Mar. 1965	147	Unknown
OV2-1LCS 2 R/B	15 Oct. 1965	470	Propulsion: Titan Transtage
COSMOS 95	15 Jan. 1966	1	Unknown
OPS 3031	15 Feb. 1966	38	Unknown
GEMINI 9 R/B	Mid June 1966	51	Unknown
AS-203	05 July 1966	34	Deliberate Self Destruct
COSMOS U-1	17 Sep. 1966	53	Deliberate Self Destruct
COSMOS U-2	02 Nov. 1966	41	Deliberate Self Destruct
COSMOS 199	24 Jan. 1968	3	Deliberate Self Destruct
APOLLO 6 R/B	13 Apr. 1968	16	Propulsion: Saturn S-IV Stage
COSMOS 249	20 Oct. 1968	108	Deliberate Self Destruct
COSMOS 248	1 Nov. 1968	5	Deliberate Debris Impact
COSMOS 252	1 Nov. 1968	139	Deliberate Self Destruct
METEOR 1-1 R/B	28 Mar. 1969	37	Unknown
INTELSAT 3 R/B	26 July 1969	23	Propulsion: TE 364-4 Stage
OPS 7613 R/B	04 Oct. 1969	259	Unknown
NIMBUS 4 R/B	17 Oct. 1970 23 Jan. 1985 17 Dec. 1985 02 Sep. 1986 23 Dec. 1991	372 2 3 2 5	Unknown Unknown Unknown Unknown Unknown
COSMOS 374	23 Oct. 1970	102	Deliberate Self Destruct
COSMOS 375	30 Oct. 1970	47	Deliberate Self Destruct
COSMOS 397	25 Feb. 1971	116	Deliberate Self Destruct
COSMOS 462	03 Dec. 1971	25	Deliberate Self Destruct
SALYUT 2 R/B	03 Apr. 1973	25	Propulsion: Proton-K Second Stage
COSMOS 554	06 May 1973	195	Deliberate Self Destruct
NOAA 3 R/B	28 Dec. 1973	197	Propulsion: Delta Second Stage

Satellite Name	Event Date	Quantity of Debris Catalogued	Assessed Cause
COSMOS 699	17 Apr. 1975 02 Aug. 1975	50	Unknown Unknown
LANDSAT 1 R/B	22 May 1975	226	Propulsion: Delta Second Stage
PAGEOS	12 July 1975 20 Jan. 1976 10 Sep. 1976 Mid Jun. 1978 Mid Sep. 1984 Mid Dec. 1985	79 UNK UNK UNK UNK UNK	Unknown Unknown Unknown Unknown Unknown Unknown
NOAA 4	20 Aug. 1975	146	Propulsion: Delta Second Stage
COSMOS 758	06 Sep. 1975	76	Deliberate Self Destruct
COSMOS 777	25 Jan. 1976	62	Unknown
LANDSAT 2 R/B	09 Feb. 1976 19 June 1976	206 UNK	Propulsion: Delta 2nd Stage Propulsion: Delta 2nd Stage
COSMOS 844	25 July 1976	248	Deliberate Self Destruct
COSMOS 886	27 Dec.1976	76	Deliberate Self Destruct
COSMOS 884	29 Dec. 1976	2	Deliberate Self Destruct
COSMOS 862	15 Mar. 1977	11	Deliberate Self Destruct
COSMOS 838	17 May 1977	40	Unknown
HIMAWARI 1 R/B	14 July 1977	169	Propulsion: Delta Second Stage
COSMOS 839	29 Sep. 1977	69	Battery
COSMOS 931	24 Oct. 1977	6	Deliberate Self Destruct
COSMOS 970	21 Dec. 1977	70	Deliberate Self Destruct
NOAA 5 R/B	24 Dec. 1977	159	Propulsion: Delta Second Stage
COSMOS 903	08 June 1978	2	Deliberate Self Destruct
EKRAN 2	23 June 1978	2	Battery
COSMOS 1030	10 Oct. 1978	4	Deliberate Self Destruct
COSMOS 880	27 Nov. 1978	50	Battery
COSMOS 917	30 Mar. 1979	1	Deliberate Self Destruct
COSMOS 1124	09 Sep. 1979	4	Deliberate Self Destruct
COSMOS 1094	17 Sep. 1979	1	Unknown
COSMOS 1109	Mid Feb. 1980	9	Deliberate Self Destruct
CAT R/B	Apr. 1980	13	Unknown
COSMOS 1174	18 Apr. 1980	46	Deliberate Self Destruct
LANDSAT 3 R/B	27 Jan. 1981	210	Propulsion: Delta Second Stage
COSMOS 1261	Apr/May 1981	4	Deliberate Self Destruct
COSMOS 1191	14 May 1981	3	Deliberate Self Destruct
COSMOS 1167	15 July 1981	12	Unknown
COSMOS 1275	24 July 1981	305	Battery

Satellite Name	Event Date	Quantity of Debris Catalogued	Assessed Cause
COSMOS 1305 R/B	11 Sep. 1981	8	Propulsion: MOLNIYA Final Stage
COSMOS 1247	20 Oct. 1981	4	Deliberate Self Destruct
COSMOS 1285	21 Nov. 1981	8	Deliberate Self Destruct
NIMBUS 7 R/B	26 Dec. 1981	1	Unknown
COSMOS 1260	08 May 1982 10 Aug. 1982	68 UNK	Unknown Unknown
COSMOS 1220	20 June 1982	81	Unknown
COSMOS 1306	12 July 1982 18 Sep. 1982	8 UNK	Unknown Unknown
COSMOS 1286	29 Sep. 1982	2	Unknown
COSMOS 1423 R/B	08 Dec. 1982	29	Propulsion: MOLNIYA Final Stage
COSMOS 1217	12 Feb. 1983	3	Deliberate Self Destruct
COSMOS 1481	09 July 1983	4	Deliberate Self Destruct
COSMOS 1355	08 Aug. 1983 01 Feb. 1984 20 Feb. 1984	29 UNK UNK	Unknown Unknown Unknown
COSMOS 1456	13 Aug. 1983	4	Deliberate Self Destruct
COSMOS 1405	20 Dec. 1983	32	Unknown
COSMOS 1317	Late Jan. 1984	4	Deliberate Self Destruct
WESTAR 6 R/B	03 Feb. 1984	14	Propulsion: PAM-D Upper Stage
PALAPA B2 R/B	06 Feb. 1984	3	Propulsion: PAM-D Upper Stage
ASTRON UM	03 Sep. 1984	1	Propulsion: Proton-K SOZ Motor
COSMOS 1461	11 Mar. 1985 13 May 1985	159 UNK	Unknown Unknown
COSMOS 1654	21 June 1985	18	Deliberate Self Destruct
P-78	13 Sep. 1985	285	Deliberate Impact
COSMOS 1375	21 Oct. 1985	60	Battery
COSMOS 1691	22 Nov. 1985	14	Battery
COSMOS 1714 R/B	28 Nov. 1985	2	Propulsion: Zenit Second Stage
NOAA 8	30 Dec. 1985	7	Battery
COSMOS 1588	23 Feb. 1986	45	Unknown
USA 19 & R/B	05 Sep. 1986	18	Deliberate Impact
SPOT 1/VIKING R/B	13 Nov. 1986	488	Unknown
COSMOS 1278	Early Dec. 1986	3	Deliberate Self Destruct
COSMOS 1682	18 Dec. 1986	23	Unknown
COSMOS 1813	29 Jan. 1987	194	Deliberate Self Destruct
COSMOS 1866	26 July 1987	9	Deliberate Self Destruct
AUSSAT/ECS R/B	Mid Sep.1987	4	Unknown

Satellite Name	Event Date	Quantity of Debris Catalogued	Assessed Cause
COSMOS 1769	21 Sep. 1987	4	Unknown
COSMOS 1646	20 Nov. 1987	24	Unknown
COSMOS 1823	17 Dec. 1987	113	Battery
COSMOS 1656 UM	05 Jan. 1988	6	Propulsion: Proton-K SOZ Motor
COSMOS 1906	31 Jan. 1988	37	Deliberate Self Destruct
COSMOS 1916	27 Feb. 1988	1	Deliberate Self Destruct
COSMOS 1045 R/B	09 May 1988	48	Unknown
COSMOS 2030	28 July 1989	1	Deliberate Self Destruct
COSMOS 2031	31 Aug. 1989	9	Deliberate Self Destruct
FENGYUN 1-2 R/B	04 Oct. 1990	83	Propulsion: CZ-4 Final Stage
COSMOS 2101	30 Nov. 1990	4	Deliberate Self Destruct
USA 68	01 Dec. 1990	28	Propulsion: TE-M-364-15 Upper Stage
COSMOS 1519-1521 UM	04 Feb. 1991	6	Propulsion: Proton-K SOZ Motor
COSMOS 2125-2132 R/B	05 Mar. 1991	86	Propulsion: COSMOS Second Stage
NIMBUS 6 R/B	01 May 1991	240	Propulsion: Delta Second Stage
COSMOS 2163	06 Dec. 1991	1	Deliberate Self Destruct
COSMOS 1710-1712 UM	29 Dec. 1991	12	Propulsion: Proton-K SOZ Motor
OV2-5 R/B	21 Feb. 1992	3	Unknown
COSMOS 2054 UM	July 1992	9	Propulsion: Proton-K SOZ Motor
COSMOS 1603 UM	05 Sep. 1992	22	Propulsion: Proton-K SOZ Motor
GORIZONT 17 UM	17-18 Dec. 1992	1	Propulsion: Proton-K SOZ Motor
COSMOS 2227 R/B	26 Dec. 1992 30 Dec. 1992	219	Propulsion: Zenit-2 2nd Stage Propulsion: Zenit-2 2nd Stage
GORIZONT 18 UM	12 Jan. 1993	1	Propulsion: Proton-K SOZ Motor
COSMOS 2225	18 Feb. 1993	6	Deliberate Self Destruct
COSMOS 2237 R/B	28 Mar. 1993	29	Propulsion: Zenit-2 2nd Stage
TELECOM 2B/ INMARSAT 2 R/B	21 Apr. 1993	11	Unknown
COSMOS 2243	27 Apr. 1993	1	Deliberate Self Destruct
COSMOS 2259	25 July 1993	1	Deliberate Self Destruct
COSMOS 1484	18 Oct. 1993	48	Unknown
COSMOS 2262	18 Dec. 1993	0	Deliberate Self Destruct
CLEMINTINE R/B	07 Feb. 1994	0	Unknown
ASTRA 1B/MOP 2 R/B	27 Apr. 1994	5	Unknown
COSMOS 2133 UM	07 May 1994	3	Propulsion: Proton-K SOZ Motor

Satellite Name	Event Date	Quantity of Debris Catalogued	Assessed Cause
COSMOS 2204-2206 UM	08 Nov. 1994	3	Propulsion: Proton-K SOZ Motor
COSMOS 2238	01 Dec. 1994	1	Unknown
RS-15 R/B	26 Dec. 1994	23	Unknown
ETS-VI R/B	31 Mar. 1995	1	Aerodynamic Loading
ELEKTRO UM	11 May 1995	1	Propulsion: Proton-K SOZ Motor
COSMOS 2282 UM	21 Oct. 1995	2	Propulsion: Proton-K SOZ Motor
GORIZONT 22 UM	14 Dec. 1995	1	Propulsion: Proton-K SOZ Motor
RADUGA 33 R/B	19 Feb. 1996	2	Propulsion: Proton-K SOZ Motor
ITALSAT1/ EUTELSAT2 R/B	01 May 1996	8	Unknown
PEGASUS HAPS II R/B	03 June 1996	704	Propulsion
CERISE	24 July 1996	2	Collision
COSMOS 1883-1885 UM	01 Dec. 1996	14	Propulsion: Proton-K SOZ Motor
EKRAN 17 UM	22 May 1997	1	Propulsion: Proton-K SOZ Motor
COSMOS 2313	26 June 1997	13	Unknown
COSMOS 2343	16 Sep. 1997	1	Deliberate Self Destruct
COSMOS 1869	27 Nov. 1997	2	Unknown
COSMOS 1172	23 Dec. 1997	2	Aerodynamic Loading
ASIASAT 3 R/B	25 Dec. 1997	1	Propulsion: Proton-K SOZ Motor
MOLNIYA 3-16	05 Feb. 1998	1	Aerodynamic Loading
ELEKTRON 1-2 R/B	13 Feb. 1998	2	Aerodynamic Loading
METEOR 2-16 R/B	15 Feb. 1998	79	Unknown
SKYNET 4B/ASTRA 1A R/B	17 Feb. 1998	7	Unknown
COMETS	21 Feb. 1998	1	Propulsion: H-II Second Stage
COSMOS 2109-2111 UM	14 Mar. 1998	2	Propulsion: Proton-K SOZ Motor
MOLNIYA 3-16 R/B	July 1998	1	Aerodynamic Loading
COSMOS 1987-1989	03 Aug. 1998	7	Propulsion: Proton-K SOZ Motor
COSMOS 1650-1652 UM	29 Nov. 1998	2	Propulsion: Proton-K SOZ Motor
COSMOS 1970-1972 UM	09 Mar. 1999	1	Propulsion: Proton-K SOZ Motor
COSMOS 2079-2081 UM	28 Mar. 1999	1	Propulsion: Proton-K SOZ Motor
COSMOS 2053 R/B	18 Apr. 1999	26	Unknown
COSMOS 2157-2162 R/B	09 Oct. 1999	34	Unknown
COSMOS 2347	22 Nov. 1999	9	Unknown

Satellite Name	Event Date	Quantity of Debris Catalogued	Assessed Cause
GORIZONT 32 UM	13 Dec. 1999	1	Propulsion: Proton-K SOZ Motor
CBERS-1/SACI-1 R/B	11 Mar. 2000	>300	Propulsion: Long March 4 Third Stage
MOLNIYA 3-36 & R/B	19 May 2000 28 June 2000	2	Aerodynamic Loading Aerodynamic Loading
GORIZONT 29 UM	06 Sep. 2000	1	Propulsion: Proton-K SOZ Motor
COSMOS 2316-2318 UM	21 Nov. 2000	1	Propulsion: Proton-K SOZ Motor
INTELSAT 515 R/B	01 Jan. 2001	6	Unknown
MOLNIYA 3-26	21 Feb. 2001	1	Aerodynamic Loading
COSMOS 1701	29 Apr. 2001	>10	Aerodynamic Loading
COSMOS 2139-2141	16 June 2001	> 31	Propulsion: Proton-K SOZ Motor
GORIZONT 27	14 July 2001	> 14	Propulsion: Proton-K SOZ Motor
COSMOS 2367	21 Nov. 2001	> 200	Unknown
MOLNIYA 3-35	14 Dec. 2001	24	Aerodynamic Loading
INDIAN PSLV	19 Dec. 2001	> 300	Propulsion
INTELSAT 6D1 R/B	24 Dec. 2001	Several	Unknown

Abbreviations: R/B = Rocket Body, UM = Ullage Motor, UNK = Unknown Quantity/Safe Assumption at $\geq$1
Causes: Propulsion = Non-compliance with passivation, Battery = Non-compliance with passivation,
Deliberate = Non-compliance with collision or intentional break-up prohibitions.