

THE DISPOSAL OF SPACECRAFT AND LAUNCH VEHICLE STAGES IN LOW EARTH ORBIT

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ABSTRACT

Spacecraft and launch vehicle stages abandoned in Earth orbit have historically been a primary source of debris from accidental explosions. In the future, such satellites will become the principal cause of orbital debris via inadvertent collisions. To curtail both the near-term and far-term risks posed by derelict spacecraft and launch vehicle stages to operational space systems, numerous national and international orbital debris mitigation guidelines specifically recommend actions which could prevent or limit such future debris generation. Although considerable progress has been made in implementing these recommendations, some changes to existing vehicle designs can be difficult. Moreover, the nature of some missions also can present technological and budgetary challenges to be compliant with widely accepted orbital debris mitigation measures.

1. BACKGROUND

As a result of the increasing number of debris in low Earth orbit (LEO), numerous national and international orbital debris mitigation guidelines recommend

restricting the orbital lifetimes of spacecraft and launch vehicle stages residing in or passing through LEO after mission termination. The primary purpose of this action is to enhance space safety by significantly constraining the potential of future accidental collisions, which in turn could result in the creation of large numbers of new orbital debris.

Not surprisingly, the majority of mass in Earth orbit today (> 5000 metric tons) resides in non-operational spacecraft and launch vehicle stages. This mass also represents the largest segment of cross-sectional area, *i.e.*, collision hazard, for future debris generation. In the 1980's, early National Aeronautics and Space Administration (NASA) projections of the potential long-term growth of the Earth's satellite population identified the increasing amount of mass in Earth orbit as a significant source of collision-derived debris, beginning in the 21st century.

During the 20-year period from January 1987 to January 2007, the number of spacecraft in Earth orbit increased by 80%, and the amount of related mass more than doubled (Figs. 1 and 2).

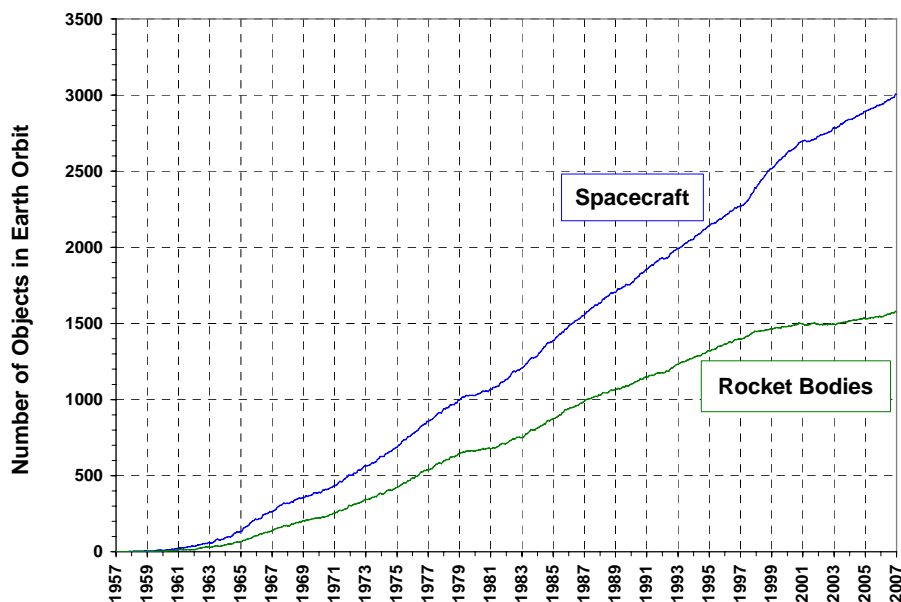


Figure 1. The accumulation of spacecraft and launch vehicle stages in Earth orbit has now exceeded 4500.

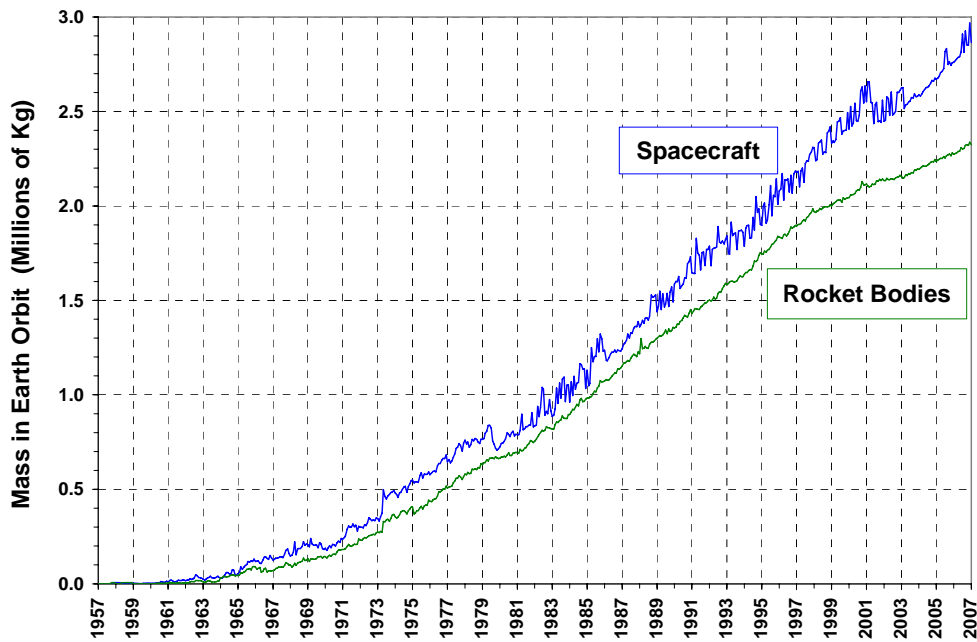


Figure 2. Although the annual growth rate of launch vehicle stage mass in Earth orbit has fallen during the past decade, the combined rate of accumulation of mass has recently (2004 to 2007) been more than 130 metric tons per year.

The total cross-sectional area of spacecraft and stages has increased at an even faster rate. During 2006, 87% (55 of 63) of space missions left at least one spacecraft or launch vehicle stage in or transiting LEO. Consequently, a limitation on the orbital longevity of satellites placed into LEO is desired to better preserve the near-Earth environment.

Likewise, the passivation, *i.e.*, the removal of residual stored energies, of these non-functional objects while they remain in orbit is important to prevent the generation of debris via self-induced explosions. To date approximately 90% of all known satellite breakups have involved explosions of spacecraft and launch vehicle stages which had been abandoned in orbit after mission termination.

2. NASA POLICY DEVELOPMENT AND RECOMMENDATIONS

In 1995 NASA released the first detailed set of orbital debris mitigation guidelines [1]. Two of the guidelines specifically addressed the issues of passivation and LEO longevity.

2.1. Postmission Prevention of Satellite Explosions

One of NASA's policy objectives is to control the amount of orbital debris generated by accidental

explosions. Such explosions could occur either during or after the conclusion of the mission, if the spacecraft or launch vehicle stage were to be left in Earth orbit. Guideline 4-2 of the aforementioned document is entitled "Limiting the risk to other space systems from accidental explosions after completion of mission operations" and states that

"All on-board sources of energy will be depleted when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload." [2]

The NASA safety standard goes on to identify typical systems that should be passivated, including propulsion and pressurant systems, electrical power systems, attitude control systems, and range safety systems. More than a decade of experience with this guideline has revealed that the primary actions should include the following:

- the expenditure by burning or venting of all residual propellants,
- the release of all pressurants,
- the discharge of all batteries and their disconnection from charging circuits,
- the removal of electrical power from control moment gyroscopes, and
- the deactivation of range safety control units.

Propellants and pressurants have been the primary source of explosions involving non-operational spacecraft and launch vehicles stages. Such explosions have come as early as the first hour in space or as late as 25 years after launch. The most severe accidental satellite break-ups have been propellant- or pressurant-induced. The worst accidental fragmentation was apparently caused by the failure of a pressure regulator between a high-pressure helium tank and a hydrazine propellant tank on a Pegasus launch vehicle upper stage, two years after a successful payload delivery mission [3]. The cause of a large number of explosions has been assessed to be due to over-pressurized or inadvertent detonation of residual propellants [4].

Spacecraft and launch vehicle designers and operators should have a goal of complete passivation of propellant and pressurant systems. Even leaving modest residual pressures (*e.g.*, 10% of tank maximum expected operating pressure, aka MEOP) and small amounts of propellants can lead either to a direct explosion or to an enhancement of damage (*i.e.*, new orbital debris) in the event of a future collision.

The subject of spacecraft battery disconnection from charging circuits can sometimes lead to extensive debates between the operational community and those responsible for environmental safety. Leak-before-burst designs, while beneficial, do not eliminate the possibility of an explosion. Inadvertent disconnection of the battery from the charging line can easily be avoided with separate, multiple separation systems. If planned early in the design phase, such circuits are low cost and low weight.

Some exceptions to the rules have also arisen. Many modern spacecraft batteries are highly pressurized and cannot easily be depressurized at the end of mission. If properly disconnected from charging circuits, these batteries are normally safe despite their internal pressures. Launch vehicle batteries are designed for short lifetimes and typically discharge quickly with no means of recharging on orbit. Hence, no special actions are normally required.

Heat pipes by design contain internal fluids at high pressure and, again, are not easily depressurized. On the other hand, these ruggedly-built systems have never been identified as the likely source of a satellite break-up. Therefore, depressurization of heat pipes is currently not considered a requirement to comply with passivation guidelines.

Unused pyrotechnic charges which are designed to activate a system, but which are not capable of causing vehicle fragmentation, need not be fired at the time of decommissioning. Should these charges accidentally

fire in the future, the result should not be the generation of orbital debris.

2.2. Curtailment of Postmission Orbital Longevity

NASA space debris mitigation Guideline 6-1 addresses the physical disposition of spacecraft and launch vehicle stages residing in or passing through LEO. The objective is to ensure the removal of the satellite from the LEO region no later than 25 years after the end of vehicle operations. The three major removal options cited in the guideline are (1) controlled or uncontrolled atmospheric reentry, (2) transfer to a disposal orbit above LEO, and (3) direct retrieval, *e.g.*, with the U.S. Space Shuttle.

With rare exceptions uncontrolled atmospheric reentry of spacecraft and launch vehicle stages is chosen for compliance with this guideline. For vehicles in low orbits (typically below 600 km), natural orbital decay will be sufficient to meet the 25-year restriction. For objects in higher orbits which would normally experience longer orbital lifetimes, some explicit action is required to shorten the time in Earth orbit.

Often the most effective action is to lower the perigee of the satellite at the end of mission to a value from which atmospheric drag will cause the vehicle to reenter within 25 years. This option has been selected by several of the satellites of NASA's Earth Observation System, which operates at a mean altitude of 705 km, and by many launch vehicle stages which can use their residual propellants to move to lower orbits after the delivery of their payloads. In addition to typical high-thrust burns, such maneuvers could be effected by long-duration, low-thrust propulsion systems, by momentum or electromagnetic tethers, by drag augmentation devices, or by other means.

The 25-year longevity constraint is measured from the end of mission of the vehicle in question. For spacecraft, the mission duration might be five, ten, or more years. For launch vehicle stages, the 25-year clock normally starts on the day of launch.

A decision to employ the reentry option often results in replacing a future risk to the space environment with a near-term risk to people and property on Earth. Consequently, NASA Guideline 7-1 seeks to limit the risk of human casualty to no more than 1 in 10,000 per reentry event. In the case of a controlled reentry, an atmospheric interface point can be chosen to place the footprint of all surviving debris over broad ocean areas and uninhabited territories. For the more common uncontrolled reentries, human casualty risks are normally driven by the design and construction of the space vehicle, *i.e.*, the number, size, and mass of

components which survive to the surface of the Earth. To further limit human casualty risks, NASA evaluates the risk potential for each new spacecraft early in the design phase and has established a design-to-demise program which emphasizes material selection and construction techniques that reduce the number and mass of surviving components.

3. OTHER ORBITAL DEBRIS MITIGATION POLICIES

During the past decade a growing number of space agencies and national governments have published orbital debris mitigation guidelines. Although these documents vary in composition and complexity, their guidelines bear remarkable similarity. In fact, it has been this general consensus of opinion which has led to the relatively rapid development of international orbital debris mitigation guidelines.

3.1. U.S. Government

In 1997 NASA and the U.S. Department of Defense began drafting a set of orbital debris mitigation standard practices for use by all U.S. government organizations responsible for the design or operation of spacecraft and launch vehicles. The existing NASA orbital debris mitigation guidelines were used as the basis for developing the standard practices. After consultations with industry and other government departments and agencies, the *U.S. Government Orbital Debris Mitigation Standard Practices* was officially adopted in February 2001.

With regard to passivation and permitted LEO postmission longevity, the standard practices closely follow the mitigation guidelines of NASA.

Standard Practice 2-2 states “All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload. Propellant depletion burns and compressed gas releases should be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion.”

Standard Practice 4-1 addresses postmission disposal of space structures and contains guidance for the three basic options of atmospheric reentry, transfer to a long-lived storage orbit, and retrieval. This standard practice also adopts the 25-year postmission limit for LEO vehicles and the 1 in 10,000 human casualty risks for individual reentry events.

3.2. Inter-Agency Space Debris Coordination Committee (IADC)

The IADC was established in 1997 for the purpose of exchanging scientific and technical data on the orbital debris environment and promoting debris mitigation measures. The organization is now comprised of the space agencies of 10 nations (China, France, Germany, India, Italy, Japan, the Russian Federation, the Ukraine, the United Kingdom, and the United States), as well as the European Space Agency.

In 1999 the IADC undertook an action item to develop the first consensus set of orbital debris mitigation guidelines for the world’s major space agencies. At the Second World Space Congress in Houston, Texas, in 2002, the *IADC Space Debris Mitigation Guidelines* was accepted by all members [5].

Guideline 5.2.1 seeks to minimize the potential for postmission break-ups resulting from stored energy. It reads, in part:

“In order to limit the risk to other space systems from accidental break-ups after the completion of mission operations, all on-board sources of stored energy of a space system, such as residual propellants, batteries, high-pressure vessels, self-destructive devices, flywheels and momentum wheels, should be depleted or safed when they are no longer required for mission operations or post-mission disposal. Depletion should occur as soon as this operation does not pose an unacceptable risk to the payload. Mitigation measures should be carefully designed not to create other risks.”

The topic of disposal of space structure passing through the LEO region is addressed by Guideline 5.3.2:

“Whenever possible, space systems that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct re-entry is preferred) or where appropriate, maneuvered into an orbit with a reduced lifetime. Retrieval is also a disposal option.”

This latter guideline goes on to note that studies by the IADC and others have found “25 years to be a reasonable and appropriate lifetime limit” [6].

3.3. United Nations

Space debris has been an agenda item for the Scientific and Technical Subcommittee (STSC) of the United Nations’ Committee on the Peaceful Uses of Outer

Space (COPUOS) since 1994. In 1999, after a four-year effort, the STSC produced an assessment of the severity of the space debris environment [7]. During 2003 and 2004 the STSC evaluated the then new IADC Space Debris Mitigation Guidelines and, during the next two years, developed its own similar set of mitigation recommendations [8].

Explicitly derived from the IADC Space Debris Mitigation Guidelines, the STSC guidelines follow the former's lead in its handling of space vehicle passivation and postmission orbital longevity:

Guideline 5: "In order to limit the risk to other spacecraft and launch vehicle orbital stages from accidental breakups, all on-board sources of stored energy should be depleted or made safe when they are no longer required for mission operations or post-mission disposal."

Guideline 6: "Limit the long-term presence of spacecraft and launch vehicle orbital stages in low-Earth orbit (LEO) region after the end of the mission."

4. RECENT APPLICATIONS OF SPACECRAFT AND LAUNCH VEHICLE DISPOSAL GUIDELINES

The response of most members of the international aerospace community to these guidelines on the disposal of spacecraft and launch vehicle stages in LEO has been very positive. For example, in 2006 NASA conducted three flights of the Space Shuttle and launched four robotic missions, as shown in Table. 1.

Table 1 — NASA space missions of 2006

Mission	Launch Date	Destination	Other Objects Produced
New Horizons	19 January	Pluto	No objects left in Earth orbit
ST-5 (A, B, C)	22 March	Elliptical Earth Orbit	One rocket body and one mission-related debris in short-lived orbits
Cloudsat / Calipso	28 April	LEO	Rocket body decayed; one mission-related debris to decay within 25 years
STS-121	04 July	LEO (ISS)	No debris left in Earth orbit
STS-115	09 September	LEO (ISS)	No debris left in Earth orbit
STEREO A and B	26 October	Heliocentric Orbit	One rocket body and one mission-related debris in short-lived orbits
STS-116	10 December	LEO (ISS)	Six small payloads and three mission-related debris in short-lived orbits

Very few orbital debris were generated during the deployment and operation of these missions, and all of the LEO objects associated with these missions have already reentered or will reenter within the recommended 25-year period.

NASA is also applying orbital debris mitigation guidelines to older spacecraft, some in orbit for over

20 years. The agency's Earth Radiation Budget Experiment (ERBS) spacecraft had been operating near 600 km for nearly 18 years in 2002 when the spacecraft's perigee was lowered more than 50 km to ensure that the vehicle would naturally decay within 25 years after its end of mission (Fig. 3).

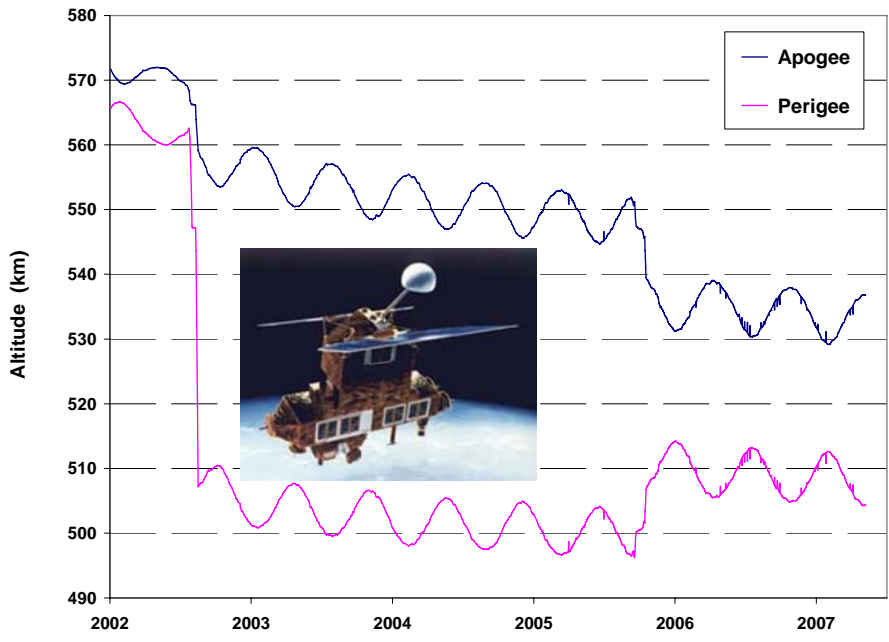


Figure 3. The orbit of NASA's ERBS spacecraft was lowered three years before its end of mission to ensure that its subsequent orbital lifetime would be less than 25 years, in compliance with NASA and national orbital debris mitigation guidelines.

As part of the decommissioning process for the spacecraft in 2005, all residual propellants were expended during a two-month interval. In fact, the lowering of the orbit three years earlier was fortuitous, since ERBS's propulsion system had further degraded and was no longer capable of such a maneuver.

NASA's Upper Atmosphere Research Satellite (UARS) also reached the end of its mission in 2005 after highly

successful operations for 14 years. The satellite's remaining propellant was expended from a nearly circular orbit over 550 km high, reducing its mean altitude by more than 100 km and significantly accelerating its natural orbital decay to less than five years (Fig. 4). Most of the propellant was used to lower perigee, which leads to the shortest remaining orbital lifetime.

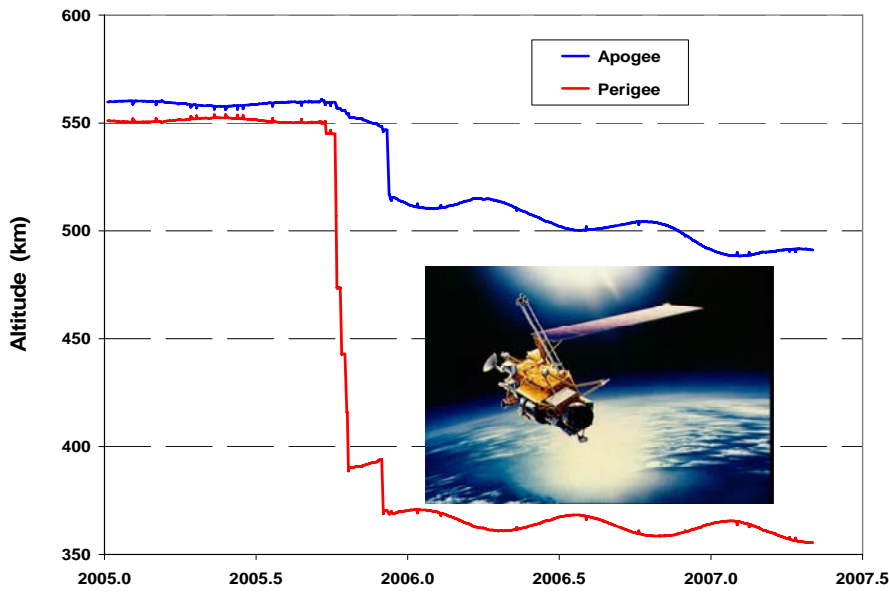


Figure 4. Near the end of its mission, NASA's UARS spacecraft maneuvered into a lower orbit with a lifetime of less than five years.

The commercial Globalstar network of communications satellites operates in an orbit of approximately 1415 km. From this altitude considerable energy would be required to transfer the vehicles to a lower orbit with a lifetime of only 25 years. Less energy is needed to raise a Globalstar spacecraft to an orbit above LEO, *i.e.*, above 2000 km. Although the spacecraft were deployed in the 1990's before any U.S. Government regulations on satellite disposal had been issued, some of the spacecraft have sufficient propellant remaining at the end of their missions to reach an altitude near to or in excess of 2000 km.

Fig. 5 indicates the orbital history of one of the first Globalstar satellites. After completing its communications mission in 2001, the vehicle was maneuvered into an orbit 100 km higher for more than three years of extended spacecraft systems tests. Then, in 2005, the spacecraft employed its residual propellant to reach a disposal orbit of nearly 1900 km. Two other Globalstar spacecraft in a similar test bed orbit are expected to reach 2000 km when their secondary mission is completed.

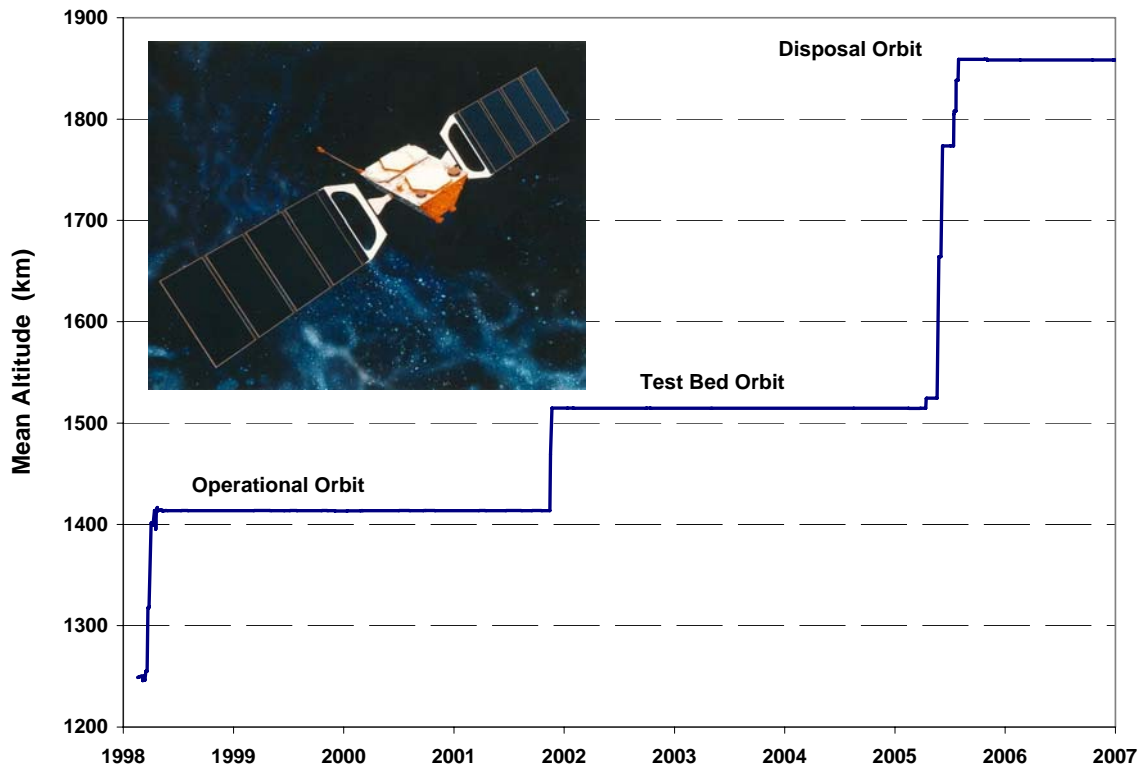


Figure 5. Globalstar spacecraft will be sent to disposal orbits above LEO or as close to 2000 km as possible.

For a new mission, the most cost-effective time to ensure that disposal guidelines can be met for both the spacecraft and its launch vehicle orbital stages is in the early spacecraft design phase. At NASA, the first such evaluation is required at the time of the spacecraft Preliminary Design Review. An excellent example of how the process can work is NASA's Solar Dynamics Observatory. The 3200-kg spacecraft is scheduled to be launched in 2008 by an Atlas V launch vehicle for a five-year scientific mission in an inclined geosynchronous orbit.

In accordance with NASA Safety Standard 1740.14, the first orbital debris assessment report was submitted to

the office of the Chief Safety Officer in March 2004. At the time, three potential non-compliance items were noted:

1. no means of venting unused helium pressurant from the spacecraft were available,
2. the spacecraft battery could not be disconnected from its charging circuit at end of mission, and
3. the disposal orbit of the Centaur upper stage and its subsequent reentry risk did not meet NASA guidelines.

However, by the time of the Critical Design Review one year later, all three problems had been resolved. A bypass valve was added to permit venting of the helium

pressurant. A relay was added to the power subsystem to permit isolating the battery at end of mission. The mission deployment profile was altered to leave the Centaur upper stage in an acceptable orbit between LEO and geostationary orbit. This decision also eliminated the concern about reentry risks. In the end, cost-effective solutions were found to meet all orbital debris mitigation objectives without impacting spacecraft reliability or the program schedule.

The disposal of launch vehicle orbital stages can sometimes present significant orbital debris mitigation challenges. One of the reasons for this is that the selection of a launch vehicle is often made after the design of the spacecraft is largely complete. This situation can leave little trade-space to meet launch vehicle disposal requirements. On the other hand, early planning can lead to some remarkably innovative and effective solutions.

One of the greatest success stories involving the disposal of launch vehicle stages is found in the deployment of three U.S. commercial LEO communications networks in the late 1990's. In all, 175 spacecraft were launched within only a few years to establish the Globalstar, Iridium, and Orbcomm networks. To accomplish this feat, five different types of launch vehicles from three countries were employed: Delta and Pegasus from the United States, Proton and Soyuz from the Russian Federation, and Long March from the People's Republic of China.

Even with extensive use of flying multiple satellites on a single launch vehicle, a total of 53 stages were initially placed into low Earth orbits. For the Globalstar and Iridium constellations, spacecraft were released into initial staging orbits well below the intended operational orbits. From here, the spacecraft propelled themselves to the desired altitudes, leaving their launch vehicle stages in short-lived orbits. The orbital longevities of the launch vehicle stages were further dramatically shortened by controlled de-orbits (Proton and Soyuz) and by perigee-lowering maneuvers (Delta, Long March, and Pegasus). Of the 53 stages, only a few still remain in orbit, and only four will fail to meet the 25-year-lifetime objective, two of which are due to launch vehicle malfunctions.

A comprehensive assessment of the disposal of all orbital stages launched around the world in 2006 is also very encouraging. In total, 63 space launchings to Earth orbit or beyond left behind 65 orbital stages. By the end of the year, 20 stages had already fallen back to Earth, and 36 stages remained with perigees in LEO. Of these, 29 are expected to reenter within 25 years from date of launch. Hence, a total of 88% of the stages with initial perigees in LEO are expected to be compliant with

recommended orbital lifetime restrictions. Nearly all launch vehicle orbital stages world-wide are also passivated at the end of mission.

One final example of note was the Delta IV mission of November 2006, which placed a U.S. meteorological spacecraft into an operational orbit of 850 km. After separation of the payload and at the end of its first revolution about the Earth, the main engine of the Delta IV second stage was reignited to effect a controlled reentry over a mid-Pacific Ocean region (Fig. 6). Not only was the stage immediately removed from Earth orbit and eliminated as a potential target for future accidental satellite collisions, but also the directed reentry over a broad ocean area ensured that any risk of human casualty from surviving debris in an uncontrolled reentry was prevented.

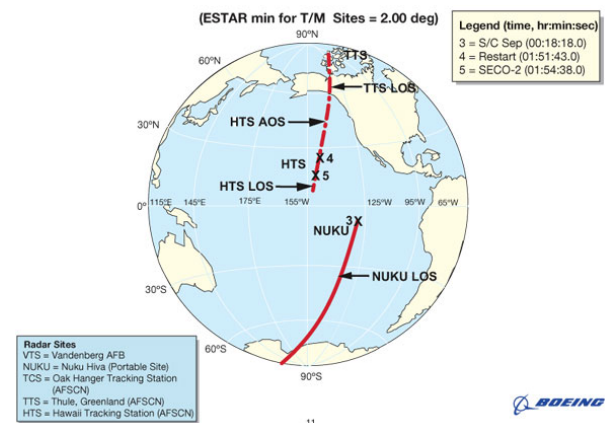


Figure 6. A Delta IV second stage was able to execute a controlled de-orbit from an altitude of 850 km after delivering its payload in November 2006.

5. COMPLIANCE AND REMAINING CHALLENGES

Overall, compliance with both end-of-mission passivation and LEO-lifetime limitation guidelines for both spacecraft and launch vehicle orbital stages is improving, due to the increasing promotion of these guidelines by space agencies and national regulatory organizations and due to the inherent self-interest of the aerospace industry, which seeks to avoid further contamination of near-Earth space. However, changes to long-established designs and processes can sometimes be difficult to achieve, even if costs are minimal.

Some spacecraft and launch vehicle orbital stages are still not completely passivated at end of mission, but their risk of subsequent explosion is typically low. Over

time, these systems will be replaced with newer, more compliant designs.

Perhaps the greatest challenge to most spacecraft and launch vehicle designers and operators is limiting orbital lifetimes in LEO after a mission has been accomplished. Most LEO spacecraft inserted into operational orbits above 700 km will not naturally fall back to Earth within 30 to 35 years, i.e., mission lifetimes of 5-10 years plus 25 years after end of mission. Moreover, due to very little atmospheric drag at such altitudes, many spacecraft have minimal or no maneuver capabilities and, thus, are unable to perform significant perigee-lowering maneuvers when decommissioned. Some potential solutions are the addition or upgrade of propulsion systems, drag enhancement devices (such as deployable or inflatable lightweight structures), and momentum or electrodynamic tethers. However, many of these concepts can involve non-trivial direct and indirect costs.

Whereas some launch vehicle orbital stages have demonstrated the ability to perform major maneuvers after completing their payload delivery missions, others are currently constrained by design or mission requirements. Some of these limitations could be overcome by technical alterations to the vehicles with very little additional weight. More problematic are solid-propellant orbital stages used to deliver payloads to orbits above 650 km. Such stages normally do not fall back to Earth within 25 years and have little or no ability to execute post-delivery maneuvers.

Although not a major focus of this paper, the issue of human casualty risk from uncontrolled spacecraft and launch vehicle stage reentries remains a serious one, particularly for objects with a mass of 1000 kg or more. The principal solutions are either to conduct more controlled de-orbits with their associated payload penalties or to construct vehicles in a manner that fewer components will survive the intense conditions of reentry. The previously mentioned NASA program of design-to-demise is making noticeable inroads in this area by replacing materials with high melting points with those of lower melting temperatures.

6. SUMMARY

Controlling the orbital debris population is now widely recognized as essential for preserving near-Earth space for the use of future generations. During the past two decades, substantial progress has been made on both technical and policy levels. The implementation of orbital debris mitigation guidelines, now recommended by all the major space-faring countries as well as the United Nations, is steadily gaining ground.

The most influential actions for the future space environment are those involving the disposal of spacecraft and launch vehicle stages in LEO. The passivation of space vehicles at the end of their missions and the limitation of their subsequent orbital lifetimes are clearly the two most important issues. Addressing these issues early in the initial system definition phase will lead to the most efficient and cost-effective solutions. The examples cited above demonstrate the many accomplishments in meeting space vehicle disposal guidelines and the commitment of both industry and policy-makers to achieve even greater compliance.

7. REFERENCES

1. anon., *Guidelines and Assessment Procedures for Limiting Orbital Debris*, NASA, NASA Safety Standard 1740.14 (1995). (www.orbitaldebris.jsc.nasa.gov/library/references.html)
2. *Ibid.*, p. 4-1.
3. Johnson, N.L., "The Cause and Consequences of a Satellite Fragmentation: A Case Study", *Ad. Space Res.*, 23 (1999), pp. 165-173.
4. Johnson, N.L., et. al., *History of On-Orbit Satellite Fragmentations*, 13th ed., JSC-62530 (2004), NASA Johnson Space Center.
5. anon., *IADC Space Debris Mitigation Guidelines*, IADC-02-1 (2002), Inter-Agency Space Debris Coordination Committee. (www.orbitaldebris.jsc.nasa.gov/library/references.html)
6. *Ibid.*, p. 6.
7. anon., *Technical Report on Space Debris*, A/AC.105/720 (1999), United Nations. (www.orbitaldebris.jsc.nasa.gov/library/references.html)
8. anon., "Space Debris Mitigation Guidelines of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space", Annex IV in *Report of the Scientific and Technical Subcommittee on its forty-fourth session, held in Vienna from 12 to 23 February 2007*, A/AC.105/890 (2007), pp. 42-46.