Chapter of: <u>Safety Design of Space Operations</u>

Risk Management of Jettisoned Objects in LEO

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The construction and maintenance of the International Space Station (ISS) has led to the release of many objects into its orbital plane, usually during the course of an extra-vehicular activity (EVA). Such releases are often unintentional, but in a growing number of cases, the jettison has been intentional, conducted after a careful assessment of the net risk to the partnership and to other objects in space. Since its launch in 1998 the ISS has contributed on average at least one additional debris object that is simultaneously in orbit with the station, although the number varies widely from zero to eight at any one moment. All of these objects present potential risks to other objects in orbit.

Whether it comes from known and tracked orbiting objects or from unknown or untrackable objects, collision with orbital debris can have disastrous consequences. Objects greater than 10cm are generally well documented and tracked, allowing orbiting spacecraft or satellites opportunities to perform evasive manoeuvres (commonly known as Debris Avoidance Manoeuvres, or DAMs) in the event that imminent collision is predicted. The issue with smaller debris; however, is that it is too numerous to be tracked effectively and yet still poses disastrous consequences if it intercepts a larger object. Due to the immense kinetic energy of any item in orbit, collision with debris as small as 1cm can have catastrophic consequences for many orbiting satellites or spacecraft.

Faced with the growing orbital debris threat and the potentially catastrophic consequences of a collision-generated debris shower originating in an orbit crossing the ISS altitude band, in 2007 the ISS program manger asked program specialists to coordinate a multilateral jettison policy amongst the ISS partners. This policy would define the acceptable risk trade rationale for intentional release of a debris object, and other mandatory constraints on such jettisons to minimize the residual risks whenever a jettison was accepted. Although ISS-related debris often presents untenable risks to the EVA crew, IVA crew, or to a departing cargo vehicle for a controlled disposal, such released objects also present a ballistic nuisance to the visiting vehicle traffic, and a potential fragmentation threat to the hundreds of other functional and debris objects whose perigees lie below the ISS orbital altitude. Thus, every such jettison decision is a conscious risk trade.

After more than three years of refinement and negotiation, the Multinational Partner Program Directive (PPD) #1101 was signed March 8, 2010 in Japan, binding the six partner agencies (ASI, CSA, ESA, JAXA, NASA, & RSA) to an analytical process and risk trade criteria that guide the decision-making in every such intentional jettison. The decision to jettison an object is not taken lightly, as it adds measurable risk with high potential consequences to all partners, and indeed, all space-faring nations. For that reason, the decision to jettison each candidate object is one of the only detailed procedural steps decided at the highest management level of the program. The Space Station Control Board, whose membership is comprised of the top program manager of every partner agency, must approve every intentional jettison by any partner. No single low-level procedural step routinely gets as much senior management scrutiny as the jettison decision receives in this measured risk trade.

The ISS Jettison policy recognizes and supports all recommendations of United Nations Committee On the Peaceful Uses of Outer Space (UNCOPUOS) Space Debris Mitigation Guidelines (June 2007), to which all ISS partner agencies are signatories. Ref: Annex pg 47 at http://www.unoosa.org/pdf/gadocs/A_62_20E.pdf. However, the UN guidelines are necessarily high-level, and must be interpreted at a tactical level with more measurable constraints and requrements. Such detailed risk trade criteria and standard practices are reflected in the policy letter, that establish the agreed standard procedures and criteria for analyzing and accepting the risks associated with jettison. With six agencies all committed to this set of standard criteria, the ISS Jettison policy serves as a broad international consensus of the detailed risk trade process and criteria to be applied when assessing whether a new orbital debris object is acceptable.

The ISS partnership recognizes that several conditions merit the discussion of intentional jettison as part of a larger risk assessment. These candidates for jettison, as defined in the directive, are as follows:

1. Items that pose a safety issue for the ISS or for return onboard a visiting vehicle (contamination, materials degradation, etc.)
2. Items that negatively impact ISS utilization, return or on-orbit stowage manifests
3. Items that represent an Extravehicular Activity (EVA) timeline savings large enough to reduce the sum of the risks of EVA exposure time and the orbital environment's hazardous debris population, compared to the sum of such risks without a jettison
4. Items that are designed for jettison

Category 1 items have included materials soaked with highly toxic, partially-combusted propellants, degraded/abraded fibreglass blankets (asbestosis risk), and other materials. Category 2 items have arisen when dedicated flight service equipment to hold the object during a controlled de-orbit would otherwise displace necessary upmass on a visiting vehicle. (This was the case of the large Early Ammonia Servicer (EAS) in 2007. Other situations arise when chronically-full interior volumes cannot be stuffed further, and the interior clutter becomes untenable.). Because EVA is inherently risky, a probabilistic risk assessment is performed in category 3 to weigh the risks to the crew if significant extra time must be allocated to temporarily stow and then transport cumbersome material to the airlock. This trade varies by EVA location and task length. Category 4 includes many proposed small satellites, some of which are expected to be deployed by mechanical means.

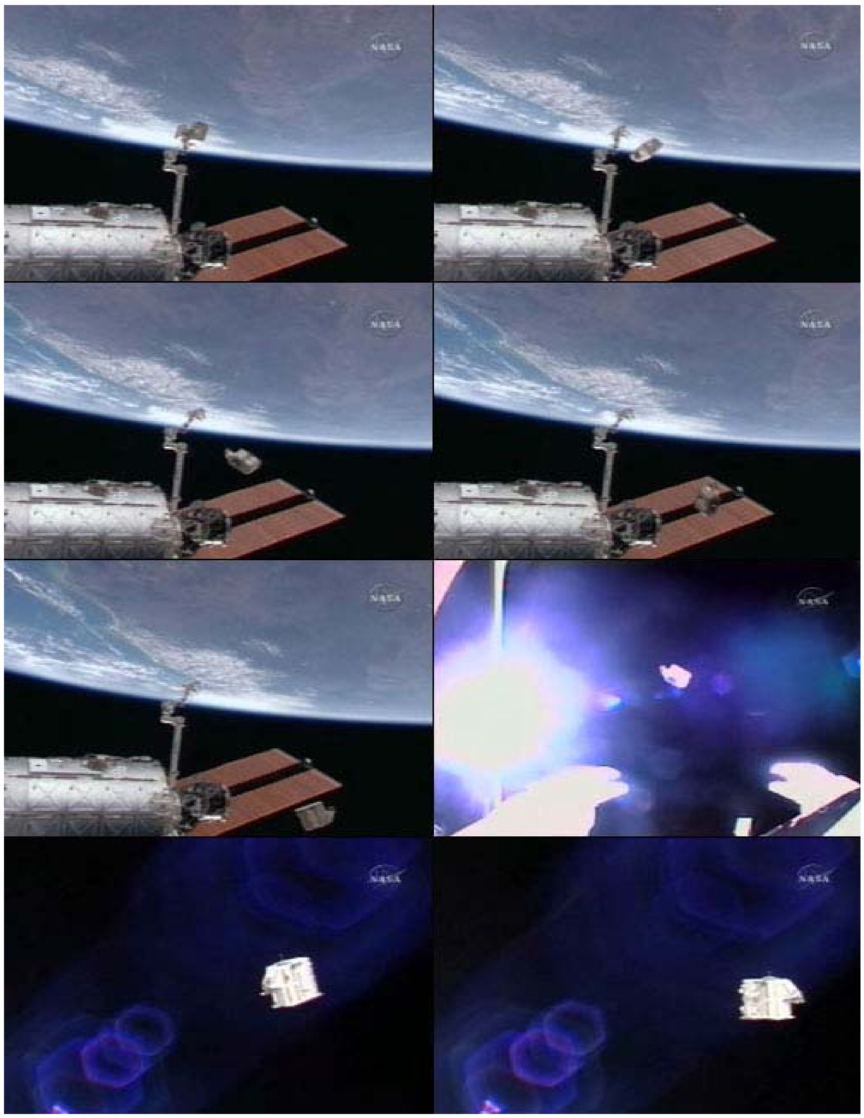

Figure: Astronaut Clay Anderson Jettisoning the Early Ammonia System (EAS) from the ISS

Every time a jettison is authorized, the policy enforces several steps to minimize the residual risks that are to be accepted. These accepted risks occur in four distinct time frames that begin at the moment of jettison. These timeframes and associated risks are as follows:

1) Initial trajectory away from the release point. (Measured in seconds)
    a. A collision risk occurs at the edge of a "keep out" cone whose axis is the intended jettison velocity vector. Controllability and judgment issues could cause the outbound object to collide with ISS structure, so this jettison cone has mandatory minimum clearance conditions.
2) First-orbit curving relative motion that might lead to contact with ISS structure. (Measured in minutes)
    a. As all separating objects in orbit follow complicated relative motion (obeying the Clohessy-Wiltshire solutions to Hill's equations), it is important to account for potential interferences with the ISS's large extensions into all three orthogonal axes, and to achieve adequate separation throughout the first orbit. The jettison cone therefore has directional conditions relative to the V-bar and ISS attitude, whose initial conditions are known to provide adequate clearance along Clohessy-Wiltshire curves. By the end of the first orbit, the ISS partners require >200 meter clearance from the ISS centre of gravity.
3) The natural decay of the object. (Measured in days or weeks)
    a. A collision of the jettisoned object with any crossing piece of debris could lead to a cascade of lethal finer debris in the path of the ISS (and of all other spacecraft which have perigees below the apogee of the intercepting object). Fragmentation of the jettisoned object by any means is cause for concern in this time period. Generally, the most likely cause of fragmentation is the release of stored energy in a collision with an untracked small debris particle, but thermal and other failures are considered. Further, the jettisoned object joins the catalogue of

tracked objects that provide potential operations overhead to all ISS visiting vehicles. If the object is of very high ballistic number, it has the potential to revisit the ISS itself, but generally it is the visiting vehicle fleet and other spacecraft that are most probably affected by ISS jettisoned objects.

4) The final re-entry of the jettisoned object through the atmosphere (Measured in minutes)
    a. Surviving fragments of the object pose a risk of injury to the ground population.

Initial clearance of all ISS/visiting vehicle structures is accomplished by ensuring that the planned velocity vector of the jettisoned object is the axis of an unobstructed cone of a 30^{o} half-angle (minimum), and that the object is within acceptable EVA control (i.e., "handle-able") as characterized by the responsible EVA Office. The desired cone axis is defined to the EVA crew in relation to readily-identifiable landmarks such as structure or the horizon, and the jettison process is a required training step.

The jettisoned object is required to clear a 200 m radius keep out sphere (centreed around the ISS c.g.) within 1 orbit, and maintain positive clearance during the first orbit at all times. This is accomplished by assuring sufficient velocity component in the –Vbar direction from anywhere within the allowed jettison cone.

During any single revolution following the second orbit after the jettison, while the altitude of the object is within 5 km of the altitude of the ISS, the jettisoned object shall not decrease its total range from ISS to less than 50% of the minimum total range that occurs during the previous revolution.

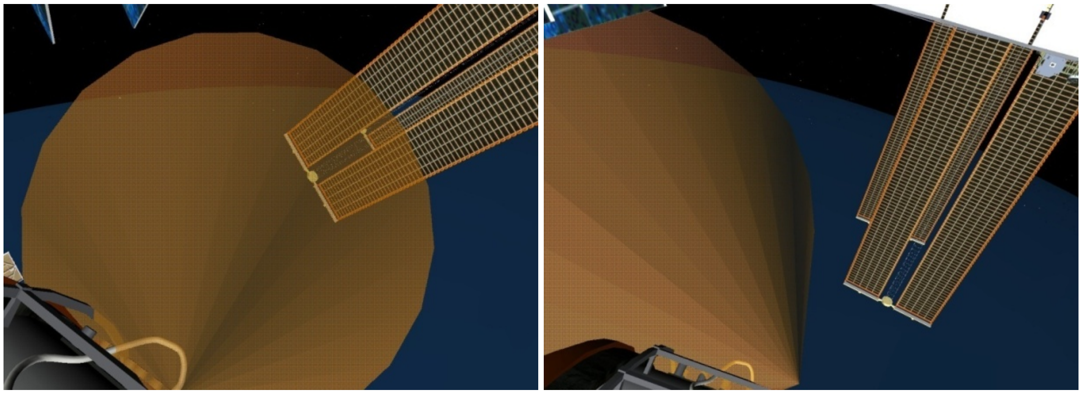

Figure: Analyzed EVA crew viewpoints from a potential jettison location along jettison corridor. To allow a safe jettison, clearance requirements led to a constraint to lock the position of US solar arrays in a specific location and to manage reduced power. Although the cone axis is substantially below the earth horizon, and thus has a significant radial component, its aft velocity component was analyzed in advance to be large enough to assure safe departure and permanent separation from ISS.

The relative velocity applied to the jettisoned object is generally the maximum possible within operational constraints and crew capability. However, an object must not require more than 0.05 m/s total delta V to meet recontact keep-out zone criteria. This is to ensure an adequate safety margin in the event of crew error.

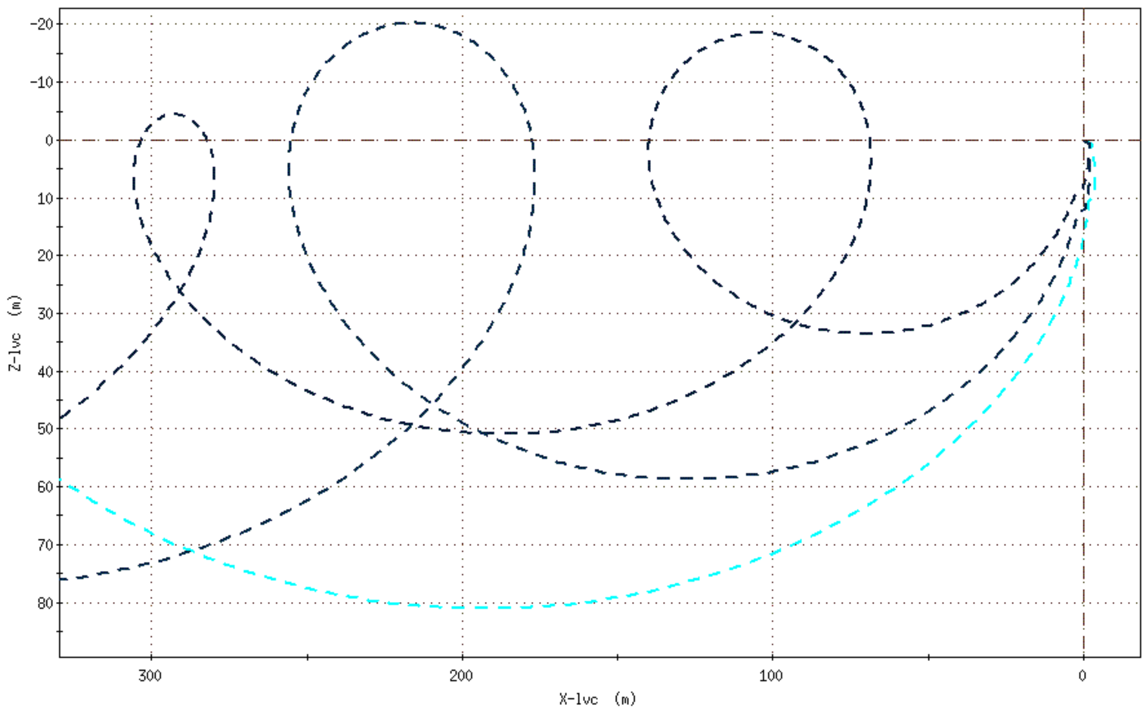

Figure: Relative Motion Plots at various points within a jettison cone for one candidate jettison from ISS

To be considered, the object's owner/creator must show a less than 1:10,000 risk of human injury to the ground population avert a random re-entry. CAD models and other relevant data are fed to NASA's Object Re-entry Survival Analysis Tool (ORSAT) as a required analytical step to prove that this threshold is not exceeded. The ORSAT tool predicts an object's likely re-entry path, including altitude of break-up and projected risk to the earth population based on surviving objects impacting the ground. Any waivers to accept violations of this threshold must be endorsed by the highest authority in any jettisoning agency, before the Space Station Control Board will consider the jettison. The policy encourages the bundling of candidate items if more than one is to be jettisoned during an EVA or across several coupled EVAs, as is the case with the nine EVAs to externally configure the Russian Multipurpose Laboratory Module (MLM). During this intense EVA activity, candidate jettison items are to be temporarily stowed and connected together into a single jettison bundle on the last EVA, decreasing overall mass/area ratio and minimizing the net collision probability over a the probability of collision resulting from a dispersion of smaller pieces.

Bundling together of multiple candidate jettison items (often utilizing wire ties or other available EVA materials) is also occasionally necessary to assure that the jettisoned item is trackable by the US Space Surveillance Network, which feeds the necessary data to the Joint Space Operations Center (JSPOC), which in turn issues potential conjunction warnings to all operational spacecraft whenever a conjunction is forecast. This trackability requirement is strictly enforced. Although the lower limit of the trackable radar cross section is classified, the ISS partners have reached agreement (with concurrence of the knowledgeable specialists) that a minimum of 100 cm2 of metal or metal foil shall be included in every jettisoned item, or that the radar cross section shall be equivalent or greater than this. Sometimes this minimum can only be achieved if the item (say a fibreglass ring) is bundled with another, trackable item. This was the case in the outfitting of the second Russian Mini Research Module (MRM2), where four multi-layer insulation blankets (containing many hundreds of cm2 of foil) and two otherwise untrackable fibreglass fixtures were collected into two loose, trackable bundles.

Figure: Jettison Candidate Bundle of three items for Russian EVA 29 on ISS. The fabric panel is not trackable by itself, but may be jettisoned in combination with the aluminium shell pieces. All items are bundled with a single additional copper wire tie. As a single item (vs. three), the net risk to other orbiting objects is substantially reduced.

Additionally, the date of a jettison is planned to assure that the object is catalogued and tracked in enough time to guarantee that its future position is knowable before any visiting vehicle traffic is in the vicinity. Because the ISS itself has such a large radar signature, it nominally takes more than a day before a separated small object can be clearly distinguished form the ISS signal. The general path of a jettisoned object downwards and forward of the ISS means that jettisoned objects are mostly a concern for departing vehicles, which follow the same general corridor.

The partners enforce the UNCOPUOS guideline that a jettisoned object must not fragment before it decays into the atmosphere. The fragmentation potential is always expressed as a probability. The multilateral policy has adopted the NASA internal requirement that the jettisoned object must have a probability of fragmentation less than 1:10,000. The ability of an object to meet this criterion is dependent upon the nature of any stored energy, the susceptibility and vulnerable fraction of the object to MMOD particles or to thermal issues, and the expected time to decay.

Since the policy's development, many interesting challenges and policy subtleties have emerged, some of which are still under debate. For example: does the policy affect ISS visiting vehicles that deploy equipment or sub-satellites below the orbital altitude of the ISS? Does it affect visiting vehicle operations above the ISS altitude? Does the partnership need to pre-approve every item that might need to be discarded if its flight service/attachment equipment fails and cannot accommodate the object in a nominally-planned controlled re-entry? If a cube-sat launcher is approved, does every cube-sat need to be individually approved by the partnership, and must each of these cube-sats be individually analyzed against all policy requirements? How should the program treat requests for constellations of jettisons, such as proposals for cube-sat wide-area sampling of the mesosphere, or other constellations? Are there restrictions to be enforced on fluid venting?

In the case of the last question, it is known that the lifetime of particles in LEO is only a few days at most, but there is a wide range of possible location of the edges of the dispersed particle ‘cloud” as the particles decay. This variability results from wide variance in initial conditions and the uncertainty in sublimation physics (and thus ballistic number) in a cloud of vented particles. Fortunately, within the orbital plane, the relative velocity at intercept with an orbiting visiting vehicle is subsonic, and thus not a fragmentation concern, although minor damage and contamination is still possible.   NASA has developed a Sublimating Particle Orbit Calculator (SPOC) that can assess the boundaries and population densities in orbiting plumes of water (and other sprays) relative to other objects in the same orbit plane.   This tool has been used on occasion to confirm that the plume from a planned venting will miss active visiting vehicles orbiting below the ISS, and occasionally to bound the maximum particle fluence. Although impossible to certify with current measurement capability, extensive analysis and data have been incorporated in the tool to account for high drag, varying ballistic number particles (whose sublimation rate varies with orbital lighting), and a varying atmospheric density. Such analyses provide a precise model of particle propagation in orbit, accurate to best understanding of the freezing and sublimation process of the particles: an understanding that still has several unknowns.   These unknowns are bounded in a range of possible particle sublimation models propagated by the tool.   NASA has used this tool on several occasions to clear operational zones for other spacecraft when shuttle or ISS have conducted vents.

Productive space operations will forever be performed in the presence of significant risk from orbital debris. The six partner agencies in world's most visible spacecraft--the International Space Station--have collectively addressed their responsibility to manage the risk in a globally-optimized, responsible way. They continue to develop tools, analyses, and processes to minimize the risk for all space-faring nations.