Operational Considerations for Crew Fatality on the International Space Station

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BACKGROUND: While catastrophic spaceflight events resulting in crew loss have occurred, human spaceflight has never suffered an on-orbit fatality with survival of other crewmembers on board. Historical plans for management of an on-orbit fatality have included some consideration for forensic documentation and sample collection, human remains containment, and disposition of remains; however, such plans have not included granular detailing of crew or ground controller actions. The NASA Johnson Space Center Contingency Medical Operations Group, under authority from the Space and Occupational Medicine Branch, the Space Medicine Operations Division, and the Human Health and Performance Directorate, undertook the development of a comprehensive plan, including an integrated Mission Control Center response for flight control teams and Flight Surgeons for a single on-orbit crew fatality on the International Space Station (ISS) and subsequent events. Here we detail the operational considerations for a crew fatality should it occur during spaceflight onboard the ISS, including forensic and timeline constraints, behavioral health factors, and considerations for final disposition of decedent remains. Future considerations for differential survival and crewmember fatality outside of low-Earth orbit operations will additionally be discussed, including consideration of factors unique to planetary and surface operations and disposition limitations in exploration spaceflight. While the efforts detailed herein were developed within the constraints of the ISS concept of operations, future platforms may benefit from the procedural validation and product verifications steps described. Ultimately, any response to spaceflight fatality must preserve the goal of handling decedent remains and disposition with dignity, honor, and respect.

KEYWORDS: human spaceflight, crew fatality, low Earth orbit, International Space Station.

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Human spaceflight requires highly precise events to take place in unforgiving operational environments. Even small missteps can result in catastrophic events; historically, loss of crew life has occurred in ground training events, launches, reentry, and landings.[43,53,56] At the National Aeronautics and Space Administration (NASA), protocols have been developed for planning, training, and coordination of responses in the aftermath of these types of contingencies. While catastrophic events resulting in crew loss have occurred, to date human spaceflight has never suffered an on-orbit fatality or a loss of a subset of crewmembers with differential survival of those onboard. Nonetheless, the possibility exists.

Prior plans for the management of an on-orbit fatality have included some consideration for human remains containment and disposition as well as the possibility of forensic sample collection, though such plans have not included dedicated preflight protocol training for crew or granular detailing of crew or ground controller actions.[29] Historical plans involving remains containment and disposition were largely untested

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and equipment unvalidated for use in the microgravity environment.[28,29,31] Further, ground support personnel, including flight controllers, were rarely privy to details of decedent management protocols; in general, these topics were not discussed widely outside of expert teams.

Early probability studies estimated the incidence of a significant medical event for a three-person crew onboard the International Space Station (ISS) would be once every 5.5 yr and the incidence of an incapacitating event necessitating orbital evacuation was estimated at once every 33 yr.[31,55] For expanded ISS operations of six crewmembers, the incidence of a significant medical event was estimated at once every 3.2 yr and the incidence of an incapacitating medical event requiring evacuation at 1–3 events per 15 yr of continuous ISS operations.[10,31,55] More recent probabilistic analysis applied to ISS conditions, with a crew of six, current ISS medical capabilities, and missions lasting 180 d, predicts a 0.5% chance of loss of crew life.[1] This would predict a fatality in 1 out of 200 ISS crewmembers, or once every 10–15 yr. At the time of writing, around 250 people have flown to the ISS in just over 20 yr of operations—even current models predict at least one fatality and multiple evacuations for serious medical events over that timeline.[1] Actual operational experience has not borne these estimates out. Between 1971 and 2022, one evacuation and two early mission terminations have occurred during crewed spaceflight,[11,31,53] far fewer than the estimates outlined above.

A fatality onboard ISS, like that in any analogous high-profile austere and hazardous venue, would result in a tragic and disruptive event with heavy media coverage and public scrutiny.[3,4] Lack of preparedness for such an event could render a situation far worse as stakeholders would be forced to formulate responses and actions in real time. Thus, the value of preparedness for a crew fatality and aftermath cannot be overstated.[25] Terrestrially, analog expedition scenarios demonstrate the implications of inadequate planning for a team member fatality.[32,52,59] Insufficient supplies, inadequate skillsets and capabilities, and the psychological impact of the loss of a member of a small team can all contribute to poor outcomes after a fatality, ranging from disruption and worsened psychological trauma to disorganized responses, and even increased risk to surviving crewmembers.[5,51,52] A cogent, orderly plan to respond to a traumatic event, such as the loss of a crewmember, can instead ensure the safety of the surviving team members, allow for expedited response for activities that are time-sensitive, ease psychological distress through appropriate actions, and protect the privacy and dignity of the decedent, survivors, and their families. Further, a well-established protocol allows for the collection of forensic evidence such that causal and contributory factors related to the fatality may be identified, providing the opportunity to gain a full understanding of the event, identify lessons learned, and drive program iteration and implementation of preventive measures.

The NASA Johnson Space Center (JSC) Contingency Medical Group, under authority from the Space and Occupational Medicine Branch, the Space Medicine Operations Division, and the Human Health and Performance Directorate, undertook the development of a comprehensive plan, including an integrated Mission Control Center response, in an organized, contemporaneous timeline for flight control teams and Flight Surgeons for a single on-orbit crew fatality on the ISS and subsequent response. This project included the following:

- Development of a comprehensive plan and integrated response for the flight controllers[29];
- Ground validation of pronouncement and forensic sampling procedures;
- Verification of equipment specifications for forensic sampling supplies[14,28,29];
- Verification of equipment specifications for a human remains containment unit (HRCU), including validation study using ISS analog pressure, temperature, and humidity[14,28,29];
- Determination of an appropriate ISS stowage location for the HRCU; and
- Designation of responsible entities within the NASA JSC Flight Operations Directorate and ISS Program Office tasked with the responsibility of determining the final disposition of remains.

This collaborative effort involved stakeholders from NASA and its international partners, as well as military and academic institutions, to develop and validate operational considerations for a single crewmember fatality in this scenario. Following development, this effort was reviewed and approved by Directorate stakeholders for operational implementation; these validated procedures and verified equipment were subsequently manifested on the ISS.

Prior publication has discussed the detailed procedures surrounding forensic sample collection, preparation of decedent remains for disposition, and validation of an HRCU modified for the space environment.[29] Here we discuss in detail the operational considerations for a single crew fatality occurring during NASA-crewed spaceflight, highlighting the historical background and risks of spaceflight and a timeline for management of an onboard fatality to ensure an orderly and timely response for pronouncement, forensic sampling, preparation, stowage, and disposition of remains. Further, we will discuss factors considered to ensure the protection of the surviving crew and vehicle from potential contamination risk, goals and rationale for forensic sampling, and efforts to ensure that the decedent will be handled with dignity, honor, and respect at all times while gathering forensic data needed to assist in determining the cause of death. Protocol development was heavily influenced by coordination with the Behavioral Health and Performance Operations Group; thus, psychological considerations for crew and ground support team members will additionally be addressed. Finally, future implications for programmatic development and customization of protocols to address fatality, decedent remains disposition, and postmortem management will be discussed, with factors to be considered for future and exploration-class missions outside of low Earth orbit.

Historical Perspective

The possibility of crewmember fatality during spaceflight has garnered considerable attention in previous human spaceflight programs. NASA's Project Mercury and Project Gemini protocols were influenced heavily by the high-performance flight programs that preceded them, with protocols adopted in parallel to those used in military test flight projects.[17] Missions were relatively short and crew rescue or evacuation options were limited in the nascent human spaceflight efforts. During the Apollo Program, mission duration increased and risks evolved due to distance from Earth and limited to no evacuation options during substantial portions of each mission. Astronauts were aware of the risks that they were undertaking and simultaneously recognized the need to prioritize the protection and safety of any survivors against the natural desire to recover a deceased crewmember's remains. During a retrospective review of the Apollo Program, in providing recommendations for developing future lunar missions, former Apollo astronauts highlighted their own awareness of the lack of evacuation or rescue options available during lunar missions and strongly recommended that future crews be similarly prepared to leave behind a deceased crewmember, as retaining or recovering decedent remains could threaten the safety of survivors.[50] Additional recommendations from Apollo crewmembers included advanced and detailed planning for contingencies, including death during a mission, ensuring that all individuals (including crew, ground support, and families) would be prepared in the event of a spaceflight fatality and that educational and psychological services were available and familiar to astronauts and their families.[50] Similar recommendations were received from former Skylab Medical Operations Project crewmembers and project personnel.[35]

This need for planning and integration of support services, and the benefits of early activation of crew and employee support in the aftermath of disaster, was again highlighted after U.S. Space Shuttle mishaps.[41,56] Further, during the U.S. Space Shuttle Program there was some effort to improve upon the capability to return crew to Earth, primarily for the return of ill or incapacitated crewmembers, but potentially applicable to return of remains. This included efforts to improve the crew survivability envelope, such as the development of the Crew Escape System after the U.S. Space Shuttle *Challenger* disaster, and the interest in development of an emergency crew return vehicle during the 1980s and 1990s.[31,41,60]

With the return to capsule-based crew transport in current operations, crew capsule vehicles provide nominal transit to and from orbit and crew return capabilities in contingency scenarios. Return of decedent remains in a capsule vehicle poses significant challenges, including the maneuverability of remains within an HRCU to fit within capsule seats, incorporation of seat restraints with the HRCU, and ensuring the safety of surviving crewmembers exposed to remains in a volume-limited capsule.[3,17,29] Additional challenges include the lack of validation studies for decedent remains containment or relevant equipment in microgravity conditions and the limited refrigeration and freezer capabilities available on current operational vehicles.[29] On the ISS, small volume refrigeration and freezer capabilities do exist with temperature storage ranges of −160°C to +4°C.[17] However, the volume available is exceptionally limited and use of this space would require sacrifice of other payloads or items requiring refrigeration; further, return vehicles may lack refrigeration capability after departure from the ISS. Large-volume refrigeration capable of preserving a human body is not available onboard current launch vehicles or on the ISS.[29] In the absence of refrigeration, isolation of remains in an HRCU and further sequestering the HRCU from the crew (such as placement in the airlock or similar compartment that could be then sealed off from the primary habitable volume) could provide some protection for crewmembers from any loss of contamination or biohazardous exposure while simultaneously offering some degree of psychological protection.

Recent efforts into developing a robust human remains capability for use in a microgravity environment have been detailed elsewhere, including feasibility analysis regarding the incorporation of an HRCU into a return vehicle.[29] However, even if effective remains containment resources are available, there is still a need for continued iteration and development of processes regarding the preparation, containment, and return of human remains from spaceflight in current or future vehicles.

Timeline: Decedent Remains Management and Forensic Pathology

An onboard fatality may involve a single crewmember with a medical event or multiple crewmembers due to a larger mishap. Multiple fatalities would likely prompt urgent or emergent evacuation of any survivors, which may preempt forensic procedures or disposition of decedent remains. However, there are circumstances that could conceivably result in a single crewmember fatality with the remaining crew preserved, such as an acute medical illness or event (for example, a sudden cardiac event), injury (vehicular, environmental, etc.), or an event uniquely related to spaceflight factors [for example, a failure of critical hardware during extravehicular activity (EVA)]. In the case of a single crewmember fatality on orbit where the circumstances do not drive an emergent evacuation of ISS by surviving crewmembers, procedural goals include the collection of forensic data, management of remains to ensure containment and prevent contamination of the survivors' habitable environment, and, by providing effective isolation, ensure time for the determination of best options for disposition of remains.[5,29]

An ISS plan for management of a fatality must ensure a mature and orderly response coordinated across critical disciplines. Any plan must be flexible, as it is not possible to anticipate all circumstances surrounding a potentially fatal event on orbit. Extraneous circumstances will influence the execution of any plan or timeline; thus, training of the crew and established procedural tasks increase the likelihood that necessary actions can be accomplished, with appropriate prioritization, in the case of a fatality. Further, development of such procedural actions for ISS operations allows for the application of lessons learned toward future programs and vehicles, scaled appropriately to platform size and crew complement, remote nature of the operation, available communication and support, and possibility of evacuation and return to Earth.

In the case of an on-orbit fatality, initial actions would include confirmation of death and pronouncement, followed by possible forensic collection and preservation of samples (**Fig. 1**). The need for collection of samples must be considered in balance with contraindications to sampling, including safety of the crew (for example, if sample collection delays isolation of potentially dangerous biohazards), cultural and religious sensitivities, and the risk of worsening psychological trauma to crew from sampling procedures or other manipulation of remains.[5,38]

Compared to a controlled, terrestrial forensic effort, any attempt to pursue forensic pathology in the spaceflight environment after crewmember fatality will undoubtedly be complicated by spaceflight-specific factors.[2–4] While crew are provided some preflight medical skills training (such as phlebotomy and catheterization) upon which the forensic sampling procedures are based, and many sample collection techniques are familiar to crew due to similar research sample collection and preservation procedures, crewmembers lack formal forensic training and any procedural training prior to a mission will likely be minimal. Inexperience will be compounded by real-time stressors, including psychological considerations and the circumstances that led to a crew fatality (for example, an altered vehicular environment). Additional factors include microgravity and altered fluid dynamics (and related procedural impacts),[15] the closed vehicle atmosphere, unknown decomposition rates in spaceflight environments, the challenges inherent to validating procedures in the unique operational environment, and the variable but limited options for disposition of remains.[29]

The goals of forensic examination following a spaceflight crew fatality include photographic documentation, removal of personal effects and clothing, forensic sample collection and storage, preparation of the body for disposition, and placement in an HRCU.[29] Desirable forensic samples include hair, fingernails, urine, blood, and vitreous humor[38]; such samples allow for delayed qualitative analysis[21] and are balanced against spaceflight storage and transportation considerations (**Table I**). In the absence of large-volume refrigeration, sample collection should occur as early as possible, preferably within 4 h but certainly within 12 h of death, to minimize alteration of samples from decomposition[14,21,38] and to allow for early isolation of remains in appropriate containment to avoid unnecessarily biohazardous contamination of habitable space.[29] Sample accommodation in available small-volume ISS cold storage would require real-time coordination with appropriate ground controllers to identify best options and appropriate temperatures. In general, freezing would be preferred over refrigeration for longer sample stability.

To minimize manipulation of remains and associated biohazardous and psychological risk, it is likely that preparation of remains will be concurrent to or immediately following forensic sampling, with subsequent isolation and stowage of remains. Decomposition of human remains in a microgravity environment has not been validated, though decomposition in a nonrefrigerated terrestrial environment similar to the environment of the ISS can provide some context for expected timeline. In a room-temperature (~72°F, 22.2°C) environment, rigor mortis can occur within 3–6 h of death and remain present for 24–36 h. This timeline may be altered by environmental conditions (particularly temperature and humidity),[24,37] internal body temperature, and premortem decedent activity.[13,22,27] Initial autolysis and tissue degradation can be expected to occur within a few hours of death.[13,23] Within 24 h, autolytic changes

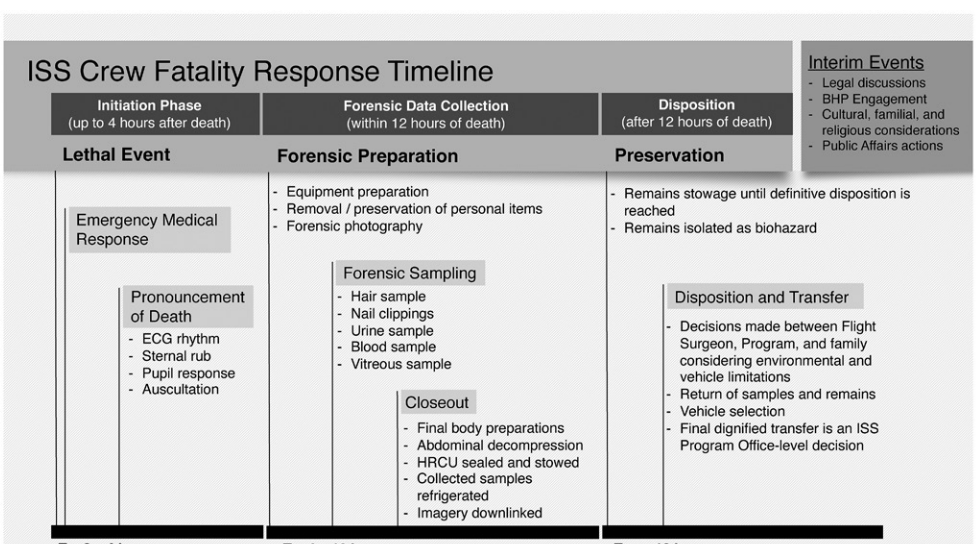

Fig. 1. ISS crew fatality response timeline. Following pronouncement of death, protocol timelines prioritize early sample collection and body preparations for stowage, to be completed no later than 12 h following death. Final disposition of remains will follow, with the ISS Program Office responsible for final determination of remains disposition. Discussions regarding legal, cultural, familial, and religious considerations, as well as behavioral health support plans and public affairs actions, will be concurrent with other timeline actions. BHP: Behavioral Health and Performance Team; ISS: International Space Station; ECG: electrocardiogram; HRCU: human remains containment unit.

Table I. Desirable Spaceflight Forensic Samples and Associated Rationale and Collection Considerations.[29,38]

SAMPLE	RATIONALE	COLLECTION CONSIDERATIONS
Blood	Provides expanded analysis capability compared to other samples [e.g., complete blood count (CBC), thyroid stimulating hormone (TSH), serum protein electrophoresis (SPEP), cortisol, glycosylated hemoglobin (HbA1c), acetone, cholinesterase, carbon monoxide level (CO), microbial cultures].	Anterior parasternal approach for ease of landmarks, adequate sampling volume. Increased likelihood of success compared to great vessels due to postmortem vascular collapse, fluid shifting, loss of pulsatile landmarks.
Urine	Corroborates some serum analyses, culture to rule out source of infection.	Crew already trained on urinary catheterization, equipment available. Should be performed early given potential postmortem incontinence.
Vitreous Humor	Preferred sample substance, more stable than blood for metabolic study. Remains stable and valid for longer periods of time.	Familiarity of decedent and intimate nature of vitreous sampling anticipated to be most likely sampling technique to be associated with psychological stress.
Hair	Stable specimen, allows for toxicological and xenobiotic analysis; further provides segmental analysis for timeline or chronicity of exposure.	Prioritization of scalp hair then forearm for sampling. Postmortem sampling preferably includes bulb extraction.
Fingernails	Collagen can provide insight in protein expression, long-term studies.	Standard nail clippers provisioned for collection

may become externally visible; more concerning for the habitable environment, development of decomposition-related volatiles would be expected by 24 h of decomposition.[36,61] Unless contained, in an enclosed, pressurized environment, production of volatiles such as methanethiol and hydrogen sulfide will adversely affect air quality and pose a health risk to remaining crew.[29] The presence of rigor can be expected to complicate forensic collection and remains stowage, and visible evidence of decomposition would certainly have psychological impact on any surviving crew; development and release of volatile compounds into the habitable environment is clearly undesirable. Thus, these issues would be high-priority drivers for timeline considerations. Ideally, any necessary manipulation of remains should occur as soon as possible; protocols developed for crew fatality on ISS prioritize forensic data collection and final remains preparations for stowage within 12 h of death to minimize exposure to advancing stages of decomposition.[5,29,38]

Behavioral Health Considerations

An in-flight crewmember fatality would necessitate that the remaining crew act as first responders, provide confirmation of death, complete forensic sampling procedures, consider and execute options for remains disposition, honor the fallen colleague, and grieve, along with remote family and friends, all while safely continuing the mission.[3,8] The complexity of these needs will undoubtedly lead to significant behavioral health and performance challenges. Due to pre-mission crew training requirements and schedule constraints, procedural training for actions following an on-orbit fatality is prone to be minimal, and crew are unlikely to be fully briefed on the scope or granular details of procedures until the aftermath of a crewmember fatality. All forensic sampling and crew disposition procedures are designed to be remote-guided by a Flight Surgeon,[29] which ensures that a trained ground support physician is available to assist while simultaneously offering real-time assessment of the crew to determine if a crewmember may need to take a break, refocus, or receive additional psychological support. Crew can opt out of any procedures and the Flight Surgeon has the authority to terminate any forensic sampling procedures to protect the health and safety of the surviving crew.

Even so, given mission demands, procedural timelines, and mission management expectations, it is doubtful that a crewmember will be immediately forthcoming with reporting emotional distress that may interfere with their ability to perform operational tasks, including postmortem procedures. It is expected that crewmembers would initially attempt to suppress their emotional reactions, as compartmentalization is a necessary and effective short-term coping skill that facilitates operational performance.[8] However, compartmentalization can lead to delayed and occasionally unexpected reactions of grief and trauma, and long-term compartmentalization can further interfere with the natural trauma recovery process. Natural human mourning and grief will occur and should be effectively addressed and facilitated when circumstances permit to determine if subsequent mission duties can be undertaken safely. Thus, ground support personnel would need to maintain high suspicion and awareness of crewmember emotional responses and provide increased opportunities for support as well as modifications of crew work schedules to ensure adequate time for grieving, rest, or utilization of the support framework.

The ISS has the benefit of preexisting architecture to enable real-time communication and evaluation by NASA's Behavioral Health and Performance team via established protocols for private medical and psychological conferences.[9,33] Given this pre-existing structure for behavioral support and the familiarity of such protocols to crew, integration of support after a fatality onboard the ISS would more likely to be successful than in operational settings with less established psychological support practices, or where communication delays or telemetry complexity may interfere with the availability of support services. Similarly, commercial operators may be more likely to experience challenges in integration of support when integration has not been prioritized throughout architectural and operational development.

It is worth noting that a death in space will affect the entire spaceflight community, including ground controllers, family, friends, governmental and private spaceflight organizations, and international partners, particularly in countries of crew origin. At NASA JSC, the Behavioral Health and Performance Operations Group and the Employee Assistance Program are trained to respond immediately to both crew and support personnel needs in the case of such a tragedy.[56] Aspects of such a response include:

- Consultation with mission crew surgeons, flight directors, and senior management for guidance and support.
- Consultation with astronaut family support providers and engagement, as desired or needed, with crew family members.
- Consultation with international partners, including coordination with subject matter experts on medical, cultural, religious, ethical, and legal matters.
- Provision of private psychological conferences with surviving crewmembers.
- Initiation of a Center-wide Employee Assistance Program crisis response.
- Enabling crew virtual participation in memorial services.
- Monitoring and facilitating grief in crew and ground support teams for the ongoing mission.

Pre-coordination of psychological support assets before a mission increases the ability for behavioral support personnel to engage with crew and others in the case of tragedy, as trust and friendship built over years of association allow for empathy and a better understanding of what each individual may need to optimally cope with the grieving process.[56]

At NASA, the Employee Assistance Program is tasked with providing Critical Incident Stress Management services to the entire workforce of the Agency in the aftermath of a catastrophic event, including providing a means for employees to understand and manage the emotional response to mishaps in a structured and supportive way, identifying highly impacted individuals, and promoting individual and team recovery and functionality.[56] The timing of services is dependent on the level of impact and the completion of mission operations related to the loss and follow-on investigations. Long-term follow-up is essential, including post-investigational or post-mission support, to ensure delayed psychological needs are met. While NASA's workforce tends to be resilient and hardy by nature, the dedication and investment in the crew and mission leads to significant emotional impact when there is a loss.[8,56] Comprehensive emotional first aid and ongoing behavioral health care can help to minimize any long-term negative psychological impact while improving workforce retention and resiliency.

Dignified Remains Disposition: Current and Future Considerations

Multiple factors must be considered when determining appropriate disposition for human remains following an on-orbit fatality. For a fatality occurring on the ISS, the ISS Program Office will hold the authority for final determination of remains disposition. However, onboard resources for containment, biohazard risk, and compatibility with return vehicle design will factor into decisions regarding the potential for return of human remains to Earth. Simultaneously, alternative disposition options pose additional challenges. If return to Earth is not feasible, some additional options for remains disposition include jettison into a reentry orbit such that remains are destroyed during atmospheric descent, jettison into a nondestructive, stable "disposal trajectory" orbit, or interment on an extraterrestrial surface. For a crew fatality occurring on the ISS, options would be limited to return of remains, jettison to a disposal trajectory, or destructive reentry.

Destructive reentry occurs when a descending object experiences atmospheric drag, with extreme heat generated by the friction between atmospheric gases and the object causing the object to combust. In the absence of thermal protection, reentering objects can be destroyed by this excessive heat. This process could potentially be used to provide a means of cremation of human remains. However, reentry thermal stress must be sufficient to ensure combustion and elimination of remains beyond an identifiable state. This is by no means guaranteed by all return trajectories; for example, after the U.S. Space Shuttle *Columbia* mishaps, identifiable remains were recovered from all crewmembers onboard despite unprotected reentry after the orbiter breakup.[42,56] In the case of the *Columbia,* orbiter breakup happened well after entry interface in an intended deorbit trajectory and thus remains were not exposed to full reentry stressors[56]; even so, this highlights the risk of incomplete elimination. Other uncrewed space vehicles have returned to Earth via destructive reentry only to have identifiable vehicle components recovered, in some cases from populated areas.[6,12,44] In the absence of guaranteed destruction, a desirable reentry trajectory would preferably ensure that any intact remains land in remote areas of the planet, ideally over an ocean, to minimize risk of rediscovery. However, trajectory prediction can be challenging, particularly in the absence of propulsive return.[57] Further, certain cultures and religions are strongly opposed to the practice of cremation, and crewmembers and families from such cultural experiences may be fundamentally opposed to destruction of remains in this manner. The risk of intact remains being discovered and identified after reentry violates the primary objective of ensuring the decedent will be handled with dignity, honor, and respect at all times.

Jettison of remains into a stable disposal trajectory similarly requires considerations of complex factors. Automated jettison (for example, via propulsive capsule or an automated airlock system) has historically been unavailable on crewed vehicles. However, NASA recently demonstrated an automated large-volume waste disposal capability using a commercially developed airlock module (the Bishop Air Lock, Nanoracks LLC, Houston, TX), able to jettison up 600 lb of ISS waste into a destructive reentry trajectory.[39] Even so, this nascent technology was not developed or intended for use in the case of remains disposition and would be subject to the limitations of destructive reentry described above.

In the absence of an automated capability, jettison would require either decompression of a habitable vehicle (for example, a crewed transit vehicle without an airlock) or an EVA with other crewmembers transporting remains out of an airlock (for example, on the ISS). Decompression of a nonairlocked vehicle would require that all surviving crewmembers have access to usable, working EVA suits with sufficient onboard consumables to reconstitute a habitable atmosphere after decompression and jettison of remains. Even if an airlock is available, decompression is always associated with risk; thus, the decision to jettison remains poses substantial risk to survivors regardless of vehicle architecture. Further, nonpropulsive jettison of remains (for example, transfer of remains out of the ISS airlock) would result in those remains entering essentially the same orbit as the crewed vehicle.[3] While this orbit will degrade over time, this will require tracking of the jettisoned remains to ensure there is no recontact or risk of impact to future vehicle traffic.[45,49] Placement in a low Earth orbit again risks the potential for future atmospheric reentry, incomplete destruction, and terrestrial rediscovery; placement in orbit around another object (for example, the sun) may be more appropriate given the decreased likelihood and frequency of recontact, but adds complexity, such as requiring some propulsive means and sufficient consumables for achieving the desired trajectory.

A return to the Moon via the NASA Artemis Program raises the possibility of crew fatality on a planetary surface and the potential for lunar interment. Similar possibilities may be feasible in future missions to Mars or other celestial bodies; however, disposition of remains on a planetary surface may be contrary to planetary protection statutes. The United Nations established a Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space in 1966, in which protection requirements included prevention of potentially harmful biological contamination of celestial surfaces.[34] In 2020, a NASA Interim Directive declared that existing science suggests that biological contamination of the Moon is not a significant threat to future scientific investigations except in polar latitudes and perpetually shadowed regions of the surface; this effectively decreased the restrictions surrounding the deposition of biological material on the lunar surface in most regions.[18,47] In 2021, the Committee on Space Research similarly published their Policy on Planetary Protection, in which mission destinations are categorized based on concern for biological contamination.[19] Planetary protection, particularly control of forward contamination that may interfere with the future search for life in the solar system, remains a significant concern for interment of human remains on other planetary bodies such as Mars.[46]

Even in the absence of contamination concerns, there would be numerous challenges associated with surface interment. For example, the lunar surface consists of dusty, sharp, angular, and compact soil particulates with high glass content, known to be very abrasive, as well as frequent boulders and subsurface rock.[20,30] There is no wind on the lunar surface, so there is no smoothing of sharp and irregular regolith particles. Crewmember manipulation of regolith for remains interment risks abrading, cutting, or otherwise damaging suit components with associated risk to the safety of the crew. Future missions may include tools to assist in regolith manipulation, such as robotics[20]; even so, establishing an interment location (via subsurface excavation or building up of a cairn-type structure) would require significant work from surviving crewmembers, with additional EVA/surface operations and related risks[7,16] as well as associated depletion of consumables. Given that near-future missions to the Moon are likely to involve relatively small crew complements (2–4 crewmembers for initial Artemis Program missions),[40] this would be particularly burdensome on surviving crew and substantially increase the risk to those survivors. Further, with extreme temperatures and the lack of pressure and oxygen to support bacterial growth, human remains would not be expected to undergo natural decomposition on the lunar surface; this increases the risk that future lunar missions, particularly non-NASA missions, could rediscover or disrupt the interment site.

Other novel methods of remains disposition have been considered for future missions, though frequently such methods would require development or manifesting of nascent technologies for use in the space environment.[3,58] For example, terrestrial facilities to enable human composting have become legal in some parts of the United States in recent years[54]; future technologies may allow such practices to take place on planetary surfaces and yield compost material for surface plant growth or similar applications. Alkaline hydrolysis technologies use heated and pressurized alkaline solutions to rapidly dissolve biological tissues, yielding a sterilized effluent and a small volume of brittle calcified remains that can be returned, similar to cremation ashes, to families.[26,48] However, even terrestrially, these practices have met moral, cultural, and religious opposition[26]; these factors would need to be considered if such options were to be implemented in spaceflight. Regardless, these technologies are unavailable in near-term space operations.

In addition to disposition of remains, future missions and vehicle platforms must consider decedent management and support operations to ensure streamlined, cogent processes for management of a crewmember fatality. For example, missions in which multiple vehicles will be used (such as the Artemis Program, which intends to make use of a crew transit vehicle for transport to lunar orbit, a lunar space station, and a surface landing vehicle, with integration of vehicular architecture from both governmental and commercial providers),[40] all vehicles must coordinate compatibility of forensic samples and containment protocols across platforms. Chain of custody protocols should be established to ensure appropriate forensics handling across vehicles and after return to Earth.[58] Supplies for medical and forensic kits and sample preservation capabilities should be streamlined across platforms, and crew protocols should be specific to vehicle architecture and crew needs for a given reference mission. Feasibility of disposition options should take into consideration multivehicle mission architecture and compatibility of HRCUs or other equipment (for example, refrigeration) with each vehicle that may be affected or incorporated into a disposition strategy.[29] Similarly, limitations of resources or environmental constraints should be considered when determining the feasibility of any final disposition plan.

As always, incorporation of medical and psychological support capabilities better positions such resources to be used by crew should the need arise. This may be particularly complex when commercial providers are integrated with government-run mission architecture; development of a streamlined means of ensuring crewmember and ground support team psychological support may be instrumental in ensuring the resiliency of the workforce in the case of catastrophe. Early planning and implementation of decedent management protocols, manifestation of necessary equipment, and incorporation of support architecture during vehicle and mission design stages will best protect for a smooth and coordinated approach to management of an on-orbit fatality, minimizing physical risk and psychological trauma to surviving crewmembers and support teams while ensuring dignity and respect for the decedent.

Decades of in-flight incidents and close calls demonstrate the risk of fatal events during spaceflight and the need for contingency plans inclusive of protocols to manage the unexpected. Any loss of a crewmember during a mission will have devastating and widespread impact to the surviving crew, family, and ground support team members, while the physical constraints of microgravity and spaceflight operations limit resources and the feasibility of responses. This effort was intended to provide guidance and pre-establish protocols for use in the case of an on-orbit crewmember fatality. While knowledge gaps and continued areas for improvement were identified, the effort resulted in the on-orbit provision of equipment for decedent remains management and the establishment of operational products intended to assist crew and ground operators in the case of a catastrophic event. While the efforts detailed herein were developed within the constraints of the ISS concept of operations, future platforms may benefit from the procedural validation and product verifications steps described. Ultimately, any response to spaceflight fatality must preserve the goal of handling decedent remains and disposition with dignity, honor, and respect. This project lays the groundwork for current programs to prepare for such an event while enabling future platforms to adopt and expand upon these concepts for exploration missions.

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