A Review of Existing Policies Affecting the Jettison of Waste in Low Earth Orbit and Deep Space

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The management of waste generated onboard spacecraft during future long-duration deep-space missions will require different solutions from those currently implemented on the International Space Station which consist exclusively of collecting, storing, and returning the waste to Earth. Alternative options for managing spacecraft waste are to process it for recycling and recovery of resources, and to jettison it overboard in a solid form (such as a compacted tile) or in a gaseous form after torrefaction or other trash-to-gas technologies. The waste generated during a deep-space mission is derived mainly from spacecraft logistics supplies, food and beverage residues, personal or scientific items used by the crew, human metabolic waste, and unused spare components. Uncontained and unprocessed trash is a potential health hazard and a habitat volume liability, which makes onboard long-term storage an inefficient and non-optimal option. However, the jettison of solid, processed waste appears to be an effective solution for crewed deep-space missions, leading not only to volume reduction and habitat safening, but also to considerable mass savings in the spacecraft's propulsion system. However, the disposal of trash overboard also creates a navigation hazard for spacecraft and the potential risk of contamination of planetary bodies, interfering with the search for life. This paper investigates the requirements covered by existing policies that could affect the jettison concept of operations and system design.

Nomenclature

AEPS	=	Advanced Electric Propulsion System
ARC	=	Ames Research Center

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ASI	=	Agenzia Spaziale Italiana, also known as Italian Space Agency
ConOps	=	concept of operations
CSA	=	Canadian Space Agency
DAM	=	Debris Avoidance Maneuvers
DST	=	Deep Space Transport
EAS	=	Early Ammonia Servicer
ESA	=	European Space Agency
EVA	=	extravehicular activity
GEO	=	geosynchronous equational orbit
HALO	=	Habitational and Logistical Outpost
HTV	=	H-II Transfer Vehicle
HMC	=	Heat Melt Compactor
ISS	=	International Space Station
J-SSOD	=	JEM Small Satellite Orbital Deployer
JAXA	=	Japan Aerospace Exploration Agency
JEM	=	Japanese Experiment Module
JEM-AL	=	Japanese Experiment Module Air Lock
JSC	=	Johnson Space Center
JSpOC	=	Joint Space Operations Center
LEO	=	low Earth orbit
LH2	=	liquid hydrogen
LOX	=	liquid oxygen
MEO	=	medium Earth orbit
MMOD	=	MicroMeteroids and Orbital Debris
MRM2	=	Mini-Research Module 2
NASA	=	National Aeronautics and Space Administration
NID	=	NASA Interim Directive
NPD	=	NASA Policy Directive
NPR	=	NASA Procedural Requirements
ORSAT	=	Object Re-entry Survival Analysis Tool
PP	=	planetary protection
PPD	=	Partner Program Directive
PPE	=	Power and Propulsion Element
PPO	=	Planetary Protection Officer
RCS	=	Reaction Control System
RSA	=	Russian Space Agency
SEP	=	solar electric propulsion
SSRMS	=	Space Station Remote Manipulator System
TCPS	=	Trash Compaction and Processing System
U.S.	=	United States
UNCOPUOS	=	United Nations Committee on the Peaceful Uses of Outer Space

I. Jettison in Low Earth Orbit

THE jettison of waste into space has been a little-known but common occurrence over the past five decades. The generation of waste onboard a crewed spacecraft is inevitable and its storage can present a direct or indirect health hazard to the astronauts and a habitat volume liability.

In low Earth orbit (LEO) it is generally preferable to dispose of spacecraft-generated waste using a re-entry logistics vehicle. In certain cases, jettisoning it directly overboard represents the only viable option, either because the dimensions of the waste prevent a trans-vehicle transfer, or its components pose a possible hazard to the crew.

The Soviet space stations Salyut 6, Salyut 7, and Mir had a dedicated airlock used to launch small satellites and to eject objects overboard, especially during the initial years of operation. On the International Space Station (ISS), the first and most noteworthy example of a waste object jettisoned into space was a large pressurized container that had been used to transport a replacement part in 2004 (see Figure 1)[1]. Another noteworthy example of the disposal of a spent component via jettison occurred in 2005, when the crew performed an EVA (extravehicular activity) to release and dispose of an instrument installed just a few years earlier and that had prematurely reached its end of life. Because of the poor conditions of the device, disposal via a Progress resupply vehicle or return to Earth in a Space Shuttle were not considered viable options. At the time of writing, the ISS has jettisoned a 2.9-ton pallet of nickel-hydrogen batteries, which is the largest waste object released from the ISS to date. The pallet was originally set to return aboard the Japanese H-II Transfer Vehicle (HTV) in 2020, but it was left behind due to a failed 2018 Soyuz launch that disrupted spacewalk schedules. Finally, the

Figure 1. Pressurized container jettisoned from the ISS in 2004.[1]

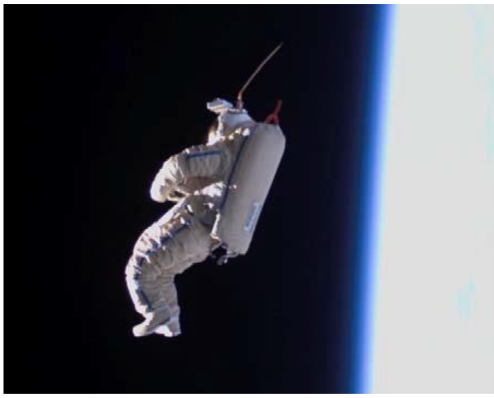


Figure 2. Russian spacesuit jettisoned from the ISS in 2006.[2]

most unusual object jettisoned from the ISS was an old Russian EVA suit, which was retrofitted with a transmitter and released in 2006, also during an EVA (see Figure 2)[2].

Following the loss of the Space Shuttle Columbia in 2003 (and the subsequent long-term grounding of the Space Shuttle fleet) the waste-management strategy implemented on the ISS, consisting exclusively of collecting, storing, and returning the waste to Earth, was disrupted. Without the periodical removal of tons of trash by the shuttles, the accumulation of waste onboard the ISS quickly began to worsen, creating difficulties for the crew and leading NASA to formally start drafting a jettison policy for situations where alternative solid waste management disposal options were not acceptable. This policy defined the acceptable risk rationale for the intentional release of waste objects, and other mandatory constraints to minimize any residual risks. In fact, jettison might pose a lower risk than returning certain objects on a logistics vehicle due to physical limitations or to safety concerns for the crew and the ISS itself. Moreover, jettison would significantly reduce EVA task times otherwise necessary for returning an external spent object onboard the station prior to its loading into the reentry vehicle.

Jettisoning waste can also pose a ballistic hazard to the ISS or other spacecraft by generating a collison risk during operation and a secondary risk for the few days after release due to fragmented objects orbiting below the ISS. In LEO, objects should be ejected in a retrograde direction to accelerate their separation from the spacecraft and to lessen their total orbital lifetime. The jettison cone (see Figure 4) that accounts for any directional errors and the minimum release speed of the object need to be carefully predetermined and controlled to avoid a potential collision with any portion of the originating spacecraft during its initial outward bound trajectory. This is particularly limiting on the ISS since it is not always possible to eject an object from the aft of the station.

Even after having successfully cleared a spacecraft after its release, a jettisoned object might still pose a later collision risk during future orbits, and thus, any potential close transits need to be predicted based on estimates of its ballistic coefficient and on tracking data. Most objects will deorbit faster than the ISS. However, if a released object is predicted to have an apogee too close to the ISS's orbital altitude, a collision avoidance maneuver, also known as Debris Avoidance Maneuver, (DAM) must be performed. Such was the case in 2007 as a result of the jettison of the Early Ammonia Servicer (EAS).

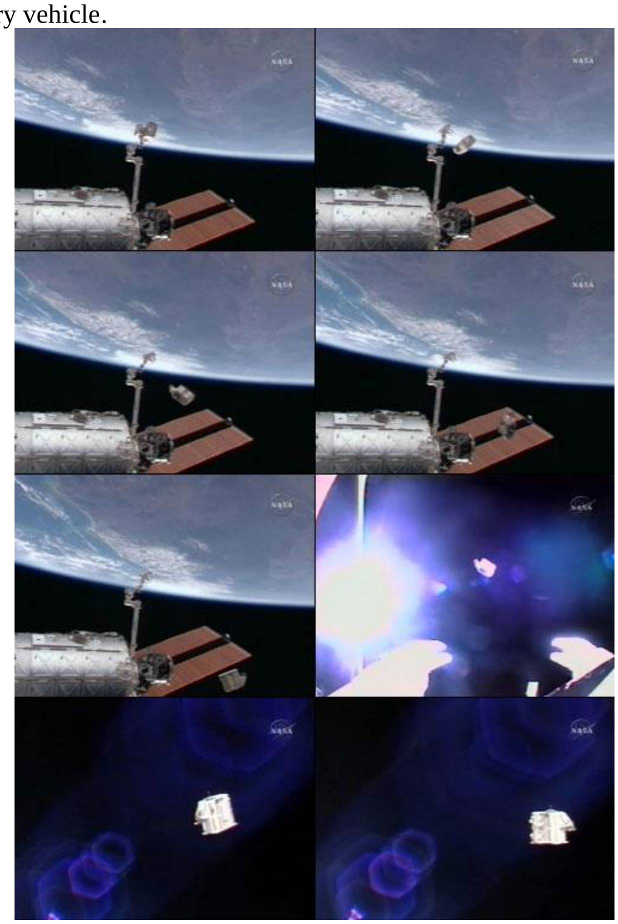


Figure 3. Jettison of the Early Ammonia Servicer from the ISS in 2007.[3]

The EAS was an ammonia reservoir the size of a refrigerator mounted on the exterior of the ISS and was designed to top off the station's cooling system in the event of a leak. The ISS cooling system proved to be leak-free, and thus the EAS was still fully-loaded at the end of its five-year design life. However, since its structural integrity could no longer be guaranteed and it was too dangerous to be carried back to Earth on a Space Shuttle, the decision was made to jettison the EAS by manually pushing it away in the direction opposite to the station's orbit during an EVA. Simulations showed that a surprisingly small delta V of only about 0.03 m/s was required to avoid future collisions. However, despite all the analyses and simulations, it remained unproven that an EVA astronaut in foot restraints at the end of the ISS's robotic arm could push the massive EAS with enough velocity and accuracy to ensure separation within the directional cone predicted by the orbital mechanics calculations (Figure 3)[3]. Thus, a short time after jettison, the ISS crew performed a thruster burn to raise the station's orbit for added insurance. The EAS re-entered the atmosphere about 16 months later, splashing into the Pacific Ocean.

II. ISS Jettison Policy

After several years of negotiations and refinements, in 2010 six space agencies (ASI, CSA, ESA, JAXA, NASA, & RSA) signed the Multinational Partner Program Directive (PPD) #1101, an analytical process and risk trade criteria that guides the decision-making of every intentional jettison.[6] The decision to jettison an object adds measurable risk with high potential consequences not only to all partners but also to other space-faring nations and in certain cases to the population on the ground. For this reason, the Space Station Control Board, comprised of program managers from every partner agency, must approve of every intentional jettison by any partner. The detailed procedural steps of this measured risk trade are scrutinized at the highest management level of the program.

The ISS Jettison policy integrates all the recommendations from the United Nations Committee On the Peaceful Uses of Outer Space (UNCOPUOS) Space Debris Mitigation Guidelines.[4,5] However, such guidelines are high-level and are interpreted at a techical level with measurable constraints and requirements. Such detailed risk trade criteria and standard procedures for analyzing and assessing whether the jettisoning of an object is acceptable or not are reflected in the ISS Jettison policy and serve as a broad international consensus. According to the policy, only objects belonging to one of the following four categories can be considered as candidates for intentional jettison:[6]

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;
3) Items that represent an 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.

Following the preliminary authorization of a jettison operation, several steps are enforced according to the policy in order to minimize the residual risks. These accepted risks are divided into the following four distinct categories, which are based on their chronological timeframe starting at the moment the object separates from the ISS:[6]

1) Initial trajectory away from the release point (measured in seconds). A collision risk occurs at the edge of a conical corridor where the cone's axis is the intended jettison velocity vector. Controllability and judgment issues could cause the outbound object to collide with the ISS structure, so this jettison cone has mandatory minimum clearance conditions.
2) First-orbit curving relative motion (measured in minutes). The jettisoned object needs to achieve a minimum clearance of 200 meters from the ISS's center of gravity by the completion of the first orbit in order to avoid potential interferences with the ISS's large extensions on all three orthogonal axes.
3) Natural decay of the object (measured in days or weeks). A collision of the jettisoned object with any other intercepting object could lead to their fragmentation and thus to a cascade of finer debris in the path of the ISS and of all other spacecraft with lower perigees. Fragmentation of the jettisoned object might also be caused by thermal and other failures, which need to be considered. Finally, although the jettisoned object has the potential to collide with the ISS itself, it is the visiting vehicles and other spacecraft that have the highest probability of being affected.
4) Final re-entry of the jettisoned object through the atmosphere (measured in minutes). Surviving fragments of the object might reach the ground and thus pose a risk to the population.

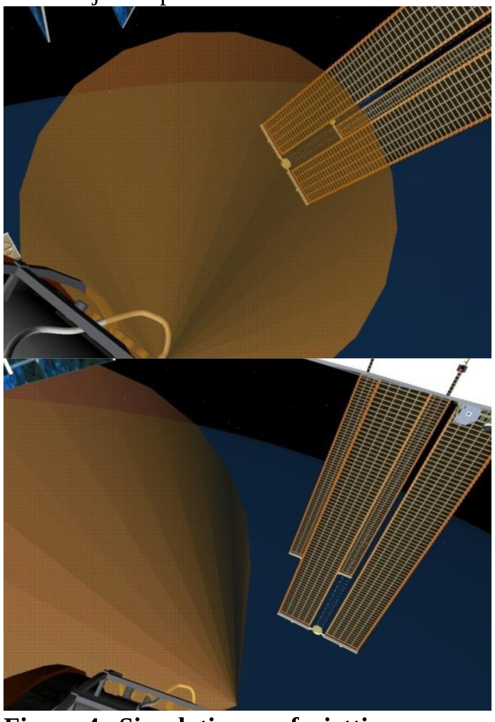


Figure 4. Simulations of jettison cones from potential ISS separation locations.[6]

The initial clearance of ISS structures is ensured by the velocity vector of the jettisoned object being within an unobstructed cone with a minimum half-angle of 60° (see Figure 4). The desired cone axis is defined in relation to readily-identifiable landmarks such as structure or the horizon.

The required 200m-radius minimum clearance sphere around the ISS's center of gravity after the first orbit is ensured by a sufficiently high velocity component in any direction within the allowed jettison cone. However, the required total delta V applied to the jettisoned object must not exceed 0.05 m/s to ensure both crew capability and an adequate safety margin in the event of a crew error.

During any revolution following the second orbit and until the altitude of the object is within 5 km of the altitude of the ISS, the distance of the jettisoned object from ISS shall never decrease to less than 50% of the minimum distance achieved during the previous revolution.

Moreover, to be compliant with the Space Debris Mitigation Guidelines, the jettisoned object must not pose a human injury risk in excess of 1:10,000 to the population on ground following its atmospheric reentry. Analytical models of the fragmented debris are provided to NASA's Object Re-entry Survival Analysis Tool (ORSAT) 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.

The ISS Jettison Policy encourages bundling candidate items by stowing and connecting them together if more than one object is to be jettisoned during one or multiple EVAs. This operation facilitates a decrease in the overall projected-area/mass ratio and thus the collision probability compared to a dispersion of smaller pieces. Moreover, this practice assures that the released object has sufficient size and materials to be trackable by the US Space Surveillance Network, which provides the necessary information to the Joint Space Operations Center (JSpOC). The JSpOC in turn issues potential conjunction warnings to all operational spacecraft whenever a conjunction is forecast. Jettisoned objects are of particular concern for ISS departing vehicles since they follow the same general corridor and since it takes several hours before a separated small object can be clearly distinguished from the large radar signature of the ISS. To meet the trackability requirement, a minimum of 100 cm^2 of metal or metal foil must be included in every jettisoned object whenever its radar cross section is smaller than the equivalent of this value. Sometimes this can be achieved only if the candidate object is bundled with other trackable items, such as the otherwise untrackable fiberglass fixtures jettisoned from the Russian Mini Research Module (MRM2) in 2009. These fixtures were bundled with insulation blankets containing hundreds of cm^2 of aluminized foil (see Figure 5)[7].

Figure 5. Cosmonaut on EVA outside the Russian Mini Research Module (MRM2).[7]

Additionally, according to UNCOPUOS guidelines, a jettisoned object must not fragment before it enters the atmosphere. Thus, the jettisoned object must have a probability of fragmentation lower than 1:10,000. The ability of an object to meet this requirement is a function of stored energy, the vulnerability of fraction of the object by MicroMeteroids and Orbital Debris (MMOD) particles, thermal issues, and of the expected decay time.

III. Jettison of Cubesats and Microsats from the ISS

After the ISS Jesttison Policy's development and since their first deployment in 2012, hundreds of Cubesats and Microsats have been successfully jettisoned from the ISS using five different launchers. Cubesats and Microsats are small, low-cost satellites, with mass between 10 and 100 kg, used mainly for earth science and technology demonstration missions which are delivered to the ISS as pressurized cargo. They are transferred outside the ISS via the Japanese Experiment Module Air Lock (JEM-AL) and then moved to the deployment position by the JEM robotic arm (see Figure 6[8]) or the Space Station Remote Manipulator System (SSRMS). Each of the five launchers is unique and presents different separation velocities (from 0.5 m/s to 1.7 ms/s) and payload capacities (from 3-U cubesats to single, large Microsats up to 100 kg).

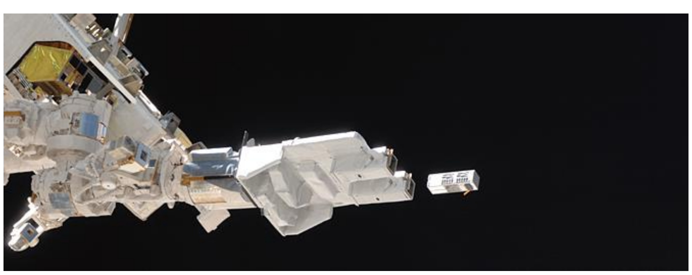


Figure 6. A 3-U cubesat jettisoned using the JEM Small Satellite Orbital Deployer (J-SSOD).[8]

Spacecraft operators employ conjunction assessment and risk analysis to assure the safety of the space environment as well as the spacecraft, relying on JSpOC screening of catalogued objects. Following the jettison, the ISS reports to JSpOC for tracking and cataloging. However per the Jettison Policy, four days are allotted for JSpOC tracking of three or fewer objects, and six days for more than three. Once the ISS-jettisoned object is catalogued, the ISS and other spacecraft orbiting at the same/lower altitudes can predict possible conjunctions and prepare DAMs, if necessary. Prior to cataloging, the collision risk posed by the jettisoned object is undefined because its orbit is unknown. Thus, a region relative to ISS where the jettisoned object can theoretically be during the first six or eight day window is defined as the "Deployment Zone" (DZ). If the ISS or any other spacecraft is outside of the DZ, then there is no possibility for a conjunction with the jettisoned object during the six or eight days post-separation, and the deployment is considered safe. However, if a jettison is made while the ISS or other spacecraft are in the DZ, they cannot be declared safe but rather will require further analysis to assure that the collision risk is acceptable.

IV. Jettison of Waste in Deep Space

The requirements for waste management onboard crewed spacecraft are strongly dependent on the mission scenario, in particular on mission location and duration. The solutions currently implemented on the ISS consist almost exclusively of collecting, storing, and returning the solid waste to Earth, recycling liquid waste onboard, and venting carbon dioxide and other gasses into space. Venting of gases and liquids are not considered here, but they too could pose issues, especially on Mars where scientists would not want the spacecraft's own systems to contaminate the environment they are trying to study. Future long-duration, deep-space missions will require alternative solutions for managing spacecraft waste, such as processing it to recycle and recover more resources, and possibly jettisoning part of it overboard. The waste generated during a deep-space mission will include crew biological products (carbon dioxide, water, human liquid and solid waste), solid and liquid wastes derived from spacecraft logistics supplies, food and beverage residues, personal or scientific items used by the crew, and broken or unused spare components. Uncontained and unprocessed trash is a health hazard and a habitat volume liability, which makes onboard long-term storage an undesirable option. High-velocity and low-velocity jettison of solid, processed waste appear to be an effective solution for crewed deep-space missions. This could enable not only significant volume reduction and habitat safening, but in certain cases also considerable mass savings in the spacecraft's stored fuel mass (and propulsion system mass).

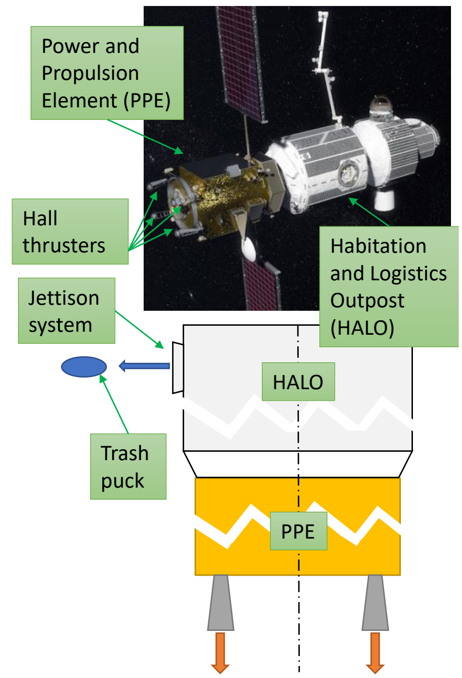
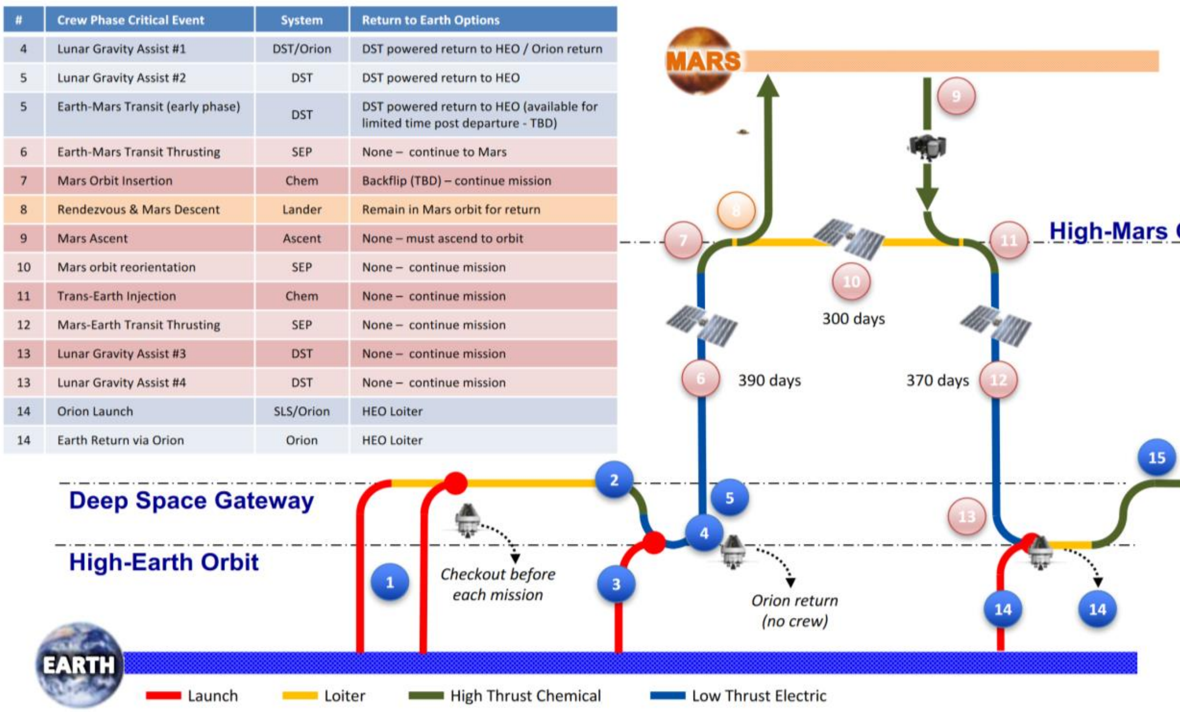


Figure 7. Solid waste jettison concept from Gateway.

The Gateway cislunar outpost is planned to be deployed in a highly elliptical, seven-day orbit around the Moon. Initially, the Gateway will be a minimalistic space station composed of only two modules, the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). It will be deployed to the Earth-moon L2 libration point without crew using the Advanced Electric Propulsion System (AEPS) Hall-effect thrusters. During the first phase, the Orion crew module will deliver up to four astronauts, and the logistics module will store up to 2700 kg of supplies, allowing a maximum mission length of 90 days. For a second phase, additional modules will be added to the station at L2, creating the ability for longer duration stays of up to 180 days.[9,10] The waste mass produced per Gateway crew member is expected to be similar to that generated on board the ISS. In order to be jettisoned at a resoneable frequency, the trash will have to be compacted and processed with a system like the Trash Compaction and Processing System (TCPS), during which the water content, corresponding to about 20% of its initial mass, is recovered. Thus, assuming that the solid waste generated onboard is 0.8975 kg per crewmember per day[11] and that the jettison is performed only at a frequency of 7.3 days in order to maximize its effect when Gateway reaches the X-Z plane crossing, the ejected waste mass would be around 26.2 kg per jettison. Based on the examination of returned waste samples from the ISS, the density of hand-compressed trash "footballs" is approximately 160 kg/m^3.[12] Thus, the habitat volume savings amount to about 0.164 m^3 per jettison. The use of a low-velocity launcher similar to the ones currently used on the ISS will create the risk of impact of the jettisoned object on the lunar surface or with Gateway itself during its future orbits, due to the unique dynamic environment of the L2 location. To avoid these risks, a high-velocity launcher must be implemented. Assuming a separation velocity of the jettisoned waste of 100 m/s, the total mass of xenon fuel (used in the AEPS) saved during the crewed phases would be approximately 22% of the total mass required for station-keeping. However, since a jettison vector parallel to the the thrust vector is unlikely, an additional mass of hydrazine is required by the RCS to rotate the spacecraft to the desired jettison attitude. The small amount of xenon mass saved is negligible compared to the hardware mass necessary to process the trash onboard and to jettison it overboard. However, jettisoning waste would still be beneficial in terms of volume savings onboard Gateway (approximately 4 m^3 during a 180-day mission) and in terms of fuel mass savings when compared to the alternative of returning it to Earth in a logistics vehicle at the end of a mission.

The Deep Space Transport (DST), also called Mars transit vehicle, is a crewed interplanetary spacecraft concept for exploration missions to Mars of up to 1,000 days. It would be propelled by both electric and chemical propulsion, and it would carry a crew of four. The vehicle would depart and return from the Lunar Gateway, where it is serviced for reuse on a new Mars mission. It uses a lunar flyby to build up speed and accelerate into a heliocentric orbit using solar electric propulsion (SEP). It uses chemical propulsion for Mars orbit insertion. At the end of the 300-day surface stay mission, the vehicle uses chemical propulsion to depart Mars and enter a trans-Earth orbit. Finally, the DST would use a mix of SEP and lunar gravity assists to rendezvous with Gateway[13] (see Figure 8).

Due to the limited habitat volume, long-term storage of waste generated onboard is not an efficient option. Trash generated by the crew is derived mainly from spacecraft logistics supplies, food and beverage residues, personal or



#	Crew Phase Critical Event	System	Return to Earth Options
4	Lunar Gravity Assist #1	DST/Orion	DST powered return to HEO / Orion return
5	Lunar Gravity Assist #2	DST	DST powered return to HEO
5	Earth-Mars Transit (early phase)	DST	DST powered return to HEO (available for limited time post departure - TBD)
6	Earth-Mars Transit Thrusting	SEP	None – continue to Mars
7	Mars Orbit Insertion	Chem	Backflip (TBD) – continue mission
8	Rendezvous & Mars Descent	Lander	Remain in Mars orbit for return
9	Mars Ascent	Ascent	None – must ascend to orbit
10	Mars orbit reorientation	SEP	None – continue mission
11	Trans-Earth Injection	Chem	None – continue mission
12	Mars-Earth Transit Thrusting	SEP	None – continue mission
13	Lunar Gravity Assist #3	DST	None – continue mission
13	Lunar Gravity Assist #4	DST	None – continue mission
14	Orion Launch	SLS/Orion	HEO Loiter
14	Earth Return via Orion	Orion	HEO Loiter

Figure 8. Mars transit mission architecture.[13]

scientific items. It is estimated to be 0.8975 kg per crewmember per day and it will need to be processed for habitat safening and short-term storage, and then jettisoned overboard.

Moreover, a Mars transit vehicle that jettisons waste before entering Mars orbit can save fuel mass upon return. For example, assuming that all the generated solid waste is jettisoned overboad at 100 m/s during the 192-day outbound transfer, the mass savings of liquid oxygen (LOX) and liquid hydrogen (LH2) amounts to about 350 kg (without considering storage tanks), corresponding roughly to 2.3% of the total required mission fuel. In this scenario, the habitat volume savings during the outbound transfer alone would amount to approximately 4.3 m^3.

Spare components not used during the Earth-Mars transit should also be jettisoned to contribute to an even higher fuel mass savings. For example, if the unused spare components are also jettisoned, then the estimated generated waste increases to 11.11 kilograms per day, and the LOX/LH2 mass savings is more than a metric ton (without considering storage tanks), or about 7% of the total required mission fuel.

Since chemical propulsion is not planned during the Mars-Earth transit, jettisoning waste during this phase eliminates onboard health hazard risks and habitat volume liabilities, but has a negligible contribution to mass savings in the spacecraft's propulsion system.

In addition to limiting the generation of debris for all Earth orbits, NASA also desires to limit the generation of debris in other orbits where they might pose a hazard to future spacecraft, in particular around the Moon, Mars, and in the vicinity of Sun-Earth and Earth-Moon Lagrange Points. All NASA missions traveling beyond Earth orbit must comply with NASA's Planetary Protection policy and the requirements described in NPD 8020.7,[14] NPR 8020.12,[15] NID 8715.129,[15] and NID 8715.128.[16] Moreover, NASA and its partners must preserve the space environment in accordance with the U.S. Government Orbital Debris Mitigation Standard Practices document and must mitigate the risk to human life and space missions due to orbital debris and meteoroids.[16] Orbital debris is defined as any artificial object placed in space by humans that remains in orbit after the end of its life. Such objects range from spacecraft and spent launch vehicle stages to components like materials, fragments, or other objects which are intentionally or inadvertently cast off or generated.[17] Any solid waste items jettisoned from spacecraft would be included in this catagory.

According to the U.S. Government Orbital Debris Mitigation Standard Practices document, the disposal of spacecraft, their components, and other payloads at the end of their mission life can be performed by relocating them to one of the following storage orbits:

1) Between LEO and MEO (medium Earth orbit): maneuver to an orbit with perigee altitude above 2,000 km and ensure its apogee altitude will be below 19,700 km for a minimum of 100 years.
2) Between MEO and GEO (geosynchronous equational orbit): maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km, for a minimum of 100 years.
3) Above GEO: maneuver to an orbit with perigee altitude above 36,100 km for a minimum of 100 years.

These requirements are unlikely to represent a constraint to the jettisoning of waste objects from Gateway's cislunar orbit or from DST even during its initial transfer from Earth to a rendezvous with Gateway. Additional requirements for limiting the generation of orbital debris are provided by the NASA's Procedural Requirements (NPR) 8715.6[18] document, which includes the guidelines contained in NASA Standard (NASA-STD) 8719.14,[19] *Process for Limiting Orbital Debris*, and NASA-Handbook (NHBK) 8719.14,[20] *Handbook for Limiting Orbital Debris*. This NPR applies to all space structures, payloads, and components that are expected to be released (jettisoned or deployed) from spacecraft in normal operations while in Earth or lunar orbit. These requirements are not mandatory but recommended while in Mars orbit, in the vicinity of the Sun-Earth or Earth-Moon Lagrange Points. Their main objectives are to minimize the generation of orbital debris as part of normal operations, to mitigate their growth from accidental explosions, intentional breakups, and on-orbit collisions, to ensure that they are characterized, and that the risk that they pose to human life and spacecraft is minimized. Moreover, spacecraft orbiting around the Moon, Mars, or in the vicinity of the Sun-Earth or Earth-Moon Lagrange Points are required to provide NASA with ephemeris data containing a time-ordered set of position and velocity measurements describing an object's predicted trajectory after a maneuver or release in order to allow other spacecraft operators to evaluate any potential conjunctions. Reducing the jettison frequency of waste objects, especially from Gateway, would help comply with these NPRs.

The requirements for the control of debris released during normal operations apply to all spacecraft that release objects with the potential of intersecting GEO and other Earth orbits. Any such released debris with diameter of 5 mm or greater shall be left in orbits which will not lie within ±200 km from GEO for at least 100 years after release. Waste objects lanched from Gateway and even from DST can potentially intersect Earth orbits in the long term. However, this occurrence can be easily avoided by controlling the jettison vector and separation velocity of the jettisoned object.

Aside from controlling the release of orbital debris, NASA needs to comply with planetary protection obligations under the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space,

Table 1. Mission Planetary Protection Categories.[10]

Planetary Target Priority	Mission Type	Mission PP Category
Not of direct interest for understanding the process of chemical evolution or where exploration will not be jeopardized by terrestrial contamination. No protection of such planets is warranted, and no requirements are imposed.	Any	I
Of significant interest relative to the process of chemical evolution but only a remote chance that contamination by spacecraft could compromise future investigations.	Any	II
Of significant interest relative to the process of chemical evolution and/or the origin of life and for which scientific opinion provides a significant chance that contamination by spacecraft could compromise future investigations.	Flyby, Orbit	III
Of significant interest relative to the process of chemical evolution and/or the origin of life and for which scientific opinion provides a significant chance that contamination by spacecraft could compromise future investigations.	Lander, Probe	IV
Any Solar System Mission	All Earth Return	V

Including the Moon and Other Celestial Bodies (commonly known as the Outer Space Treaty).[21] All space flight missions, robotic and human, which may intentionally or unintentionally carry terrestrial organisms and organic constituents to planets or other solar system bodies are subject to the NASA Policy Directive (NPD) 8020.7 *Biological Contamination Control for Outbound and Inbound Planetary Spacecraft*.[14] The jettisoned waste needs to meet the requirements included in NPR 8020.12 *Planetary Protection Provisions for Robotic Extraterrestrial Missions*[15] and comply with the directives NID 8715.129 *Biological Planetary Protection for Human Missions to Mars*,[22] and NID 8715.128 *Planetary Protection Categorization for Robotic and Crewed Missions to the Earth's Moon*.[23]

The requirements in NPR 8020.12 apply to all space vehicles intended to land, orbit, flyby, or otherwise encounter extraterrestrial solar system bodies but are not applicable to human missions, except for robotic planetary missions launched using manned spacecraft. In the absence of directives for non-robotic objects launched from manned missions, the waste jettisoned from Gateway or DST should be considered as a robotic object for the purpose of biological contamination control, and thus comply with this NPR. To ensure compliance, a Planetary Protection Officer (PPO) monitors all planetary protection (PP) related activities and conducts reviews and evaluations to ensure that all PP requirements have been met. Each planetary mission shall be assigned one or more PP categories based on the planetary protection priorities of each extraterrestrial solar system body and the mission plan (see Table 1)[10]. Planetary protection priorities and corresponding mission PP categories are assigned by the PPO. Each PP category has different PP requirements. Although any objects jettisoned from Gateway are unlikely to flyby or enter in conjunction orbits with planetary bodies other than the Moon and Earth, the same cannot be said for waste jettisoned from the DST. Moreover, although any jettisoned trash or spare component cannot be defined as a lander, it should be considered as such if it voluntarily impacts a planetary surface. Thus, PP category II, which includes the moon, should be assigned to objects jettisoned from Gateway, and PP categories III and IV, which include Mars, should be assigned to objects jettisoned from DST. Any missions that target asteroids, all other inner and outer planets, and most of their satellites have a lower, and thus less stringent, categorization (either I or II). PP requirements for category II missions consist of documentation only, and include the preparation of a PP Plan in order to state intended or potential impact targets with detailed impact strategies, and mission reports that provide the location of impact, if such an event occurs. PP requirements for category III missions consist of more involved documentation, some implementing procedures including trajectory biasing, the use of cleanrooms during spacecraft assembly and testing, and possibly microbial reduction. An inventory of possible constituent organics is required if the probability of impact is considered significant. Any waste objects jettisoned from DST would need to be treated for microbial reduction before release into space. PP requirements for category IV missions consist of detailed documentation, biological assays to enumerate the microbial burden, a probability of contamination analysis, an inventory of the bulk constituent organics, and an increased number of implementing procedures, which include trajectory biasing, cleanrooms usage, microbial reduction, possible sterilization of the direct contact hardware and use of biobarriers to protect it from recontamination, and, in some instances, system-level sterilization. Protocols for the required microbiological assay are provided in the NASA-HDBK-*6022 NASA Standard Procedures for the Microbiological Examination of Space Hardware*.[24] Alternate methods, such as chemical, radiation, heat, or various combinations of these techniques may be used for microbial reduction, upon approval of the PPO. It is likely and strongly desired that any waste objects would be jettisoned from the DST before a burn to enter Mars orbit, and thus assigned to PP category III rather than IV. However, depending on the type of separation, (low-velocity versus high-velocity), and on the ejection vector, a future conjunction orbit cannot be excluded. Moreover, limited jettison might also occur after Gateway's entry into Mars orbit to ensure the safety of the spacecraft's habitat.

Generally, the probability that a planetary body will be biologically contaminated from any exploration mission is required to be lower than $1\text{x}10^{-3}$ for at least 50 years after a PP category III or IV spacecraft arrives to its protected target destination. In addition to all other PP category III or IV requirements, Mars has specific PP requirements:[15]

1) Any flyby, and orbiter spacecraft shall avoid Mars impact at a probability no less than 0.99 for 20 years after launch and a probability no less than 0.95 for the period 20-50 years after launch.
2) Spacecraft that do not meet impact avoidance constraints shall limit their total (surface, mated, and encapsulated) bioburden level to $5 \text{ x } 10^5$ spores.
3) Mars orbiters shall include the probability of impact on approach in their calculations, unless numerical bioburden requirements are met at launch.

All bioburden constraints are defined with respect to the number of aerobic microorganisms that survive a heat shock of 353 Kelvin (80°C) for 15 minutes and are cultured on Trypticase Soy Agar at 305 Kelvin (32°C) for 72 hours.

Any waste objects jettisoned from DST and that could potentially flyby Mars would have to be considered as a spacecraft per se and thus should comply with the above PP requirements. Trash processing with a TCPS-like system would ensure that bioburden constraints were met in case the jettisoned waste impacted the Martian surface.

No protection of the lunar surface is warranted since the moon is not considered of direct interest for understanding the process of chemical evolution and thus its exploration would not be jeopardized by terrestrial contamination. Thus, all missions to the Moon are assigned PP category I except for missions to Permanently Shadowed Regions (PSRs), which have scientific value in the study of the history of the solar system as well as potential value for In-Situ Resource Utilization (ISRU) and Apollo landing sites, which have both historical and scientific value, specifically protecting studies of the biological materials left by the Apollo astronauts. These regions are assigned PP category II since only a remote chance that biological contamination by spacecraft could compromise future investigations. Thus, no heat-processing of the trash would be required for waste jettisoned from Gateway and impacted on the lunar surface.[16]

V. Conclusion

Recognizing the occasional need to jettison objects, the six partner agencies operating the ISS developed a formal jettison policy. Logistics vehicles remain the primary means of removing waste and non-functional items from the ISS and the jettison of debris is restricted to special occasions dictated by safety and/or operational needs. Future deep-space missions such as Gateway and DST will require alternative solutions for managing spacecraft waste, such as processing it and consistently jettisoning it overboard to ensure volume reduction, habitat safening, and also to facilitate considerable mass savings in the spacecraft's propulsion system. Until a jettison policy derived from the current ISS one is developed for missions beyond Earth orbits, the jettison of any solid waste objects from spacecraft in cislunar or Earth-Mars transit orbit will have to comply with existing orbital debris mitigation and planetary protection policies, which will affect the system's concept of operations (ConOps) and design. However, no major showstoppers have been identified that would preclude Gateway and DST missions from jettisoning waste objects overboard as long as their launch frequency, separation velocity and vector, and microbial concentration are controlled. Moreover, the option of impacting the waste jettisoned from Gateway on the lunar surface would be acceptable according to current policies and regulations and could reduce risks from orbital debris in L2 orbit, although it should be avoided to prevent risks to existing historical sites as well as future human settlements and negative public perception.

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