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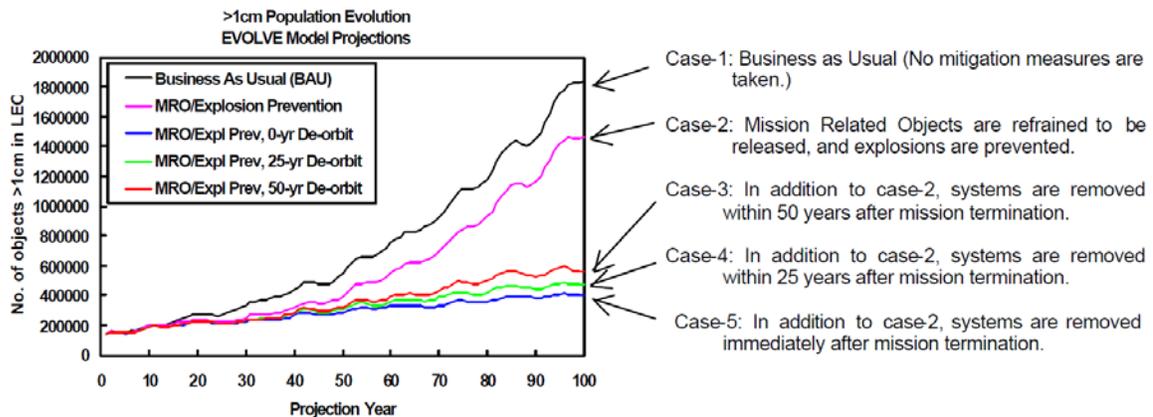
Annotated Bibliography

30 End of Mission Considerations

Scott M. Hull, NASA Goddard Space Flight Center

While a great deal of effort goes into planning and executing successful mission operations, it is also important to consider the End of the Mission during the planning, design, and operations phases of any mission. Spacecraft and launch vehicles must be disposed of properly in order to limit the generation of orbital debris, and better preserve the orbital environment for all future missions. Figure 30-1 shows a 1990's projected growth of debris with and without the use of responsible disposal techniques. This requires early selection of a responsible disposal scenario, so that the necessary capabilities can be incorporated into the hardware designs. The mission operations must then be conducted in such a way as to preserve, and then actually perform, the planned, appropriate end of mission disposal.

Figure 30-1 Debris Growth with Various Mitigation Approaches (reference iii, page 22)



Computer simulations have shown that the orbital debris population already present on-orbit is self-propagating; that is, the orbital debris density will continue to increase through random collisions alone, unless reduced by outside effortsⁱ. This may well result in a cascade effect that eventually renders some orbits impractical for space operations. Since it is not yet economically practical to remove a significant amount of existing debris from orbit, it is critical that responsible end of mission disposal be practiced for all current and future missions, in order to help control the rate of increase of mission-lethal debris objects in commonly used orbits. Had such methods been employed throughout the history of space operations, the cascade effect might have been prevented, or at least substantially delayed.

End of Mission disposal (also known as End of Life disposal, Decommissioning, or simply Disposal) has been addressed primarily at the international level in discussions by the Inter-Agency Space Debris Coordination Committee (IADC). The IADC is an international forum of national space agencies and the European Space Agency (ESA) for the coordination of activities related to the issues of man-made and natural debris in spaceⁱⁱ. In 2002, the IADC issued a set of guidelines (IADC-02-01) addressing, among

other things, prevention of post mission explosions, and acceptable disposal options. These guidelines, described in Section 30.1, were slightly refined in 2007.

Spacecraft **mission designers need to consider disposal early in the design process**, in order to incorporate the necessary hardware and procedures to ensure a safe disposal. The first step is to select a baseline disposal method, as described in Sections 30.2 and 30.3 below. That disposal method will determine the key design factors which will need to be considered throughout the remainder of the design process. It may, for example, be necessary to size the propulsion system and navigation hardware for an orbit change or controlled reentry. Alternatively, it may be necessary to design the power and propulsion systems for postmission passivation, as described in Section 30.4. As the design develops, and the reentry risk is determined, it is occasionally necessary to change the baselined disposal method, but at a cost which increases dramatically as the design matures. In any event, it will be necessary to develop and test spacecraft operations procedures specific to the disposal (Section 30.5). The disposal of the FireSat II and SCS sample missions are discussed in Section 30.6, as examples of the application of the disposal principles. Early consideration of the end of mission disposal is among the most effective ways to minimize the growth of orbital debris, to the benefit of all missions.

30.1 IADC End of Mission Guidelines

While they do represent agreements among the leading space agencies of the world, it is important to note that the IADC guidelines are not currently legally binding. They are generally reflected, however, in numerous national space policies, and are followed at least in part for the majority of scientific and military space missions. Despite whether commercial and other missions are legally bound to comply with the IADC guidelines, meeting the standards has been shown to be crucial for limiting the growth of orbital debris, which is in the interests of all space users. The guidelines are summarized here, and the specific text is readily available on the internet. In addition, there is a “Support Document to the IADC Space Debris Mitigation Guidelines” (IADC-04-06), which provides valuable insights and background information on the specific guidelines.

The IADC guidelines provide guidance for limiting the generation of orbital debris both during and after space operations. They begin by describing the need for limiting the growth of orbital debris, and defining the relevant terms used throughout the document. The guidelines refer to direct creation of debris through operational debris (lens caps, for example), and potential breakage of tethers. They also consider on-orbit breakups caused by explosions during and after the mission, as well as intentional destruction by internal or external sources. The guidelines also define accepted disposal orbits and other conditions such as the timeline for abandoning commonly used orbits, and controlling the risk to people and property on the Earth. Finally, they address limiting the potential for damage by collisions with other space objects and with small orbital debris that could prevent the ability to successfully execute end of mission disposal. The IADC guidelines are written to apply throughout the mission lifetime, from design through operations and decommissioning.

It is worth noting that while the IADC Guidelines do lay the foundation for general agreements on the limitation of orbital debris, with few exceptions they do not provide

specific quantitative requirements. In fact, the stated purpose of the guidelines is to “demonstrate the international consensus on space debris mitigation activities and constitute a baseline that can support agencies and organizations when they establish their own mitigation standards”. Only in the case of the definitions of the protected orbit regions, and the GEO disposal conditions, do the guidelines provide specific limits. The remaining limitations are described as qualitative measures, which are left to individual agency requirements documents to define in detail.

In addition to the IADC guidelines, various other organizations have adopted similar guidelines and requirements. In 2007, the United Nations General Assembly endorsed the “Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space”, which are very similar to, and cover the same general topics as, the IADC guidelines, while being generally less specific. Most nations look to their national space agency (often an IADC member) for orbital debris policy and control. The United States, however, has issued not only the “US Government Orbital Debris Mitigation Standard Practices”, but also has a number of individual agency documents that address orbital debris limitation to varying degrees. In general, the requirements documents issued by the IADC member agencies themselves are the most specific and restrictive. Examples of national orbital debris limitation documents are shown in Table 30.1-1.

Table 30.1-1 International Orbital Debris Limitation Documents
(self-generated)

Domain	Document
IADC	IADC-02-01, Rev 1
US Government	U.S. Government Orbital Debris Mitigation Standard Practices
NASA	NPR 8715.6A, NASA-STD-8719.14
US DoD	DoD Space Policy Directive, 3100.10, AFI 91-217
US FAA	Title 14, CFR Part 415.39
Japan	JAXA JMR-003
France	CNES MPM-50-00-12
Europe (ESA)	European Code of Conduct for Space Debris Mitigation
Russia	Space Technology Items. General Requirements on Mitigation Of Space Debris Population

30.2 LEO Disposal Options

Responsible exit from Low Earth Orbit (LEO) is one of the most important steps that can be taken to limit the growth of debris in that region of space. An IADC working group has examined the long-term effects of various guideline optionsⁱⁱⁱ, and shown that by limiting the amount of time that each vehicle remains in LEO, growth of the orbital debris environment is greatly reduced. Thus, it is desirable and recommended for space objects (both launch vehicle stages and spacecraft) to be removed from the LEO region as soon as practical. The minimum orbital lifetime possible for an individual vehicle might be determined, however, by the remaining maneuvering capability of the vehicle at the

end of the mission or by the initial orbit. There are three basic approaches to LEO disposal. The most desirable, if possible, is to perform a controlled (or ‘targeted’) reentry into an unpopulated region of ocean soon after the end of the mission, either using on-board propulsion or by external retrieval. If this is not possible, it may be possible to boost into a storage orbit between LEO and GEO, safely removed from both regions. Finally, a spacecraft can be allowed to reduce its orbit by atmospheric drag, resulting in an uncontrolled reentry and impact on an unpredictable portion of the Earth’s surface.

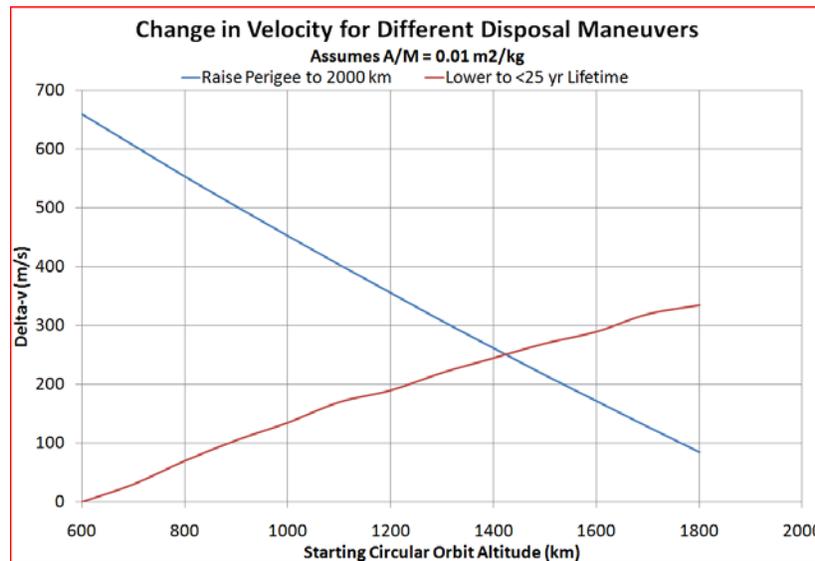
Controlled reentry is the preferred LEO disposal method for several reasons. Not only does it provide positive removal of the vehicle from orbit, but the removal also tends to occur as soon as possible after the mission. By selecting a reentry location over a large unoccupied area of ocean, the reentry risk to the ground population is minimized. This, along with the lack of postmission passivation, can result in greater flexibility for the mission hardware designers. Controlled reentry is not without significant challenges, however. Reentry maneuvers typically require extensive planning, and notification to the relevant air and maritime traffic authorities prior to performing the maneuvers. In practice, controlled reentry is best performed using at least three separate maneuvers in order to better control and refine the orbit, with a final perigee of less than 50 km, to prevent atmospheric skip. In order to accomplish this, the spacecraft design must incorporate sufficiently large thrusters to ensure adequate control authority at low altitude. Controlled reentry also requires that the vehicle reserve sufficient fuel to reliably perform the reentry maneuvers at the end of the mission, which will result in a larger fuel mass at launch. Section 9.6 discusses the ΔV needed to accomplish controlled reentry, and gives examples. With the advent of robotic servicing and retrieval capabilities, it also may become a practical option for missions to further extend mission lifetime, and still perform a controlled reentry, but at the expense of an additional launch.

Disposal into a storage, or ‘graveyard’, orbit may be a practical option for some high-altitude LEO missions. The storage region is located between LEO and GEO, and is generally considered to extend from 2000 km to approximately 35,586 km (GEO – 200 km) altitude. Within this region, however, care must be taken to also avoid commonly used orbits, such as the circular 12 hour orbits used by navigation and other satellites. Both the apogee and perigee of the disposal orbit must be within the storage orbit region. As with controlled reentry, the spacecraft design must incorporate sufficiently large maneuvering thrusters, and fuel must be reserved for the orbit raising operation. Figure 30.2-1 shows the typical ΔV required to maneuver from a circular LEO orbit to the 2000 km storage orbit. Any vehicle left in a storage orbit must be passivated at the end of the mission, as described in a later section. In general, only those missions operating above about 1400 km altitude can reach the storage orbit region with less delta V than re-entering within the recommended timeframe.

If neither controlled reentry nor storage orbit disposal are practical for a LEO mission, then disposal will eventually occur by uncontrolled reentry. If possible, the final altitude and Area-to-Mass Ratio need to be tailored to ensure that a reentry by atmospheric drag is predicted to occur within 25 years after the end of the mission. The IADC study mentioned above concluded that this orbit duration is a reasonable compromise between unlimited orbital lifetimes and immediate de-orbit at the end of the mission. For a

spacecraft with no propulsion system, that limits the maximum orbit altitude to about 600 to 700 km, depending on the Area-to-Mass Ratio and launch year. Figure 30.2-1 shows the typical ΔV required to maneuver from a circular LEO orbit to an orbit that will reenter the atmosphere within 25 years. Note that the solar flux is an important component of this prediction, and varies throughout the solar cycle, complicating the reentry date prediction considerably. Current predictions of future solar activity are available for download from NASA, NOAA, and other sources, and are typically updated frequently. Earlier orbit decay will further reduce the likelihood of collision, and is therefore recommended if possible.

Figure 30.2-1 Disposal Delta-V Requirements
(self-generated, see Excel spreadsheet “SMAD End of Mission Calculations.xls”)



While at first glance uncontrolled reentry may appear to be a preferred disposal method (it is surely the simplest and lowest mass approach), there are considerable challenges to doing so responsibly. It is necessary for any non-operational object left in orbit to be passivated during the orbit-decay period, as discussed in Section 30.4, in order to prevent inadvertent explosion or breakup during the potentially long orbit decay period. The risk to the ground population may also be controlled by requirements of the launching or operating organization. For example, several space agencies require a detailed assessment to show that the spacecraft hardware will burn up sufficiently during atmospheric reentry to pose less than a 1 in 10,000 risk of causing a serious injury to even one human. In some cases, the risk to the public from an uncontrolled reentry is sufficient to dictate that a controlled reentry is the only acceptable method of disposal from LEO.

Meeting a requirement to limit reentry risk can be extremely difficult or impossible for some large spacecraft, and usually necessitates specialized design techniques and materials selection. The risk is determined by how much of the spacecraft survives reentry, and by the ground population over which the reentering debris might land. In the

case of an uncontrolled reentry, the surviving debris might land anywhere in the latitude band covered by the orbit inclination, so an average population density over this band is used for the risk estimate. Object survivability is largely driven by the thermal properties of the primary construction material for the object in question, expressed as a heat of ablation. Heat of ablation is typically expressed in terms of mass, but it can also be useful to express it in terms of volume (multiplying by the material density), for comparing two material options for the same size part.

$$\text{Heat of Ablation} = \text{Specific Heat} \times \Delta \text{ Temperature} + \text{Latent Heat of Fusion}$$

The heats of ablation for several typical spacecraft materials are shown in Table 30.2-1. Notice that materials such as aluminum and graphite/epoxy composite are readily demisable, whereas titanium, glass, and beryllium all have high heats of ablation, and should therefore be avoided when possible, if reentry risk is a concern. In general, objects made from materials with melting temperature greater than 1000 K, or heat of ablation greater than 1000 kJ/kg or 2500 kJ/m³ are more likely to survive atmospheric reentry. Oxidation heating (essentially burning) on reentry also contributes the demisability of aluminum and graphite/ epoxy.

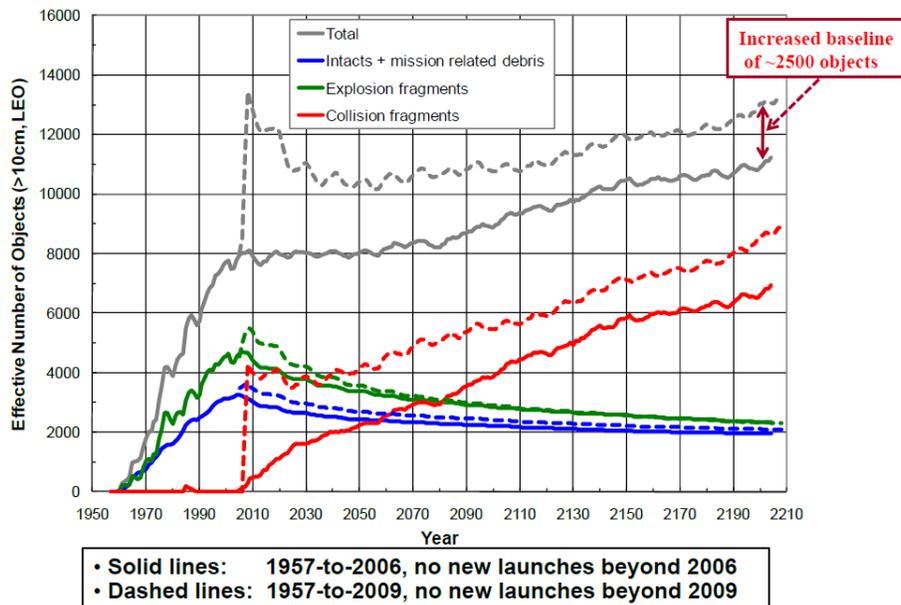
Table 30.2-1 Heats of Ablation for Several Common Spacecraft Materials (self-generated)

Material	Melting/ Softening Temperature (K)	Heat of Ablation (kJ/kg)	Heat of Ablation (kJ/m ³)
Graphite/Epoxy	700	350	550
Aluminum	850	900	2400
Stainless Steel	1700	900	7250
Titanium	1940	1600	7050
Zerodur Glass	2000	1400	3550
Beryllium	1557	4100	7550

Object survivability is also influenced by the object’s ballistic coefficient, which is a function of the shape, mass, and dimensions of the object, and determines its velocity. In general, faster moving objects accumulate more heat, and are more likely to demise. Reentry risk has been successfully reduced on some flight missions by modifying a component’s shape, size, or material, when possible. Another approach that can be used to reduce the reentry risk is to ensure that several high survivability objects are bound together, since multiple objects are more likely to cause injury than a single object. For example, if several surviving battery cells are contained within a robust battery box, then the single surviving box presents less risk than the multiple cells would. Because the survivability of spacecraft components depends on so many factors, it is necessary to combine very specialized assessment software with detailed knowledge of the spacecraft construction in order to determine and limit the reentry risk. Early avoidance of high survivability materials in component designs can help to prevent difficult and expensive redesigns late in the design phase.

For all LEO mission disposal options, it is desirable to minimize the total time that a vehicle spends in orbit. This is done to reduce the likelihood that the vehicle will experience collisions with resident objects, which usually result in the creation of additional orbital debris. Debris generation potential increases rapidly with projectile size, and even existing objects as small as 1 cm can create additional debris on impact. Simulations predict that on-orbit collisions will be the primary source of new orbital debris, so minimizing orbital lifetime is the most important step toward limiting future debris generation. Figure 30.2-2 shows that even with no new launches, collisions among existing on-orbit objects will eventually cause the debris population to rise. Any fuel remaining at the end of the mission should be used to lower perigee as much as possible during the passivation process, resulting in the earliest possible reentry. One caveat to this general rule, though, is that the last burn before an uncontrolled reentry should leave the spacecraft high enough so that its orbit remains stable long enough for ground tracking to get an accurate fix. This will allow monitoring of the vehicle for conjunction assessment and collision avoidance purposes as its apogee descends past other operating spacecraft.

Figure 30.2-2 Projected Debris Generation by Mechanism (with no new launches after 2009)



Originally from the 13th Annual FAA Commercial Space Transportation Conference, Orbital Debris & Space Traffic Control presentation by Gene Stansbery (JSC/ODPO) Also at <http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i1.pdf>, page 8.

Complicated by the 2006 data. ODPO has offered to print this for us without the confusing solid line data.

30.3 Non-LEO Disposal Options

The IADC guidelines define two protected regions of space: LEO and GEO. No space vehicles should be left in either of these regions on a long-term basis. The LEO region is simply defined as the “spherical region that extends from the Earth’s surface up to an

altitude (Z) of 2000 km”. Removal from the LEO region within 25 years is described in Section 30.2. The GEO protected region is defined as 35,786 km \pm 200 km, with latitude of $0^\circ \pm 15^\circ$. Any mission that passes through that protected region must be maneuvered at the end of the mission to remain clear. Removal from GEO should occur as soon as practical after the end of the mission.

Figure 30.3-1 The IADC-defined Protected Regions of Space (from reference iii, page 5)

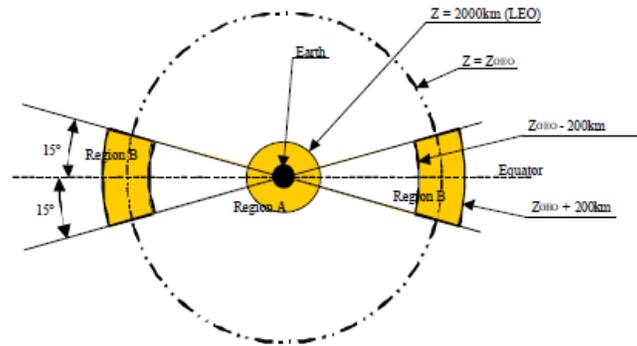
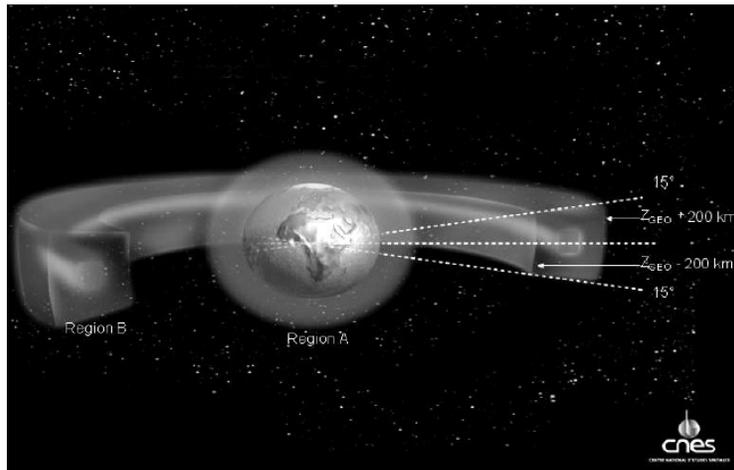


Figure 30.3-2 Artist’s rendering of the IADC-defined Protected Regions (from reference iii, page 6)



Disposal from GEO is performed by increasing the orbital radius sufficiently to remain well in excess of 200 km above the GEO altitude ($35,786\text{ km} + 200\text{ km} = 35,986\text{ km}$ minimum altitude) for a minimum of 100 years. Due to the effects of solar radiation, as well as luni-solar and geopotential perturbations, the recommended minimum increase above GEO is defined as:

(equation adapted from reference iii, page 18)

$$200 \text{ km} + 35 \text{ km} + (1000 \text{ km} \times C_R \times A/m)$$

Where: 35 km represents the effects of luni-solar and geopotential perturbations
 C_R is the solar radiation pressure coefficient (typically $1 - 2 \text{ kg/m}^2$)
 A/m is the spacecraft cross-sectional area to dry mass ratio (m^2/kg)

The altitude is generally increased, as opposed to decreasing, to prevent an accumulation of debris that future GEO missions would need to pass through to get to GEO, and to prevent potential signal interference. In addition to increasing the orbital radius, the final orbit should be circularized to an eccentricity of no more than 0.003, and the spacecraft needs to be passivated as described in section 30.4. It is estimated that the fuel required for responsible disposal of GEO missions is equivalent to that used for about 3 months of station-keeping for most spacecraft^{iv}. The “Support to the IADC Space Debris Mitigation Guidelines” document contains further details on disposal from GEO.

Disposal from Earth orbits other than LEO and GEO (high eccentricity science orbits, for example) should minimize the orbit lifetime and avoid any highly used regions. While the IADC guidelines are not specific, some national requirements documents include a protected region for 12 hour orbits, commonly used for navigation satellites. Due to the wide variety of unusual orbits, it would be impossible to cover all possibilities in detail here. The first priority of the end of mission planning, however, is minimization of the potential for on-orbit collisions. As with LEO and GEO missions, any vehicle left in orbit must be passivated (see section 30.4) after the final maneuvers.

There are, as yet, few guidelines available for disposal of lunar, planetary, or Lagrange orbit missions. The primary consideration, as it is for Earth orbits, is to minimize the potential for collisions with other current and future spacecraft, either directly or through generated debris. Therefore, it is best to avoid leaving spacecraft in long-term orbits (>10 years) at the end of the mission, except in those cases where the spacecraft continues to serve as a communications relay after its primary mission. Likewise, it is best to passivate any orbital hardware at the end of the mission, to prevent explosions and other breakups, which would generate additional debris that might interfere with future missions. If disposal is to include lunar or planetary impact, care should be taken to avoid sites of scientific or historic value, as well as preventing organic contamination whenever possible.

30.4 Passivation

At the end of the mission, the IADC guidelines call for all on-board sources of stored energy to be “depleted or safed when they are no longer required for mission operations or post-mission disposal”, also known as *passivation*. The main concern is that stored residual energy has in the past resulted in explosions, which have been a major source of orbital debris. Propulsion systems, batteries, and reaction wheels all contain stored energy, and are the most common components identified for passivation. Since a spacecraft or launch vehicle could be in orbit and unattended for many years (even centuries) after the mission, it is important to passivate to prevent generation of debris that would increase the likelihood of collisions for other missions.

30.4.1 Propulsion System Passivation

Propulsion system explosions have resulted in some of the largest debris-producing events on orbit. For example, in 1996, a Hydrazine Auxiliary Propulsion System (HAPS) upper stage spontaneously exploded two years after delivering its payload, generating over 700 pieces of debris large enough to be tracked from the ground. Because of a launch anomaly, this vehicle contained both propellant and high pressure gas, which were not able to be depleted. The most likely cause of the explosion was a long-term regulator failure, which allowed the propulsion tank to become overpressurized.^v

A propulsion system is designed to produce a controlled explosion, resulting in the desired thrust. Unexpected events, though, (small debris impact to the tank, mixing of fuel and oxidizer, etc) can produce extremely destructive explosions. Even residual pressurant gas (despite being chemically inert) can cause a propulsion tank to rupture catastrophically if, for example, the tank is struck by small debris. Propellants should be depleted by either burning or venting, and pressurant should be vented during disposal, to prevent future breakups and debris generation. Residual propellant should be used to lower the perigee of LEO vehicles, to ensure that they de-orbit as soon as possible. Unfortunately, some propulsion system designs do not allow for complete passivation, **unless this capability is specifically taken into account early in the design phase.**

There can be a number of challenges to depleting the fuel left on-board a spacecraft at the end of the mission. Because sensors can become inaccurate, particularly near the end of the mission, when the residual propellant levels are low, it can be difficult to judge exactly how much propellant remains to be depleted. It is recommended that, if possible, the propulsion system be monitored until some positive sign of completion is observed (a rapid pressure drop from pressurant venting through a thruster, for example). If a significant amount of propellant remains to be expelled, it must be done in a manner that will not cause excessive disruption to the spacecraft attitude, or cause the spacecraft to spin beyond its design limits. Since even directly opposed thrusters are not perfectly matched, this can be more difficult than first imagined. Propulsion systems have also been observed to perform very differently as the propellant nears exhaustion^{vi}.

An example of a unique challenge was passivation of the TDRS-1 spacecraft after a very long and successful 26 year career. Due to a modification in its mission, when the payload finally failed there was still a large excess of fuel on-board, which needed to be expended. Since lowering perigee was not an option for a GEO mission, and using all remaining fuel to increase the altitude would cause the spacecraft to drift out of communications range during the maneuver, an alternative solution was developed. The spacecraft was first raised to the disposal orbit, then essentially a flat spin was induced to exhaust the remaining fuel, while not disturbing the orbit or exceeding the spacecraft mechanical design. In this way, the fuel was expended and the spacecraft was passivated before it drifted out of communications range. This is an example of the creativity sometimes necessary to perform responsible passivation when it was not necessarily considered early in the design.

The IADC guidelines and most space agency regulations call for depletion of pressurant gas at the end of the mission, because residual pressure exerts stress on the tanks and

other hardware. The method of passivation varies based on the propulsion system design. In the case of a propellant tank with no diaphragm, it is usually possible to expel the pressurant gas by latching opposing thruster valves open at the end of the mission. Pressurant gas that is trapped behind a diaphragm, or in a separate tank, needs to be exhausted through a dedicated vent line. Such vent lines should be designed so that they will not impart a significant thrust or spin to the spacecraft during passivation. This can be accomplished by controlling the gas flow, and providing an omnidirectional outlet.

30.4.2 Power System Passivation

To date, batteries have exploded on-orbit on at least eight occasions, accounting for a portion of the debris currently in orbit^{vii}. Most battery explosions result from excess gas pressure generated inside the battery case due to overcharging. Nickel-hydrogen batteries, for example, typically operate at up to 1000 psi or more, directly related to the charge state. It is therefore important to provide the hardware capability to physically disconnect at least the charging capacity from the batteries at the end of the mission. The best approach is to physically disconnect the solar arrays from the power bus completely at the end of the mission. Simply minimizing the battery charging rate is not sufficient, since that setting may change due to radiation damage, part failure, or other mechanisms during the long unattended orbit-decay period. Remember that after spacecraft are decommissioned from GEO, they will be on orbit for centuries. Some designers are traditionally reluctant to include any capability to completely disconnect the solar array or battery, however, since that creates the possibility for premature mission failure. Section 30.4.4 provides more information on passivation methods that are designed to retain mission reliability.

Lithium-ion batteries present special concerns, since they not only store electrical energy, but also contain potentially dangerous materials. As with NiH₂ batteries, overcharge produces heat and gas buildup which can result in cell rupture. In addition, though, when discharged, the cells can plate out highly reactive lithium metal. Since the charge conditions cannot necessarily be guaranteed throughout the post-mission period, it is very important to prevent any possibility of discharging and recharging lithium-ion batteries. Many lithium-ion battery assemblies have built-in ground safety disconnect relays to prevent this from occurring during the integration phase. By designing in the ability to actuate these relays on-orbit, the batteries can be completely isolated from the power bus after disposal, and can neither charge nor discharge. Of course, this concern is negated if the solar arrays are completely disconnected, and there is no way to re-charge the batteries.

30.4.3 Passivation of Other Systems

The IADC guidelines also recognize the potential for post-mission damage from other systems. Pressure vessels, self-destruct devices, and momentum wheels are all examples of components which can contain mechanical and chemical energy at the end of the mission. Provisions need to be made during the design of such components to allow for them to be vented, safed, and/or spun down at the conclusion of the mission. Some of these passivation steps can be simple. For example, disabling power to momentum wheels is sufficient to allow them to spin down by internal friction. The “Support to the

IADC Space Debris Mitigation Guidelines” document contains guidance on systems that require passivation, and safe final conditions for them. One additional system to consider for passivation is communications. Whenever possible, the transmitting capability of the spacecraft should be disabled at the end of the mission, to prevent interference with future missions. If the power system is properly passivated, both the momentum wheels and transmitter capability are passivated by default. It is best to listen for any transmissions a few days after passivation, though, to ensure that the spacecraft has not recovered despite the intended shutdown.

30.4.4 Passivation Challenges

One difficulty in designing for adequate passivation is the potential creation of single points of failure for the mission. For example, if a single command could erroneously be sent to vent the propellant or pressurant before or during operations, the entire mission could be lost. Designers have long recognized this potential, and have employed techniques to positively prevent any such opportunities – preventing vent lines from being operable on orbit, for example. Such hardware designs, however, often prevent adequate passivation of the spacecraft at the end of the mission as well. In many ways, the inclusion of necessary passivation systems requires hardware designers to adopt a new approach to mission reliability. Through the use of redundant hardware and end of mission software modifications, passivation can usually be designed into the system without presenting a single point of failure.

One example of a way to provide for passivation, while preventing a single point failure mechanism is that of the Solar Dynamics Observer (SDO) battery passivation. Designers have included the capability of actuating the built-in lithium-ion battery isolation relays on-orbit, but omitted the commands to do so from the command database for the duration of the mission. Even if the commands were erroneously sent, they would not be recognized by the spacecraft. At the end of the mission, the command options will be uploaded into a new software patch, allowing the relay actuation commands to be recognized and executed by the on-board hardware. In addition, there is a pair of commands (arm and fire) necessary to actuate each relay. This design has allowed SDO to design for responsible passivation at the end of the mission, yet retain reliability throughout the operational phase of the mission.

Most spacecraft are also designed with autonomous fault detection and correction capabilities, which respond to abnormal spacecraft conditions in a way that keeps the spacecraft operating (or returns it to low level operation after a major anomaly). Such capabilities, however, are contrary to the whole notion of postmission passivation, and may work to counteract any passivation procedures. Passivation is, after all, an anomalous condition from the perspective of successful mission operations. Autonomous recovery systems, then, need to be disabled before engaging in postmission passivation. Therefore, it is important to consider this phase of the mission when designing the operations modes and command structure. Ideally, there should be a disposal mode of operations planned from the beginning, that would allow a complete and safe disposal after the mission – with proper safeguards to prevent inadvertently entering or exiting this mode, of course.

Passivating missions that were designed and launched without explicit consideration of postmission passivation can present unique difficulties. Often, it may not be possible to fully comply with the IADC guidelines, or other requirements. Typically, it may be impossible to disable the autonomous recovery hardware built into the spacecraft design, so that the spacecraft constantly returns to a safe mode. Another example is the inability to physically disconnect the battery or solar arrays from the charging circuit. In such a case, it is important to consider the intent of passivation and debris limitation guidelines, so as to minimize the potential for creating additional debris. For example, by reducing the NiH₂ battery charging current to its lowest possible level, and leaving some benign loads enabled, it is often possible to keep the battery in a perpetual discharge condition, thus greatly reducing the risk of battery explosion by overcharging. While compliance with the guidelines or other requirements is the most reliable approach, it may be necessary to perform less than complete passivation on some operational missions. Future missions, though, must be designed for complete passivation at the end of the mission, unless performing a controlled reentry disposal.

When planning passivation procedures, it is necessary to consider the order in which steps must occur. For example, the transmitter should typically be disabled last, so that all previous commands can be verified. There may also be attitude control factors that need to be considered in order to ensure adequate communications or power needs. Generally, passivation begins with disabling recovery mechanisms, followed by passivating the propulsion, attitude control, power, and communications systems. Bear in mind that as each system is disabled, its contribution to the mission is lost, and the remaining steps need to be completed quickly; for example, before battery power is lost. Each spacecraft needs to be considered on its own merits, however, including any hardware degradation that may have occurred during the mission. The specific passivation procedures for an individual vehicle should be reviewed and tested as thoroughly as possible before execution.

30.5 Disposal Planning

Depending on the method of disposal employed, the process may require anything from relatively simple to highly complex preparation. For instance, a small, low-altitude science mission with no propulsion system, reentering within 25 years, may need only to passivate the power system at the end of the mission. A large spacecraft in LEO which requires a controlled reentry will require much more extensive planning in terms of maneuvers, communications, staffing, etc. Planning for disposal often requires the coordination of a number of different disciplines, and can take months of preparation and testing. Detailed written plans are often required to be submitted well in advance of the disposal.

If the disposal involves maneuvers, care must be taken to prevent collision with other orbital assets and debris. It is important to report in advance any significant maneuvers which will change the altitude of the spacecraft more than 1 kilometer, to ensure that the maneuver will not cause a collision. In the United States, the primary tracking and conjunction assessment authority is USSTRATCOM. That service is also available to some Commercial and Foreign Entities as well, through special arrangement. In addition to checking planned maneuvers for conjunctions, it is important to plan any rapid orbit

decay periods so that they take place slowly enough that the decaying orbit can be adequately characterized for continuous conjunction assessment activities. This is especially important due to the potential threat to manned missions at low altitudes.

As the end of the mission approaches, there can be a temptation to continue beyond the originally planned termination point. The need for ending the mission might be driven by approaching the minimum fuel for de-orbit, declining reliability due to hardware degradation, or other factors which dictate that there may be a diminished or ineffective disposal, if not executed in the near-term. In the case of a science mission, though, there is a desire to continue data collection, or there may be increased profits available by continuing a commercial mission. All implications of such a decision need to be considered before continuing the mission, including increased risk of collision, orbital slot availability, RF interference, and reentry risk to the public. Only when the overall risk of continuing is truly negligible, should continuing beyond a pre-planned mission completion be considered.

30.6 FireSat II and SCS Examples

Since both the FireSat II and SCS missions are assumed to be US Government-owned assets, they would need to meet the U.S. Government Orbital Debris Mitigation Standard Practices, which is in some ways more comprehensive than the IADC guidelines. Not only the spacecraft, but also the launch vehicles for each mission must be considered for safe disposal, in terms of both orbital debris generation and reentry risk. In most cases, the individual spacecraft from each mission would likely be retired one at a time, due to equipment failure or fuel reserves. Since it is extremely rare for a mission to intentionally shed any debris during disposal, both of our example missions will be assumed to meet the operational debris requirement.

30.6.1 Disposal of the FireSat II Spacecraft

The FireSat II mission operational orbit is 700 km altitude, circular, at 55° inclination. At the end of the 3-5 year mission, it will be necessary to ensure that each spacecraft is removed from the LEO protected region within 25 years. Orbital lifetimes can vary based on spacecraft mass and the area presented in the velocity direction, as well as the solar flux effects on the Earth's atmosphere. With body-mounted solar arrays, the Firesat II spacecraft is likely to tumble slowly after the mission, so an average cross-sectional area would be assumed for orbital lifetime predictions. With deployed solar arrays, the spacecraft may be more likely to adopt a gravity gradient stabilized orientation, presenting a different (likely higher) drag area. Orbital lifetime predictions from the 700 km circular altitude can vary from just under 25 years to over 60 years, based on the launch year and spacecraft area. It will most likely be necessary, then, to intentionally reduce the perigee of each Firesat II spacecraft as a part of the End of Mission disposal using all residual propellant, including the portion reserved for disposal operations.

As discussed in Section 30.4, it will be necessary to passivate the FireSat II systems in order to prevent fragmentation during the up to 25 year orbital decay period. Ideally, the mission operations concept would include a separate operations mode for disposal,

intended to disable automatic recovery of the spacecraft after it has been shutdown. Passivation steps include venting the propulsion system (including pressurant) and disconnecting the solar arrays from the power bus. By permanently disconnecting the arrays, the remaining loads will deplete the battery and keep it discharged. With the recovery systems disabled, the spacecraft should remain in an inert state until it reenters.

Several of the other drivers for the FireSat II mission have led to a design which is relatively small, with insufficient fuel or control authority to perform a controlled reentry. Survival of even 15 individual pieces after reentry would cause FireSat II to exceed the required 1 in 10,000 reentry risk requirement. It will therefore be necessary to consider reentry risk throughout the mission design phase, and to minimize the use of highly survivable materials whenever possible. The spacecraft structure, for example, should be limited to graphite/ epoxy composite and/ or aluminum components (fasteners are generally too small to inflict significant injuries, and need not be considered for reentry risk purposes). Solar cells are fragile enough to break up into relatively benign pieces, but any solar panel hinges and deployment hardware should avoid the use of titanium and stainless steel as much as possible. Some high survivability materials are inevitable in the payload optics, but could possibly be bundled together to minimize their reentry risk.

30.6.2 Disposal of the SCS Spacecraft

The Supplemental Communications System (SCS) mission is intended to operate in a 21,000 km altitude, circular orbit with a 0° inclination, greatly simplifying the disposal procedure. In fact, this orbit is perhaps the simplest of the commonly used Earth orbits, since all that is necessary is to passivate the spacecraft in place. The operational orbit meets the US Government requirement for Medium Earth Orbit (MEO) disposal, so there is no need for end of mission maneuvers. It is still necessary, however, to expend all remaining fuel, and perform all other passivation tasks described for Firesat II, to minimize any possibility of fragmentation during the very long postmission storage period. It is not necessary to consider reentry risk for SCS, since the spacecraft will not reenter for centuries, by which time some more permanent solution should be available if necessary.

Conclusion

The need to control the growth of orbital debris, particularly in LEO, is clear. Toward this goal, the United Nations and individual space agencies have created guidelines and requirements that call for, among other things, responsible disposal of space hardware at the end of its useful mission life. In order to perform responsible disposal, though, it **must be considered during the mission planning in the earliest stages of the mission.** The chosen disposal method often drives the hardware design, including propulsion system sizing, passivation hardware, materials selection, and even potentially the orbit selection. Methods exist which will allow for passivation, while preserving mission reliability. Designing each individual mission with responsible disposal in mind is a critical step toward minimizing the risk of future collisions for all missions.

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- ^{iv} Support to the IADC Space Debris Mitigation Guidelines, IADC-04-06, October, 2004, http://www.iadc-online.org/index.cgi?item=docs_pub
- ^v “The Cause and Consequences of a Satellite Fragmentation: A Case Study”, N. Johnson, Advances in Space Research, vol 23, issue 1, 1999
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