SAFE MANUAL JETTISON

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ABSTRACT

In space, the controlled release of certain cargoes is no less useful than the maritime jettisons from which they take their name but is also much more dangerous. Experience has shown that jettisons can be performed safely, but the process is complicated with the path to performing a jettison taking months or even years. In the background, time is also required to write procedures, train the crew, configure the vehicle, and many other activities.

This paper outlines the current process used by the National Aeronautics and Space Administration (NASA) for manual jettisons, detailing the methods used to assure that the jettisons and the jettisoned objects are as safe as achievable and that the crew is adequately trained to be able to affect the safe jettison. The goal of this paper is not only to capture what it takes to perform safe jettisons in the near Earth environment but to extrapolate this knowledge to future space exploration scenarios that will likely have Extravehicular Activity (EVA) and International Partner (IP) interfaces.

1. BACKGROUND

Manual EVA jettison is sometimes considered a viable option for items that pose a safety issue for return onboard a visiting vehicle, items that negatively impact International Space Station (ISS) and/or Space Shuttle utilization or manifests, items that represent an EVA timeline savings, and/or items that are designed specifically for jettison [1]. In space this controlled release is much more dangerous due to hazards such as those involved with the hardware disconnection and handling, collision and large mass handling issues, collision with the crew and / or their vehicle, thermal extremes, and risk to persons on the ground. Sometimes the option to hold on to an item and either return it to Earth or keep it on orbit indefinitely is impossible or because it will impose an unnecessary risk to the crew, vehicle, or program.

Ever since man began to launch objects into orbit and physically explore the cosmos, dropping unnecessary cargo en route (similar to the concept of use of in-situ-type resources) has been a viable option. Shuttle and ISS missions alike have been able to capitalize on the benefits offered by being able to jettison objects both manually and robotically.

Jettison also carries with it significant costs which must be weighed against the potential benefits. On-orbit resources such as consumables, crew time, and vehicle reconfiguration costs can be imposing. Ground resources can be heavily affected as well with the extensive amount of assessment and verification that must take place prior to approval. Last, the opportunity costs of being unable to use EVA or Intravehicular Activity (IVA) time for other important tasks, such as science, could be prohibitive.

Many examples exist where jettison has been used with varying levels of success throughout the life of the space program. Specific applicable examples are addressed here to illustrate issues, hazards, workarounds, the jettison policy, and lessons learned for both the United States (US) Segment and the Russian Segment (RS) of the ISS.

1.1. US Segment Jettison Case Examples

In November of 2005 the Floating Potential Probe (FPP) was manually released from the ISS after staying there beyond its operational life. The unit was so structurally degraded that it could not be safely returned to Earth or left in its installed position. Caution had to be used not to break it during manipulation.

In 2007, several noteworthy jettisons took place. January saw the release of Truss Bays 18 and 20 Shrouds and Rotary Joint Motor Controller (RJMC) Covers, an example of a very large but also very lightweight set of objects that was very hard to collect into a small package and bundle together. However, once the object was packaged, it was simple to jettison from the Articulating Portable Foot Restraint (APFR) position. The Multiplexer / Demultiplexer (MDM_ Sunshade during that same period was an object that followed the process to a different end.

Later, in July of 2007, the Early Ammonia Servicer (EAS) was finally given a GO for release and is another example of a piece of Hardware (HW) that had been on orbit beyond its design life and was no longer needed. The EAS jettison is a good example of the complexity of the Jettison process. This object posed a risk not only to the ISS, but also to the shuttle, hence the inability to return it. EAS was very large and unwieldy, was previously filled with ammonia, had handrails but was

very hard to see around while simultaneously being held. The Video Support Stanchion Assembly Flight Support Equipment (VSSA FSE) was released by the crew on the same EVA.

1.2. RS Jettison Case Examples

RS jettisons happen just as frequently as jettisons on the American side. One of note is the Golf demo of February 2007. This jettison used a non-standard format in that the jettison was performed by swinging a golf club to release a ball from a captive 'tee'. Changes had to be made to this jettison in order to make it safe such as limiting the 'swing' motion to a lighter and more reproducible 'tap' motion, and the the standard golf balls were swapped for whiffle type balls for the sake of safety to the fragile solar arrays and to preclude later recontact hazard with station

A benign jettison case, the Splash Payload (P/L) thermal cover in July of 2008 illustrates that certain payload hardware require jettison of covers once they are installed. In general these are specific examples of the process working. The P/L developer conveys the information about the object of potential jettison and progresses through nominal channels through the process since no unique hazards are presented. This same rationale is used for such things as towels, which do not require much coordination or tracking since they are such low mass and perform another vital safety function (needed to wipe off the RS EVA crewmen when working on the Service Module (SM) where they may come in contact with propellant byproducts).

2. HAZARDS PRESENT

Manual jettison poses critical and catastrophic hazard potential. In some cases, the hazards are easily controlled, and in other cases, the respective program must accept the risk inherent to the jettison. In the jettison process these risks and hazards are addressed in Hazard Reports (HRs). Hazards include environmental thermal extremes, object-related EVA contact hazards, fatigue, several aspects of collision, and risk to persons on the ground.

2.1. Environmental Thermal Extremes in the Jettison Position

Any time the crew is placed in a location that is either known to be hot or known to be cold, the potential exists for the crewman to become overly cold or hot. For the cases where thermal assessment shows environmental thermal extremes, since safety by design is typically not an option, a valid control set consists of informing the crew of the hazard in procedures and training and preparing them for the likelihood. In the case of the VSSA FSE and EAS, the crew was put into a known cold position and was handling large masses such that reconfiguring the Display and Control Module (DCM, the manually operated thermostat for the spacesuit) thermal setting during robotic slewing was impossible. In this case the crew was warned to go to a setting that would provide comfort throughout the maneuver.

2.2. Object-Related EVA Contact Hazards

Any of the standard EVA contact hazards can be present on the jettisoned objects such as sharps edges, pinchpoints, touch temperatures, particulate contamination, etc. Each of the individual controls will differ depending on the severity of the hazard but will follow the typical hazard control mitigation hierarchy dictated in Shuttle and Station Safety documentation.

2.3. Fatigue

Due to the important function served by EVA, timelines typically become packed with high priority tasks and the hazard of crew fatigue is always a potential concern. If the crew is also performing a jettison the risk goes up since the jettisoned objects frequently require precise trajectories and velocities on release and may also need special handling due to other inherent hazards such as EVA contact hazards. The Flight Surgeon is granted the latitude, per the Flight Rules (FRs), to continue or halt EVA operations based on his or her interpretation of the crew status and abilities. For these reasons it is particularly important for the crew and ground controllers to be alert and aware of the signs of fatigue. If fatigue is sensed or predicted the crew is allowed and trained to take a break or request task omission. Depending on the priorities assigned to the tasks on the EVA, the tasks that end up getting omitted can differ from EVA to EVA.

2.4. Collision Hazards

The most significant hazards to the EVA and IVA crew, especially when handling large masses, are those of collision: EVA crew collision with structure, immediate jettisoned object contact with structure and later jettisoned object orbital recontact.

EVA crew collision with structure – For jettison of small items this is usually not a concern since the crew has many options at their disposal for body restraint and positioning: APFR, Body Restraint Tether (BRT), handhold, Remote Manipulator System (RMS), etc. However, in some cases, due to induced loads, particularly for large mass objects and the subsequent potential for uncontrolled motion after a jettison throw, it is necessary to position the crew and even limit their force input to the foot restraint platform being used.

Immediate jettisoned object contact with Structure – Most jettisons can reasonably attain retrograde

velocities on the order of tens of centimeters per second, so for most potential jettison items, it would be a catastrophic hazard for them to come into contact with the ISS or crew. In order to preclude this, the crew can be placed in a preferred body position prior to the jettison. Additionally the ISS itself can be positioned (attitude) and configured (stow or feather arrays) to eliminate or minimize the hazard potential. If further mitigation is needed, the crew can be trained to jettison to some desired levels of accuracy, historically +/- 30 degrees and within tens of centimetres per second.

Jettisoned object orbital recontact – Depending on the mass and footprint of the jettisoned item, there exists a potential for the item to cross paths with the ISS or shuttle on later orbits based on complex orbital dynamics. Johnson Space Center (JSC) and Russian Space Agency (RSA) controllers perform detailed design and analysis of orbital models to determine the likelihood of this occurrence. Once the likelihood is determined the EVA team can know the criticality of achieving certain jettison velocities and trajectories.

2.5. Stored Energy Release

Objects may contain residual stored energy such as a pressure tank or battery that could explode or otherwise release while in close vicinity to the crew or vehicle. Should the energy release at a later time, this would fall under the Jettison Policy Letter requirement of having the object 'passivated' prior to jettison so burn-up and tracking can be better assured.

2.6. Ground Impact

Last but not least is the hazard presented by the object incompletely burning up on deorbit and the catastrophic hazard potential it presents to a person on the ground. NASA has explicit agency requirements for this case and if the jettisoned item cannot control re-entry parameters the agency must be willing to either accept the risk or not perform the jettison. The following section outlines the risk threshold for NASA Headquarters (HQ) acceptance.

3. PROCESS

Experience has shown that jettisons can be performed safely but that achieving a safe jettison can be complicated. The ISS program integration office drafted a Jettison Policy Letter [2] detailing the ISS program policy for the Jettison of items from the ISS which has gone through several revisions to obtain the concurrence of all affected parties including Safety, EVA program, ISS program, RSA, Canadian Space Agency (CSA), Japanese Aerospace Exploration Agency (JAXA), and the European Space Agency (ESA). This letter forms the framework for jettisons and summarizes the agreements made by all the International Partners, Safety, EVA Program, Mission Operations Directorate (MOD), and the ISS and Shuttle Program Managers. Within the boundaries drawn by the Jettison Policy Letter, applicable flight rules, hazard reports, safety panels, operations panels, and program boards, the path to performing a jettison can take months or even years. In the background, time is also required to write procedures, train the crew, configure the vehicle, and many other activities beyond the scope of this paper.

All considerations for jettison are first subject to international law [3]. An object can be considered acceptable for jettison if it meets the following criteria: less than 1/10000 risk of injury to persons on the ground [4], trackable, object(s) must be passivated / clustered / low risk for breakup, low risk for collision with ISS, meet ISS scheduling requirements, and not require an ISS debris avoidance maneuver [5].

Figures 1 through 3 illustrate the process flow for manual jettisons drawing on operational experience and lessons learned. The following sections will discuss methods used to assure that the jettisons and the jettisoned objects are as safe as achievable and that the crew is adequately trained to be able to affect the safe jettison. The big picture of the process includes five basic steps: jettison initiation, jettison planning, addressing jettison hazards, reaching a GO decision, and assessing the jettison.

3.1. Jettison Initiation

As shown in Fig 1, before jettison planning can start, the originator brings the jettison request, through the ISS Program Integration office (OM), to the Space Station Control Board (SSCB) for approval. This approval request is the result of an ongoing discussion between the Astromaterials Research and Exploration Science Directorate – Human Exploration Science Office (KX). If approved, then the Jettison Planning process can begin.

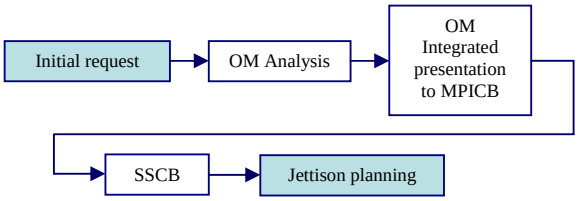

Figure 1 - Jettison Process Initiation

3.2. Jettison Planning

EVA planning forms a subset of the jettison planning, certification, and post-jettison assessment process. Only the EVA-related subset is discussed here. Reference Fig 2.

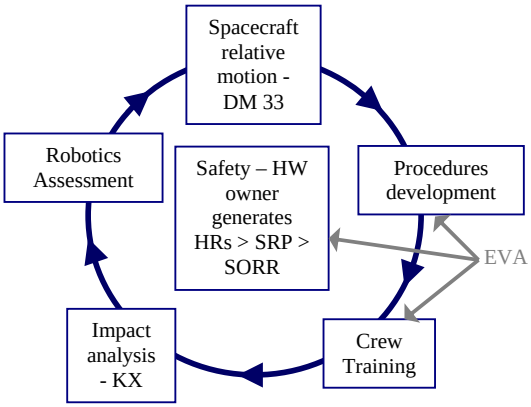

Figure 2 – Jettison Planning Flow

The desired or required jettison parameters are dictated to the EVA community through planning team activity in Joint Operations Panels (JOPs) and / or Integrated Product Teams (IPTs) and the EVA team responds by training the crew to be able to perform the jettison as specified and developing procedures. There are many challenges present, such as how to position the crew so they are in the best possible position to perform a safe release that will not contact structure immediately or in the future. That position not only refers to the location of the crewman on the space vehicle but also the optimal body positioning. For lighter objects, the body position and restraint can be simple, requiring only that the crew hold onto structure with one hand and throw with the other. Alternatively, heavier objects can require the crew to position themselves in a foot restraint and in some cases has also required that the second EVA Crewman assist in handling the jettison item, the vehicle hold a specific attitude, and the robotic arm position the crew such that they are far away from structure.

To address loading on the crewman, some specialized analysis must take place. EVA requirements state that objects being handled over 750 lbm need to be given case-by-case assessment [6]. For such cases, where the crew will not only be handling the load, but potentially throwing the object, the trainers and crew must demonstrate that the throwing action is possible, within structural limits, and safe to perform.

To that end the planning team develops a unique combination of Virtual Reality (VR) lab run demonstrations and tests, Neutral Buoyancy Lab (NBL) tests, and Precision Air Bearing Floor (PABF) tests depending on the specific item(s) being jettisoned. Each test generates different and overlapping data. In the NBL, the crew's ability to handle and jettison large sized loads can be verified as with EAS. Visibility around large sized objects and volumetric assessment is also possible in the NBL testing environment. Additionally, the logistics of the Bay 18 and 20 covers could be practiced to show the ability of the crew to handle such large-sized and uncooperative objects. In the VR lab the crew can practice and demonstrate, in as close to a zero-g environment as possible. The VR lab has been used for many years to show that the crew is capable of handling large masses in excess of 1700 lbm. On the PABF tests have been run to show the ability of the crew to jettison items of large mass within a predefined vector. Additionally, data was gathered to illustrate what the loads being input into the astronaut's bootplate and APFR structure.

Many of these EVA training activities have robotic components which must be coordinated with the appropriate robotics trainers and experts. Loading on the robotic arm and into APFR structures are calculated and analysed both by the JSC robotics group and CSA partners. They define acceptable limits which feed into the crew training skill set. The crew is then trained to stay within those stated loads and procedures remind the crew to use smooth and steady motions, minimize APFR and Space Station RMS (SSRMS) loads, minimize recoil after jettison, and to not abort mid jettison unless crew / vehicle safety dictates.

Effective handling, tethering, jettison, tool usage, and crew procedures are demonstrated similarly through VR lab runs, NBL runs, PABF tests depending on the specific item(s) being jettisoned and the unique skills needed to handle the objects.

3.3. Addressing Jettison Hazards

Part of the planning and certification process is gaining approval from the safety community for the jettison. The HW owner and the community of experts planning the EVA jettison must show the appropriate safety panel that the jettison presents acceptable risk and not introduce undue hazard potential, see Fig 2. To this end the HW owner generates and / or updates Hazard Reports (HRs), typically Collision ISS-COL-1002 and EVA Collision ISS-EVA-0301, applicable P/L HRs, and Non-compliance Reports (NCRs) as necessary to reflect the specific jettison items being brought forward.

Throughout the safety assessment process various safety boards such as the Joint American-Russian Space Working Group (JARSWG) to brief the jettison to our Russian partners, EVA Configuration Control Board (CCB) as a Certification of Flight Readiness (COFR) statement and overview for EVA management, Safety and Mission Assurance Panel (SMAP) as a special topic briefing for safety management, and to Safety and Mission Success Review (SMSR) as a special topic for HQ before and after the HRs and assessment are

presented to the ISS Safety Review Panel (SRP). Once the Hazard analysis has been approved and signed by the SRP it is briefed at Stage Operations Readiness Review (SORR) and moved forward to the Flight Readiness Review (FRR) process before given a final decision at the Mission Management Team (MMT) or the ISS MMT (IMMT).

3.4. Reaching a GO Decision

Two unique processes exist depending on the program but they both follow a similar format as shown in Fig 3. This process flow does not happen totally independently of the planning and hazard identification processes since many of the same players are present in the JOP and IPT forums.

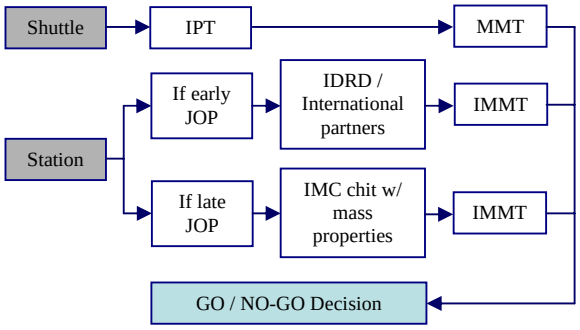

Figure 3 – Jettison GO / NO-GO Process (IMC - Increment Management Center, IDRD - Increment Definition and Requirements Document)

When the jettison planning is nearing completion and the hazard analysis has shown that the jettison can be performed safely, the GO / NO-GO decision is given at the IMMT / MMT. It should be noted that if management is not pleased with the jettison, a NO-GO decision can cause the planning process to go through more cycles.

3.5. Assessing the Jettison

On release, the crewmen provide commentary on direction, angles, speeds, similarity to training, SSRMS / APFR movement (if applicable), and rotation for up to five minutes or until Mission Control Center (MCC) is satisfied. This provides the teams with immediate feedback and an idea of the trajectory for the Flight Design and Dynamics Division – Orbital Dynamics Branch (DM 33) analysts to feed into their analysis software, giving a rough state vector. Feedback also gives the teams an understanding of any complications that may have arisen during the jettison event.

The Imagery Science and Analysis Group (ISAG) frequently records and analyzes the jettison. Within several hours to one day they are able to improve the state vector estimate. For the Golf demonstration, this imagery analysis was first shown to be useful in determining the planned versus actual trajectories. It showed that the jettison method was unacceptable in terms of its capability of preventing collision with the ISS both immediately and in the longer term.

Over the next several days after a jettison US Strategic Command Space Tracking (STRATCOM) is able to acquire and track objects of appropriate size. Once acquired DM 33 and STRATCOM are able to further refine the state vector and to track the object through reentry. This tracking provides the primary data set for assessing the effects of the jettisoned object on future ISS visiting vehicles.

4. LESSONS LEARNED

Each of the jettison cases presented herein have presented challenges throughout the jettison process. Those lessons have driven changes to the way that we perform jettisons, assess jettisons, capture hazards, and operate real-time in the control center, to name a few. The FPP jettison in 2005 showed us that the crew can successfully handle objects of questionable integrity as did the EAS jettison two years later.

EAS presented its own unique challenges for the flight control team, management, crew, trainers, safety community, and IPs. EAS and the VSSA FSE were very difficult objects for the astronaut to keep within the +/- 30 degree cone defined for both safety and for achieving the required state vector. Although the training and analysis teams were convinced that the cone could be maintained, the crew's lack of visual clues and the size / mass of the object compromised the task for EAS. For the VSSA FSE, the irregular shape and center of mass caused the problem, but the crew was still able to achieve very good retrograde velocity in excess of predictions. A revision to the Jettison Policy Letter was written to address the jettison cone issues and it should be noted that the IPs desired to know the clearances from structure rather than acceptable cone angles. Loads input into the APFR and SSRMS were very hard to limit but the crew was able to control errant motion and load inputs to the extent that arm joint slippage was minimized to acceptable levels.

For the Truss System Bays 18 and 20 Shrouds it was shown that crew training paid off with respect to stowing the shrouds. As expected the jettison cone was very easy to maintain due to the light weight of the objects.

2007 was a busy year for EVA jettison assessments. The MDM Sunshade is a story of an object that was shown to be unsafe to jettison in the midst of the approval process. Its ballistic coefficient was too close

to that of station and therefore shown to be too high of a risk for recontact. It was brought inside the ISS in January 2007 and deorbited from station aboard a Progress freighter.

On the Russian Segment, one of the jettison cases in particular has notable lessons. While the Russian process follows a slightly different flowpath, with planning done by Russian experts, IVA-only US planning involvement, and the approval process picking up in the JOPs and IMMT the result is the same. For the Golf demonstration extensive analysis and planning still could not prepare crew to perform a safe jettison, the ball was guaranteed to go in the required direction but later analysis showed that the ball was absolutely uncontrolled, and crew positioning was difficult - should have used a foot restraint for positive body control. An on-orbit demonstration showed that the task could be done safely but EVA crew still could not complete it.

Cover and towel jettisons typically go off without issue although the object information is difficult to obtain from certain IPs. The Jettison Policy Letter, once again, has been modified in order to facilitate data exchange efficiencies.

Limitations are present in any jettison situation. For example, as we have seen, some hazards cannot be adequately controlled and the risk has to simply be weighed against the other options and potentially accepted. If the risk is too great, alternative methods, even more costly ones, need to be used.

5. FUTURE USE

The goal of this paper was to capture what it takes to perform safe manual jettisons in the near Earth environment. Obviously this operational and process knowledge can be extended to future space exploration scenarios that will likely have EVA and International Partner interfaces. While Lunar mission scenarios do not have plans for manual EVA jettisons, it is likely that some hybrid scenarios could present themselves where either objects for potential intentional jettison or objects for robotic jettison will need to be assessed.

For Mars missions it is likely that crewmen will venture outside the vehicle during transit. Hence opportunities will be present for jettison. Many hazards will remain, presenting either equal or more risk than an ISS or Shuttle jettison. Since the Mars vehicle will likely be less restrictive than station in terms of size however the catastrophic potential of later recontact is just as real. To prevent later recontact new approaches to vectoring may need to be assessed, potentially orthogonal to the vehicle trajectory (out of the orbital plane). Environmental thermal extremes either in the jettison position or simply by the nature of venturing out the hatch will probably stay at about the same risk level as it is currently as will object-related EVA contact hazards. Fatigue will still be an issue since even though the EVA(s) may be shorter, the crew will be operating in a chronically degenerated state. For this same reason mass handling requirements to preclude immediate jettison item contact with structure and EVA crew collision with structure must be updated. And finally, rapid safing or any other safing required for planetary deorbit will never go away but the timeliness of the jettison could require a modification to change the 'process' to a 'plan'.

Many of the Safety hazards associated with Low Earth Orbit (LEO) jettison will either go away for transfer-type trajectories for interplanetary travel or reduce in risk. For example we will no longer need to be concerned about recontact with ground.

New hazards could also be presented due to the unique operating environment and in response to failures we may be unable to anticipate now.

6. CONCLUSION

As mentioned earlier, jettisons are documented to have been performed maritime for generations as a voluntary sacrifice of cargo to lighten a ship's load since the 15th century [7]. In the future exploration of interplanetary space this 'voluntary sacrifice' will be no less useful than it was then and is now enabling us to proceed without undue risk to the crew and vehicle of keeping unsafe or unnecessary cargo. Should situations dictate, we may even need to develop more sophisticated methods of manual and robotic jettison to further reduce the risk for near- and far-future missions.

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