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NASA Exploration Systems Maintainability Standards for Artemis and Beyond

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Acknowledgments

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NASA Engineering and Safety Center
Technical Assessment Report

NASA Exploration Systems Maintainability Standards for Artemis and Beyond

TI-22-01739

Azita Valinia, NESC Lead
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June 29, 2023

Report Approval and Revision History

NOTE: This document was approved at the June 29, 2023, NRB.

Approved: TIMMY WILSON Digitally signed by TIMMY WILSON Date: 2023.07.28 10:49:54 -04'00'

NESC Director

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Azita Valinia, NESC Chief Scientist, GSFC	06/29/2023

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Technical Assessment Report

1.0 Notification and Authorization

This assessment was requested by the NASA Engineering and Safety Center (NESC), which, based on findings from the NESC study "Safe Human Expeditions Beyond Low Earth Orbit (LEO)" (Valinia et al., 2022), determined its topic to be an underrecognized critical and urgent Agency need, due to impending Artemis vehicle procurements. The principal objective of this assessment was to review and update current Agency-level maintainability requirements for space systems to support crew on expeditions beyond LEO in both preventive and corrective maintenance. The key stakeholders and co-sponsors for this assessment are the Office of the Chief Health and Medical Officer (OCHMO) and the Office of Safety and Mission Assurance (OSMA).

Request submitted	March 8, 2022
Approval to Proceed	March 24, 2022
Assessment Plan Approval	April 21, 2022 ~ May 31, 2022
Final Report Delivery	March 31, 2023 ~ April 4, 2023

2.0 Signatures

Submitted by: NESC Lead

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Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team Members

Name	Discipline	Organization	* New to NESC Assessments
Core Team			
Azita Valinia	NESC Lead	GSFC	
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3.1 Acknowledgements

The assessment team is grateful to the subject matter experts (SMEs) whom we interviewed for valuable input, ideas, and helpful discussions and the SMEs who reviewed and provided feedback to our proposed candidate standards. The assessment team would also like to thank the following report peer reviewers for their valuable comments and input: Eric Choate, Steven Gentz, Dexter Johnson, Heather Koehler, and Michael Squire.

4.0 Executive Summary

Maintainability is a quality that reflects the speed and ease with which an operational system can be retained in, or restored to, a specified condition (Department of Defense (DoD), 1997). Throughout much of NASA's history of human spaceflight, maintenance was performed by trained mechanics at depot facilities on the ground after vehicles returned from missions. The launch of the International Space Station (ISS) and its need for continued operation brought space vehicle maintenance into a new era of in-mission maintenance using orbital replacement units (ORUs) by astronauts under the instruction and supervision of flight controllers at mission control. However, as amply illustrated in the NASA Engineering and Safety Center (NESC) study "Safe Human Expeditions Beyond Low Earth Orbit (LEO)" (Valinia et al., 2022), attempting to use the paradigm exemplified by ISS operations with the communication and resupply delays anticipated for missions beyond LEO will pose great risks for crew health and safety. This 2022 study concluded that advanced maintainability standards and sparing approaches to support preventive and corrective maintenance are crucial research and technology development initiatives. Independently, NASA's Moon-to-Mars objectives released in September 2022 (NASA, 2022) identify maintainability, along with reuse, as one of nine recurring tenets across 63 objectives spanning multidisciplinary science, lunar and Martian infrastructure, transportation and habitation, and operations that will serve as guideposts in the Agency's exploration approach and help shape future investments (Warner and Russell, 2022).

The principal objective of this assessment was to review and update current Agency-level maintainability standards. Developed primarily with consideration of LEO mission parameters, these standards must now also address challenges specific to expeditions beyond LEO (e.g., limited and delayed communication, limited to no resupply opportunities, extreme environments) for future space systems. Specifically, the task focused on updating maintainability-related standards in NASA Space Flight Human System Standard Volume 2: Human Factors, Habitability, and Environmental Health (NASA-STD-3001 Volume 2 Revision C) (Office of the Chief Health and Medical Officer (OCHMO), NASA Headquarters, 2022), and NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems (NASA-STD-8729.1A) (Office of Safety and Mission Assurance, NASA Headquarters, 2017). For NASA-STD-3001 Volume 2 Revision C, the goal was to review and update relevant human-systems requirements on the space systems design to support a crew's capability to conduct maintenance safely, effectively, and efficiently. For NASA-STD-8729.1A, the goal was to develop a notional objectives and related strategies goal structuring notation (GSN) hierarchy to be used in planning, executing, evaluating, and ensuring systems with acceptable maintainability and operational availability throughout their intended lifetime. An additional goal of this task was to begin outlining and populating content for a guidebook to help provide additional information and guidance on the process of designing systems for maintainability.

To identify potential gaps in NASA-STD-3001 Volume 2 Revision C and NASA-STD-8729.1A related to maintainability, the NESC assessment team reviewed past and current maintainability related standards from within NASA, other government agencies (DoD, the Federal Aviation Administration (FAA), and the U.S. Nuclear Regulatory Commission Regulation (NUREG)), and industry (Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE)). The NESC assessment team also consulted a wide range of sources, including NASA reports and guidebooks, maintainability/maintenance lessons learned from past space missions, crew comments, and books and papers on maintainability and maintenance. Interviews with 50 subject matter experts (SMEs) from NASA, DoD, and industry informed the NESC team's understanding about current NASA maintenance practice and challenges, maintenance-related incidents on prior NASA missions, latest trends in designing for maintainability and conducting maintenance, and the demands of performing maintenance in extreme environments with a small and isolated/remotely operating team.

From the resulting collection of more than 1500 maintainability-related requirements[1] and over 700 additional findings[2], the NESC assessment team down-selected and deliberated on 58 candidates. This process yielded a final set of 22 candidates, with the rest going into a "parking lot" for later review. The final set was then sent out to NASA SMEs (NESC and others) for comments. A revised final set of 24 candidates (18 new candidates and 6 revisions to NASA-STD-3001 Volume 2 Revision C) was delivered to OCHMO for consideration to be included in the next standard revision. Lastly, the NESC assessment team revisited the remaining candidates in the parking lot, classifying each as either a candidate to be incorporated into NASA-STD-8729.1A, a candidate to be included in a to-be-determined engineering standard document, and/or a candidate for the guidebook[3]. The NESC assessment team also drafted preliminary content for the guidebook if this option were to be pursued by another entity.

The report that follows provides a detailed description of the study approach. Then the state of practice of maintainability and maintenance across industry, government organizations (e.g., DoD, FAA, NUREG), and NASA that was assessed through interviews, literature reviews, etc. is summarized. The 18 NASA-STD-3001 Volume 2 Revision C candidate requirements are then shown as recommendations where each recommendation is supported by the findings that reflect the requirement's rationale. Recommendations are also made to close gaps identified in NASA-STD-8729.1A and in NASA's overall maintainability approach and guidance.

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[1] Visit https://airtable.com/shrV3Y64TIrqDitBD and https://airtable.com/shrrhVWkVqRgoyV4A for a complete list of the 1500+ maintainability-related requirements.

[2] Visit https://airtable.com/shrkruiNsqqHldxNK for a complete list of findings from SME interviews, maintainability books, and other industry publications.

[3] Visit https://airtable.com/shrgtQ6feReMIyuxH and select a desired view from the left to view guidebook, NASA-STD-8729.1A, and engineering candidates.

5.0 Approach

Table 5.0-1 summarizes the overall process of collecting and processing potential standard candidates. The first step taken by the NESC assessment team was to compile a collection of candidate requirements suitable for NASA-STD-3001 Volume 2 or NASA-STD-8729.1A. In addition to mining past and current maintainability related standards from within NASA, other government agencies (DoD, FAA, NUREG), and industry (IEEE, SAE), the NESC assessment team consulted a wide range of sources (NASA reports and guidebooks, maintainability/ maintenance lessons learned from past space missions, crew comments, books and papers on maintainability and maintenance in general) (see Appendix A for a list of source materials consulted). The NESC assessment team also interviewed 50 SMEs from NASA, DoD, and industry to understand current NASA maintenance practice and challenges, maintenance-related incidents on prior NASA missions, latest trends in designing for maintainability and conducting maintenance, and performing maintenance in extreme environments by a small team (see Appendix B for a list of SMEs consulted).

Table 5.0-1. Summary of Overall Process of Collecting and Processing Potential Standard Candidates

PROCESS	Standards Review	Interviews + Operations Artifacts	Literature Review
Gathering	1500+ standards reviewed	Interviews with 50 participants across NASA and analogous domains; observed crew debriefs	Books, research papers, etc.
Parsing	Identified key sources; narrowed down set by identifying duplicate standards	Organized findings by lessons learned, challenges, solutions, principles, etc.; focused literature review on reliability-centered maintenance (RCM) key sources	
Tagging	Tagged standards by key themes; compared tables of contents	Tagged findings by key themes	
Cross-comparison	Compared key themes across sources; integrated findings into one dataset; analyzed common findings; combined duplicate standards; conducted crosswalk of NASA-STD-3001 Volume 2 Revision C and duplicates; analyzed the evolution of this standard and the NASA Human Integration Design Handbook (HIDH); analyzed NASA-STD-8729.1A current maintainability objectives hierarchy		
Standards development	Developed maintenance framework; categorized standards by maintenance objectives; conducted voting exercise to consolidate list with a focus on challenges specific to Lunar missions and beyond		

The aforementioned efforts resulted in a collection of more than 1500 maintainability-related requirements[4] and over 700 additional findings[5], from which 172 were selected as potential candidates for NASA-STD-3001 Volume 2 Revision C and NASA-STD-8729.1A based on these criteria:

- Applicability to spaceflight (environment, tasks, personnel)
- Applicability to missions beyond LEO
- Reputability of source (trusted government and industry leaders)
- Preponderance across standards (i.e., is the requirement or finding important in multiple domains)
- Specificity and verifiability of the requirement or finding

The NESC assessment team identified and deliberated on the top 58 voted candidates. This process, based heavily on engineering judgment and spaceflight program experience, yielded a final set of 22 candidates, with the rest going into a "parking lot" for later review. The 22 were further refined through a series of revisions and compromises to develop the final set that was then sent to NASA SMEs (NESC and others) for review. Of the 75 SMEs whose comments were solicited, 21 responded, yielding a total of 155 inputs. The 21 respondents represented seven NASA centers (Langley Research Center, Marshall Space Flight Center, Johnson Space Center, Goddard Space Flight Center, Kennedy Space Center, Glenn Research Center, and Headquarters), with the majority of respondents (seven) from Langley. The NESC assessment team dispositioned these inputs and made further revisions to the wording and/or content of the candidates. A revised final set of 24 candidates (18 new candidates and 6 revisions to NASA-STD-3001 Volume 2 Revision C) was delivered to OCHMO for consideration to be included in revision D of NASA-STD-3001 Volume 2. (These have since been reviewed again in March 2023 as part of the Agency-wide technical review of NASA-STD-3001 Volume 2 Revision D).

Lastly, the NESC assessment team revisited the remaining candidates in the parking lot, classifying each as a candidate to be incorporated into NASA-STD-8729.1A, a candidate to be included in a to-be-determined engineering standard document, and/or a candidate for the guidebook[6]. The NESC assessment team also drafted preliminary content for the guidebook (see Appendix F).

6.0 Maintainability and Maintenance State of Practice

6.1 Industry/DoD/NASA Maintenance and Maintainability Approaches

The NESC assessment team conducted interviews with 50 maintenance SMEs from government agencies and companies across domains including defense, aviation, energy, automotive, and space, including NASA personnel with operational experience on the Space Shuttle Program (SSP), ISS Program, and Artemis missions. Concurrently, a literature review was conducted of industry approaches to maintenance and maintainability. Figure 6.1-1 is a notional map of the

[4] Visit https://airtable.com/shrV3Y64TIrqDitBD and https://airtable.com/shrrhVWkVqRgoyV4A for a complete list of the 1500+ maintainability related requirements.

[5] Visit https://airtable.com/shrkruiNsqqHldxNK for a complete list of findings from SME interviews, maintainability books, and other industry publications.

[6] Visit https://airtable.com/shrgtQ6feReMIyuxH and select a desired view from the left to view guidebook, NASA-STD-8729.1A, and engineering candidates.

domains the NESC assessment team investigated by mission factors, including mission duration, resupply, and communication delay with support teams.

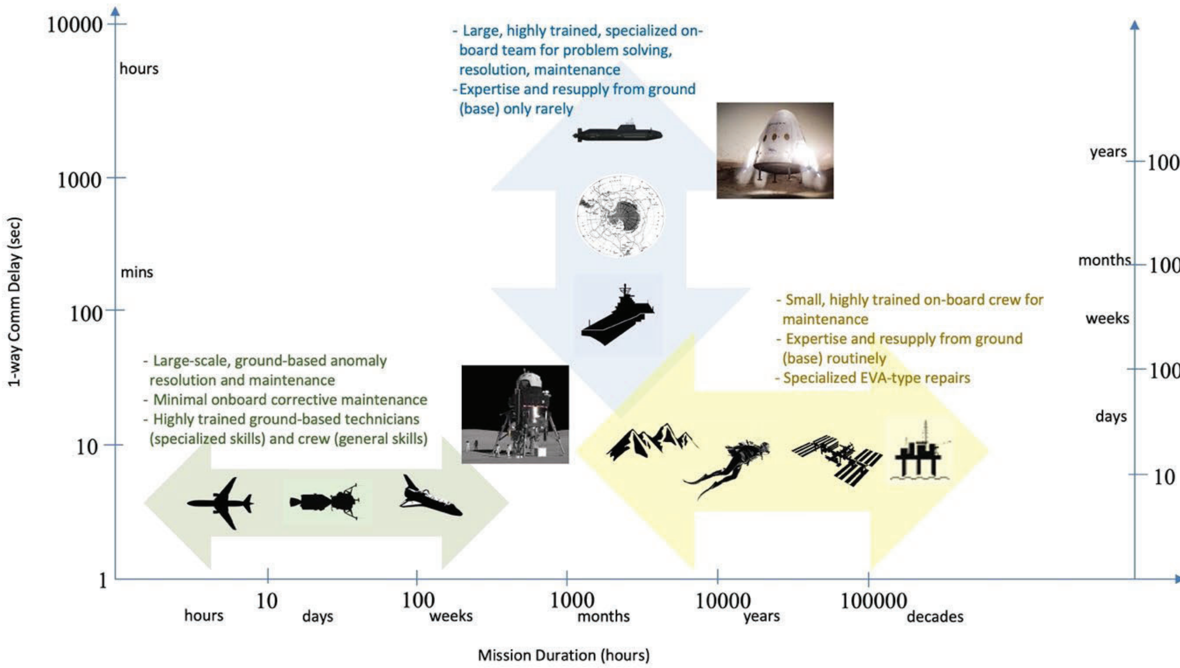

Figure 6.1-1. Expedition Experience across Domains (notional)

This analysis illustrates that in analogous domains, supportability is often dependent on mitigations that are unavailable beyond LEO (e.g., large crew size, ground-based maintenance, large reserves of supplies) (Table 6.1-1).

Table 6.1-1. Maintenance Approaches

Domains	SSP Apollo Lunar Surface Operations Joby Aviation	McMurdo Station South Pole Expedition Aircraft Carrier Submarine (Los Angeles Class)	NASA Extreme Environment Mission Operations (NEEMO) North Sea Oil Rig ISS Crew Comments ISS Urine Processor Assembly Next Gen ISS Environmental Control and Life Support System (ECLSS) ISS Operations Support Officer (OSO)
Maintenance model	Large-scale, ground-based anomaly resolution and maintenance	Large, highly trained, specialized onboard team for problem solving, resolution, maintenance Expertise and resupply	Small, highly trained onboard crew for maintenance

	Minimal onboard corrective maintenance Highly trained ground-based technicians (specialized skills) and crew (general skills)	from ground (base) only rarely	Expertise and resupply from ground (base) routinely Specialized extravehicular activity (EVA)-type repairs

6.2 Lessons Learned from ISS Operations

Sustaining systems not originally designed to be maintained onboard is a challenge.

Reliability data are often limited for complex systems in extreme environments. For ISS systems in particular, mean time between failure estimates can have large uncertainties and inaccuracies (Bertels, 2006). Some of these systems sometimes require unanticipated maintenance tasks that were never intended to be performed onboard. Crewmembers and system engineers reported challenges maintaining systems not originally designed to be maintained. A common problem is accessibility, especially at the sub-ORU level. Another challenge is a lack of diagnostics leading to ambiguous failures that may require a trial-and-error approach of replacing several components before determining where the failure had occurred.

Hands-on training with flight hardware (or high-fidelity mock-up) is helpful.

Crewmembers and trainers report that high-fidelity mockups help prepare crewmembers for working with complex systems or unfamiliar tasks. Such mock-ups provide hands-on experience with intricate system deconstruction/construction, increased awareness of spatial orientation and component location, and practice to improve task execution.

Visual aids can improve task efficiency and situation awareness.

When crewmembers work complex procedures, they may spend a considerable amount of time preparing (e.g., identifying parts, collecting resources, reviewing schematics) before starting unless they are already familiar with the system and task. Similarly, time may be spent at the end of the procedure on the "puzzle" of putting things back together again. Crew comments emphasized the need for robust visual aids that help identify the correct components and where they go.

6.3 Lessons Learned from Industry Survey

Not all failures can be prevented by maintenance.

Resilient systems are not necessarily failure-proof; rather, their failures are tolerable. In the human spaceflight environment, this means critical failures must be recovered in time for the vehicle and crew to survive. Good maintenance plans and programs accept some level of failure and are prepared to deal with degraded performance (Hupje, 2020). The RCM strategy advocates for selecting maintenance tasks based on desired outcomes (i.e., availability of systems) and the consequences of a given failure (Mowbray, 1997).

Plan maintainability into the design from the start.

History has shown that if appropriate attention and emphasis are not placed on supportability concerns and issues, particularly early in a program, the potential impacts can be significant.

Such impacts can be programmatic, e.g., schedule slips due to longer-than-expected turn-around times, or technical, e.g., degraded system effectiveness, and some may ultimately result in loss of mission or loss of life (Do et al., 2019). As illustrated by ISS and SSP missions, it is difficult and costly to "add in" maintainability late in the process. Many of the SMEs interviewed across different industries advocated for having a maintenance plan early in the system design process that identifies the maintenance-significant items and outlines how they will be maintained. There are numerous examples where design for maintainability has improved programmatic or technical performance (e.g., Heisey, 2002; United States General Accounting Office, 2003; and Sullivan, 2020).

Design to minimize human error in maintenance.

Some level of human error is inevitable. While individual human errors cannot be predicted, estimates of error rates can provide a general awareness of the level of risk introduced by human error (Hobbs, 2021). Some common factors that contribute to human error in maintenance include time pressure, interruptions, fatigue, inadequate design, and poor communication. The invasive nature of many maintenance tasks also tends to promote human error (Hobbs, 2021). In his book, "Reliability-Centered Maintenance," Mowbray (1997) states that many preventive maintenance tasks achieve nothing, while some are actively counterproductive and even dangerous. For this reason, some SMEs advocate for replacing interval-based maintenance schedules with condition-monitoring-based maintenance triggers (Gullo & Dixon, 2021; Hupje, 2020).

6.4 Status of NASA-STD-3001 Volume 2 Standards Implementation

An assessment of the implementation of standards in NASA-STD-3001 Volume 2 by the Artemis Program was made using data found in the Systems Platform for Aggregating and Relating Capabilities (SPARC) tool (https://sparc.ndc.nasa.gov/). Program requirements for the Human Landing System (HLS) and Multi-Purpose Crew Vehicle (i.e., Orion) Programs, and Exploration Extravehicular Activity Services (xEVAS) were available in SPARC at the time of the analysis. HLS and Exploration Extravehicular Activity (xEVA) requirements were traced to NASA-STD-3001 Volume 2 Revision B, while Orion requirements were traced to NASA-STD-3001 Volume 2 Revision A.

The analysis found that NASA-STD-3001 Volume 2 was well represented in HLS and Orion Program requirements. HLS levied 83% of the requirements in NASA-STD-3001 Volume 2 Revision B (a requirement was considered levied if at least one program requirement traced to it). Orion levied 90% of NASA-STD-3001 Volume 2 Revision A. Whereas, xEVA imposed 12% of the NASA-STD-3001 Volume 2 Revision B requirements.

In the process of levying requirements at the program level, some requirements were converted to "should" from "shall" statements, reducing them from requirements a program must meet to goals a program attempts to achieve. Specifically, NASA-STD-3001 Volume 2 Revisions A and B contain only "shall" statements, but HLS and Orion traced "should" statements to NASA-STD-3001 Volume 2. 44% of the HLS statements and 12% of the Orion statements traced to NASA-STD-3001 Volume 2 in SPARC were "should" statements.

These trends continued in NASA-STD-3001 Volume 2 Section 9.7, Design for Maintainability. All maintainability requirements in NASA-STD-3001 Volume 2 Revisions B and A were levied in HLS and Orion, respectively; xEVA imposed 7 of the 17 maintainability requirements in

NASA-STD-3001 Volume 2 Revision B. The HLS Program requirements traced to Section 9.7 contained 5 “shall” statements and 12 “should” statements. Orion Program requirements traced to Section 9.7 contained 14 “shall” statements and 6 “should” statements. All traced xEVA requirements were “shall” statements.

6.5 Status of NASA-STD-8729.1A Reliability and Maintainability Standards

NASA-STD-8729.1A describes the technical basis for promoting and implementing R&M concepts on new NASA programs and projects. OSMA, in tracking the application of this standard, has noted that it could provide additional assistance to traditional mission execution with enhanced implementation, streamlining, and process-improvement guidance. It also notes that as missions become longer and require more sustainable/serviceable operations and systems (e.g., flight, support, infrastructure, or remote instantiations), NASA technical standards must evolve to maintain a high level of technical excellence in achieving all programs and project goals. Thus, OSMA is in the process of updating NASA-STD-8729.1A and is targeting fiscal year 2024 for revalidation and update activities.

7.0 Results

The approach described above resulted in a revised final set of 24 candidates (Appendix D – 18 new candidates and 6 revisions to NASA-STD-3001 Volume 2 Revision C) delivered to OCHMO for consideration to be included in the next standard revision.

In addition, the NESC assessment team revisited the remaining candidates in the parking lot to identify candidates for inclusion in NASA-STD-8729.1A[7]. This process identified the need to revise the objectives structure within that standard to be more inclusive of human and robotic system needs for missions in and beyond LEO, with expected serviceable operational concepts. As a result, a notional revised objectives hierarchy for maintainability has been generated by the NESC assessment team and delivered to OSMA (see Appendix E) along with the candidates for final standard revision generation.

Lastly, candidates were identified for potential inclusion in a to-be-determined engineering and/or a cross-domain (e.g., engineering, Safety and Mission Assurance (S&MA)) standard. The NESC assessment team also drafted a preliminary annotated table of contents for the guidebook (see Appendix F). Much of the information collected in this assessment has been added to the contents of the guidebook for future consideration. While it is outside the scope of this task to produce a NASA handbook, it is hoped that this initial draft can be used as the basis for future work toward such a product. Figure 7.0-1 shows a flow chart of requirements disposition.

[7] Visit https://airtable.com/shrgtQ6feReMIyuxH and select a desired view from the left to view guidebook, NASA-STD-8729.1A, and engineering candidates.

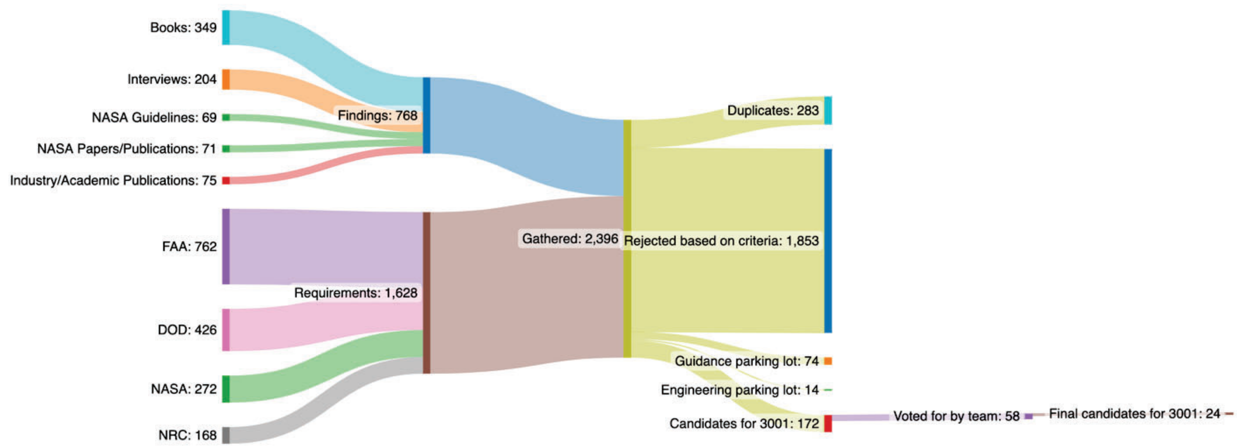

Figure 7.0-1. Flow Chart of Requirements Disposition

8.0 Findings, Observations, and NESC Recommendations

8.1 Candidates for NASA-STD-3001 Volume 2

The following findings, observations, and NESC recommendations are summarized under organizations used in the proposed D revision of NASA-STD- 3001 Volume 2.

8.1.1 Housekeeping

8.1.1.1 Dust Removal

F-1. During Apollo missions, dust brought into pressurized environments (lunar modules, command modules) was found to cause irritation to the eyes and lungs of the astronauts, potentially compromising crew health (Gaier, 2005).

R-1. Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable and withstand cleaning using planned cleaning methods.

8.1.2 Training

8.1.2.1 In-Mission Training

F-2. Maintenance skills are subject to degradation as the length of time between crew training and in-mission maintenance increases.

R-2. In-mission training/refreshers, including using tools and test equipment required for maintenance, shall be provided to ensure crew proficiency in performing maintenance activities.

8.1.3 Design for Maintainability

8.1.3.1 General

8.1.3.1.1 Maintenance Concept of Operation

F-3. If proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts to operations can be significant.

R-3. For each maintenance-level item, the human space flight program shall define and document a maintenance concept of operations considering the following factors and updated throughout the design lifecycle:

a. Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity) as specified in the SLS-SPEC-159 Cross Program Design Specification for Natural Environments (DSNE).
b. Tools, aids, and support equipment available to the maintainers in situ.
c. Skill-level of the maintainers (i.e., crewmembers).
d. Access needed to equipment.
e. Reliability- or performance-driven preventive maintenance schedule.
f. Preventive and corrective maintenance plans.

8.1.3.1.2 Availability of Critical Systems

F-4. Mission success is dependent on the availability of the critical systems that keep the crew alive and enable completion of mission objectives. Repair and replacement activities may be time constrained depending on availability requirements. Operational factors, including available onboard resources, crew capabilities, and environmental constraints, affect the design and feasibility of corrective maintenance activities.

R-4. System repairs and/or replacements shall be designed to be completed within the time-to-effect margin and with consideration of operational factors.

8.1.3.1.3 Damage Prevention

F-5. Maintenance activities can lead to increased failures because there is risk to the subject system and proximate systems each time the system is opened or disturbed, especially when systems are not designed for maintainability. Designing the system to the physical capabilities and limitations of the maintainer (e.g., ensuring parts are accessible by hand) prevents damage when proper procedures are followed. Designing systems to contain failure effects, minimize failure propagation, and minimize interaction with proximate systems also reduces the risk of damage during maintenance.

R-5. The system shall be designed to prevent collateral and inherent damage during maintenance.

8.1.3.1.4 In-mission Maintenance

F-6. Crew and vehicle health and the ability to meet mission objectives require that maintenance and check-out activities be achieved with efficiency and accuracy. Design considerations (e.g., tool interfaces) can significantly impact the performance of these activities.

R-6. All flight hardware and software shall be designed to facilitate in-mission maintenance (both preventive and corrective) and check-out.

8.1.3.2 Tools and Test Equipment

8.1.3.2.1 Tool and Test Equipment Commonality

F-7. Tool and test equipment commonality provides redundancy and contributes to crew readiness for unplanned maintenance activities. Interchangeable tools and test equipment improve mass efficiency because common items can cover multiple types of failures.

R-7. Systems and units of equipment shall be designed so that maintenance can be accomplished with the set of in-mission tools and test equipment.

8.1.3.3 Accessibility

8.1.3.3.1 Access Using Available Tools

F-8. Logistical constraints of missions beyond LEO will require maintenance to be performed at an intermediate level as sparing will be limited during extended missions without access to frequent resupply. ISS experience has shown that intermediate level maintenance is problematic if not all parts of the ORU are designed to be accessed or repaired.

R-8. Systems and units of equipment shall be accessible and openable using the on-board tool set.

8.1.3.4 Visibility and Identifiability

8.1.3.4.1 Component Identification

F-9. When beginning a maintenance activity, crewmembers often spend time up-front locating, identifying, and familiarizing themselves with the components. Clear and informative labeling can streamline this process, and help crew properly contextualize the component within the larger system.

R-9. Flight hardware shall include information and labeling that enables the crew to correctly locate, identify, and handle systems components.

8.1.3.4.2 Visual Aids for Maintenance

F-10. Locating and identifying all the components involved in a maintenance procedure can be time consuming, especially when a crewmember is working with an unfamiliar system.

R-10. For maintenance activities, visual aids shall be provided with appropriate scale, orientation, and context to enable crew to locate and identify components and execute the task.

8.1.3.5 Maintenance Data

8.1.3.5.1 Condition Monitoring

F-11. Monitoring is needed to optimize maintenance action plans and improve system availability. Condition monitoring provides maintenance triggers, reducing the need for interval-based maintenance. Condition monitoring reduces the reliance on reliability data to ensure availability, ultimately improving crew safety and efficiency.

R-11. The system shall be designed to provide condition-monitoring data to an information system that can be accessed by the crew, either automatically or by request.

8.1.3.5.2 Maintenance Management Information

F-12. Maintenance management information enables maintainers to make informed decisions about when and how to perform maintenance. Real-time maintenance triggers reduce the reliance on reliability data and eliminate unnecessary preventive-maintenance tasks.

R-12. For preventive maintenance, the following data shall be captured/available to the crew to support autonomous procedure execution:

1. Procedures
2. Visual aids
3. Functional state data (e.g., power, temperature, pressure, standby)
4. Active indication of critical procedure step completion
5. Active indication of restored functionality
6. Replacement unit maintenance history
7. Procedure execution records

In addition, for unexpected, corrective maintenance, the following information shall be available to the crew to support autonomous troubleshooting:

1. Diagnostic sensor data
2. Troubleshooting steps and decision trees
3. Description of possible faults and locations
4. Description of test points and normal reading ranges
5. Test result interpretations and corrective action recommendations

8.1.3.6 Diagnostics and Troubleshooting

8.1.3.6.1 Maintenance Activities

F-13. Designing maintenance tasks based on the capabilities of the "front-line" maintainer (as opposed to the provider) can reduce errors, reduce training time, reduce workload, and decrease task execution time.

R-13. Maintenance activities shall be designed at the skill level of the crewmembers

8.1.3.6.2 Maintenance Decision Aids

F-14. For exploration beyond LEO, intermittent and delayed communication with the ground necessitates greater crew autonomy in managing unanticipated vehicle maintenance. In lieu of continuous ground support simplified diagnostic aids are needed to assist crewmembers in narrowing down possible causes of anomalies and making time-critical decisions in the face of uncertainty.

R-14. For unplanned maintenance activities, decision aids shall be provided to support diagnosis, troubleshooting, and procedure execution at the skill level of the crewmembers.

8.1.3.6.3 Verification and Repair

F-15. Repair activities inherently introduce risk to a system. Verifying a system has returned to proper functionality before returning the system to nominal operations prevents further damage or loss of operability.

R-15. Preventive and corrective maintenance shall include means for verification of successful completion.

8.1.3.7 Environmental Control

8.1.3.7.1 Contamination Prevention

F-16. Planetary surface environments have the potential to disrupt operations on the Moon, Mars, and asteroids. Lessons learned from Apollo lunar surface missions indicate that care must be exercised to minimize dust contaminants during maintenance.

R-16. Maintenance tasks shall be designed to prevent environmental contamination of maintenance items and EVA systems.

8.1.3.7.2 Extreme Environment

F-17. Space environment can present extreme environmental (EE) conditions in pressure, temperature, radiation, and chemical or physical corrosion, as well as acidity and dust. Certain planned mission operations can also induce EE conditions in heat flux and deceleration (g-loading) during entry, descent, and landing (EDL) phases (Balint et al., 2008). Contamination with lunar dust can affect the function of equipment and instrumentation by degrading seals and valves, breaking down lubricants, jamming moving parts, and creating flow blockages (Cain, 2010).

R-17. Equipment, including tools and instruments, that is maintained on the planetary surface shall be designed to meet all performance requirements specified in NASA-STD-5017A Design and Development Requirements for Mechanisms during and after exposure to the expected environmental conditions specified in the SLS-SPEC-159 Cross-Program DSNE.

8.1.3.7.3 Dust Tolerance

F-18. Composition and transport mechanisms may vary, but in general, planetary surface dust can cause thermal management, erosion, binding, and other issues with equipment, as well as affect crew health.

R-18. When designs cannot prevent its intrusion, dust shall not reduce tool and equipment functionality below minimum performance specifications.

8.2 Evolution of NASA-STD-8729.1A Maintainability Objectives Hierarchy

Through the processes described, potential strategy gaps for NASA-STD-8729.1A were identified.

F-19. Potential strategy gaps for NASA-STD-8729.1A include:

- Understanding the design's and monitoring plan's ability to forecast and trigger maintenance actions when needed based on performance (locally and across NASA).
- Ensuring that the system's maintenance (preventive and on-demand) does not prevent it from meeting its mission objectives.
- Ensuring that the system's maintenance (preventive and on-demand) can be accomplished with tools, instrumentation, facilities, time, costs, and operators (human or robotic) available during the mission.

These considerations were decomposed to explore their incorporation in the NASA-STD-8729.1A's GSN hierarchy, and as a result, a notional revision has been generated and is shown in Appendix E. The proposed GSN hierarchy replaces the current goal 4 and objective 4.A with a more encompassing goal and four expanded objectives and decomposes that hierarchy into six additional second-level objectives and eighteen third-level strategies. These and the additional NESC recommendations resulting from gap identification will be refined as part of a NASA-STD-8729.1A revision by OSMA to enhance R&M Analysis Methods and Activities guidance in the standard.

R-19. The maintenance concept of operations should include safety and operational constraint information and tradeoffs.

R-20. Maintenance plans should consider that intravehicular maintenance is safer for the crew than extravehicular maintenance.

R-21. The system should be designed to be evacuated and isolated, electrically and functionally, following failure and during maintenance.

R-22. The system should contain failure effects to the extent possible to minimize propagation.

R-23. The system functionality and its interface equipment should be protected from damage during maintenance subsequent testing.

R-24. System design should provide flexibility to allow future design modifications, reconfigurations, or upgrades.

R-25. Flight software should be capable of update and verification in situ and from the ground.

8.3 Overarching Standards

O-1. After distributing candidate requirements to appropriate, existing human systems and S&MA standards, there are remaining requirements (i.e., engineering and/or architecture-level requirements) that have no "home." Architecture-level requirements for supportability/maintainability are particularly important as they establish the conditions and constraints for how maintenance will be performed (e.g., at the ORU level or below) and supported (e.g., resupply opportunities). For example, such program-level considerations may include: the allocation of maintenance activities among intravehicular activity (IVA), EVA, and/or autonomous operations (e.g., robots); how to plan for part commonality and reuse; and how to allocate resources for in situ manufacturing.

R-26. Develop an overarching integrated standards framework to establish architecture-level supportability/maintainability approaches and requirements (with rationale) beginning early in formulation and planning.

R-27. Integrate or consolidate R&M requirements into one design and development standard to the extent feasible.

8.4 Standards Implementation

O-2. Although Artemis Program elements levied NASA-STD-3001 Volume 2 Revisions A and B requirements, many were tailored from "shall" requirements to "should" goal statements. Tailoring is necessary in some cases; reducing the level of specification can improve programmatic viability and promote innovation. However, it also has the potential to weaken the influence of requirements on system designs and developments, which is of particular concern with regard to maintainability: maintainability, as a nonfunctional or quality requirement, is often not a primary design consideration and may be left too late in the design cycle to be addressed fully.

R-28. Establish a critical, minimum set of maintainability requirements to ensure maintainability is an early and necessary design consideration. For example, see R-3, R-4, and R-5 above.

R-29. Create entrance and exit criteria for R&M planning and approach as part of the Mission/project formulation phase (e.g., Preliminary Design Review).

9.0 Acronyms and Nomenclature List

DoD	Department of Defense
DRM	Design Reference Mission
DSNE	Design Specification for Natural Environments
ECLSS	Environmental Control and Life Support System
EDL	Entry, Descent, and Landing
EE	Extreme Environmental
EVA	Extravehicular Activity
FAA	Federal Aviation Administration
GSN	Goal Structuring Notation
HIDH	Human Integration Design Handbook
HLS	Human Landing Systems
IEEE	Institute of Electrical and Electronics Engineers
ISS	International Space Station
IVA	Intravehicular Activity
LEO	Low Earth Orbit
NEEMO	NASA Extreme Environment Mission Operations
NESC	NASA Engineering and Safety Center
NUREG	U.S. Nuclear Regulatory Commission Regulation
OCHMO	Office of the Chief Health and Medical Officer
ORU	Orbital Replacement Unit
OSMA	Office of Safety and Mission Assurance
OSO	Operations Support Officer
R&M	Reliability and Maintainability
RCM	Reliability-Centered Maintenance
S&MA	Safety and Mission Assurance
SAE	Society of Automotive Engineers
SME	Subject Matter Experts
SPARC	Systems Platform for Aggregating and Relating Capabilities
SSP	Space Shuttle Program
xEVA	Exploration Extravehicular Activity
xEVAS	Exploration Extravehicular Activity Services

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Appendix B. List of Subject Matter Experts Consulted

Domain	Organization	Discipline	Date of Interview	SME
Automotive	Ford	R&M / Systems Engineering	9/14/2022	James Fowler
			9/14/2022	Ben Mouawad
			9/14/2022	Scott Tate
			9/14/2022	David Friske
Aviation	DoD	R&M / Systems Engineering	5/10/2022	Aaron Pearlman
			5/10/2022	Michael Crowe
			5/10/2022	Karen Bain
			5/10/2022	John Govan
	Joby	R&M / Systems Engineering	6/9/2022	Matthew Lykins
Coal Mining		Coal Mining	2021 student project	Edward Holling
			2021 student project	Joe Thomas
Oil & Gas	Havfram (Ocean Installer)	Maintenance	4/14/2022	Frank Pinder
	Dow Oil & Gas	Maintenance	7/22/2022	Jason Sturgis
Space	NASA	Artemis Planning / Ops	8/12/2022	Michael Doll
			8/12/2022	Sean Duval
			8/12/2022	Jason Kish
			7/12/2022	Holly Cagle
			4/5/2022	Bill Othon
		Human Factors	4/26/2022	Susan Schuh
			4/13/2022	Charlie Dischinger
			4/7/2022	Alan Hobbs
			4/7/2022	Cynthia Null
		ISS Operations / Flight Control	2/8/2023	Kristopher Field
			2/8/2023	Corey Heath
			2/8/2023	Victor Badillo
			8/5/2022	Mark Stovall
			8/5/2022	Amanda Premer
			4/19/2022	Michael Salopek
		NASA Analogs	6/10/2022	Marc Reagan
			5/27/2022	Gerd Fischer
		R&M / Systems Engineering	7/19/2022	Jason Dake
			7/8/2022	David Howard
			6/3/2022	Tim Adams
			5/20/2022	Dave Shemwell
			5/20/2022	Dr. Mike Watson

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<tr><td rowspan="14"></td><td rowspan="11"></td><td rowspan="5"></td><td>5/17/2022</td><td>Bob Ford</td></tr>
<tr><td>5/17/2022</td><td>Bo Bejmuk</td></tr>
<tr><td>5/10/2022</td><td>Kyle Grello</td></tr>
<tr><td>4/29/2022</td><td>James Hill</td></tr>
<tr><td>4/29/2022</td><td>Arthur Brown</td></tr>
<tr><td rowspan="4">Safety / Engineering Standards</td><td>3/3/2023</td><td>Steve Hirshorn</td></tr>
<tr><td>3/3/2023</td><td>Diana Acosta</td></tr>
<tr><td>4/1/2022</td><td>Van Keeping</td></tr>
<tr><td>3/17/2022</td><td>Anthony Diventi</td></tr>
<tr><td rowspan="2">Supportability</td><td>4/26/2022</td><td>Andrew Owens</td></tr>
<tr><td>4/26/2022</td><td>William Cirillo</td></tr>
<tr><td rowspan="2">Apollo Lunar Surface Journal</td><td rowspan="2">Apollo missions</td><td>4/27/2022</td><td>Ulli Lotzmann</td></tr>
<tr><td>4/27/2022</td><td>Ken Glover</td></tr>
<tr><td>Collins Aerospace</td><td>R&M / Systems Engineering</td><td>5/13/2022</td><td>Jake Rohrig</td></tr>
<tr><td>Submarines</td><td>DoD</td><td>Maintenance</td><td>4/5/2022</td><td>Rhys Orpe</td></tr>
</table>

Appendix C. Candidate Revision Form Results

C.1 Candidate Revision - 3001 No 01 - Damage Prevention

Before

The system shall be designed to prevent collateral and inherent damage during maintenance.

[Rationale: Maintenance activities can lead to increased failures because there is risk each time the system is opened or disturbed, especially when systems are not designed for maintainability due to inaccurate reliability estimates. Designing the system to the physical capabilities and limitations of the maintainer (e.g., ensuring parts are accessible by hand) prevents damage when proper procedures are followed. Systems designed to contain failure effects, minimize failure propagation, and minimize interaction with collateral systems also reduce the risk of damage during maintenance.]

After

The system shall be designed to prevent collateral and inherent damage during maintenance.

[Rationale: Maintenance activities can lead to increased failures because there is risk to the subject system and proximate systems each time the system is opened or disturbed, especially when systems are not designed for maintainability. Designing the system to the physical capabilities and limitations of the maintainer prevents damage when proper procedures are followed. Designing systems to contain failure effects, minimize failure propagation, and minimize interaction with proximate systems also reduces the risk of damage during maintenance. Designs and maintenance strategies should be analyzed (e.g., failure/process analysis) for feasibility and risk prior to incorporation.]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Rationale should remove mention of inaccurate reliability estimates (Reviewer 1)
- ☐ Rationale should include design constraints (in addition to inaccurate reliability estimates) as factor that increases risk of damage (Reviewer 2)
- ☐ Rationale should mention collateral damage (Reviewer 2)
- ☐ Requirement is not verifiable (Reviewer 3)
- ☐ Requirement does not belong in 3001 (Reviewer 4)
- ☐ Requirement is not feasible – not all systems and components can be designed this way (Reviewer 5)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
The system shall be designed to prevent collateral and inherent damage during maintenance.

Rationale: Maintenance activities can lead to increased failures because there is risk each time the system is opened or disturbed~~, especially when systems are not designed for maintainability due to inaccurate reliability estimates~~. Designing the system to the physical capabilities and limitations of the maintainer (e.g., ensuring parts are accessible by hand) prevents damage when proper procedures are followed. Systems designed to contain failure effects, minimize failure propagation, and minimize interaction with collateral systems also reduce the risk of damage during maintenance.

Rationale for Change/Comments
Eliminate the "especially when systems are not designed for maintainability due to inaccurate reliability estimates." This reads like the requirement is already blaming someone for inaccuracy and the requirement is just a shall statement w/o judgement. The rationale just should just explain the objective fact that systems are at increased risk of failure each time it's opened for maintenance.

Response
Removed "due to inaccurate reliability estimates" to remove judgment statement. Left "especially when systems are not designed for maintainability" because evidence from our information gathering phase strongly suggests that failing to plan for maintainability from the start of the design process can be a contributing factor to later damage.

Reviewer 2 Patrick Simpkins (Consultant)

Proposed Text
The system shall be designed to prevent collateral and inherent damage during maintenance.

Rationale: Maintenance activities can lead to increased failures because there is risk to the subject system and collateral systems each time the area is opened or disturbed, especially when systems are not designed for maintainability due to design constraints and/or inaccurate reliability estimates Designing the system to the physical capabilities and limitations of the maintainer (e.g., ensuring parts are accessible by hand) prevents damage when proper procedures are followed. Systems designed to contain failure effects, minimize failure propagation, and minimize interaction with collateral systems also reduce the risk of damage during maintenance.

Rationale for Change/Comments
Requirement points to "collateral" damage so rationale should address more than the specific system subject to the maintenance activity. In addition, systems may not be designed for maintainability due to more than just inaccurate reliability estimates.

Response
Removed "due to inaccurate reliability estimates" as suggested.

Added risk "to the subject system and proximate systems" to rationale to address comment that rationale should address more than the specific system subject to maintenance.

Reviewer 3 James O'Donnell (NESC Integration Office)

Proposed Text
N/A

Rationale for Change/Comments
"The system shall be designed to prevent collateral and inherent damage during maintenance." I understand the rationale for this and it makes a lot of sense as a design principle, but it strikes me as a requirement that would be very difficult to verify, as stated.

Response
Ability to verify to be assessed by 3001 standards team.

Reviewer 4 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text
N/A

Rationale for Change/Comments
I'm not sure how this fits into an OCHMO standard? This is a standard about not damaging hardware. It doesn't seem to have any relevance to the human – which I thought was the intent of the 3001 standard. I don't think it fits in 3001.

Response
Applicability to be assessed by 3001 standard team.

Reviewer 5 Melina Naderi

Proposed Text
N/A

Rationale for Change/Comments
To design the entire system to prevent collateral and inherent damage during maintenance is not feasible. Especially in regards to access - not every component can be accessible and still make good use of volume in the vehicle design.

It is much more reasonable and attainable to assign specific maintenance reqts on the entire system - requirements such as connector keying/connector mismating, incorrect mounting, labeling and interchangeability requirements. These are sound requirements for the hardware regardless and guard against assembly errors. Using the maintenance item (LRU) list to establish the application of the complete and most stringent maintenance requirements is optimal.

Response
No change needed.

Agree. Expected that specific programs will determine the applicability of this standard and tailor standards to meet program.

C.2 Candidate Revision - 3001 No 02 - Maintenance ConOps

Before

For each maintenance level item*, the human space flight program shall define and document a maintenance concept of operations considering the following factors and updated throughout the design lifecycle:

a. Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity).
b. Tools and support equipment available to the maintainers in-situ.
c. Skill-level of the maintainers (i.e., crewmembers).
d. Access needed to equipment.
e. Reliability- or performance-driven preventive maintenance schedule.
f. Corrective maintenance plans.

* Maintenance level items are assembled units or modules that are designed to be isolated from the rest of its system, removed, maintained, repaired, and/or replaced by the maintainer on-mission. Maintenance-level items are identified through the trade space analysis considering the following factors, among others: reliability, redundancy, functionality sustainment, stress reduction, derating, accessibility, modularity, and condition-based monitoring.

[Rationale: If proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts to operations can be significant. NASA has been able to shift maintainability requirements from design phase to operations because ground support can be increased throughout the mission. This will not be possible to the same extent with longer lunar surface operations where vehicles and equipment will reside on the Moon. The same will be true for Mars compounded by long communication latencies that will not allow ground to provide real-time guidance and oversight for preventative and corrective maintenance tasks. In addition, environmental factors associated with surface operations, including dust, thermal extremes, day to night transitions, static electricity, dormancy, etc., will increase maintainability challenges. Standards and requirements for supportability, must be implemented early in missions beyond low-Earth orbit utilizing technologies that cannot be repaired on Earth and cannot be replaced from Earth. Impacts of not developing a Maintenance ConOps include loss of a mission or loss of life given the communication latencies, resupply challenges and evacuation constraints of NASA's Lunar and Martian DRMs.]

After

For each maintenance-level item, the human space flight program shall define and document a maintenance concept of operations considering the following factors and updated throughout the design lifecycle:

a. Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity) as specified in the SLS-SPEC-159 Cross Program Design Specification for Natural Environments (DSNE).
b. Tools, aids, and support equipment available to the maintainers in-situ.
c. Skill-level of the maintainers (i.e., crewmembers).
d. Access needed to equipment.
e. Reliability- or performance-driven preventive maintenance schedule.
f. Preventive and corrective maintenance plans.

[Rationale: Maintenance level items are assembled units or modules that are designed to be isolated from the rest of its system, removed, maintained, repaired, and/or replaced by the maintainer on-mission. Certain subsystems are so crucial to survival they need to be identified to drive modularity and sparing of the entire system. Maintenance-level items and subsystems are identified through the trade space analysis considering the following factors, among others: reliability, redundancy, functionality sustainment, stress reduction, derating, accessibility, modularity, and condition-based monitoring. If proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts to operations can be significant. NASA has been able to shift maintainability requirements from design phase to operations because ground support can be increased throughout the mission. This will not be possible to the same extent with longer lunar surface operations where vehicles and equipment will reside on the Moon. The same will be true for Mars compounded by long communication latencies that will not allow ground to provide real-time guidance and oversight for preventive and corrective maintenance tasks. In addition, environmental factors associated with surface operations, including dust, thermal extremes, day to night transitions, static electricity, dormancy, etc., will increase maintainability challenges. Standards and requirements for supportability, must be implemented early in missions beyond low-Earth orbit utilizing technologies that cannot be repaired on Earth and cannot be replaced from Earth. Impacts of not developing a Maintenance ConOps include loss of a mission or loss of life given the communication latencies, resupply challenges and evacuation constraints of NASA's Lunar and Martian DRMs.]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☒ Maintenance level items definition should be moved to rationale (Reviewer 1 & 4)

☐ Requirement should list *all* mission work environment factors to be covered in ConOps (Reviewer 1)
☒ Requirement should inherit from existing NASA standard on mission work environment (Reviewer 3)
☒ Preventive maintenance plans should be added to (f) (Reviewer 2)
☐ Requirement should apply to all subsystems in addition to all maintenance level items (Reviewer 5)
☐ Requirement should include definition of aids (visual aids, color coding, etc.) as additional ConOps content (Reviewer 5)
☐ Requirement does not belong in 3001 – guidance for verification (Reviewer 6)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
Rationale: [* Maintenance level items are assembled units or modules that are designed to be isolated from the rest of its system, removed, maintained, repaired, and/or replaced by the maintainer on-mission. Maintenance-level items are identified through the trade space analysis considering the following factors, among others: reliability, redundancy, functionality sustainment, stress reduction, derating, accessibility, modularity, and condition-based monitoring. If proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts to operations can be significant. NASA has been able to shift maintainability requirements from design phase to operations because ground support can be increased throughout the mission. This will not be possible to the same extent with longer lunar surface operations where vehicles and equipment will reside on the Moon. The same will be true for Mars compounded by long communication latencies that will not allow ground to provide real-time guidance and oversight for preventative and corrective maintenance tasks. In addition, environmental factors associated with surface operations, including dust, thermal extremes, day to night transitions, static electricity, dormancy, etc., will increase maintainability challenges. Standards and requirements for supportability, must be implemented early in missions beyond low-Earth orbit utilizing technologies that cannot be repaired on Earth and cannot be replaced from Earth. Impacts of not developing a Maintenance ConOps include loss of a mission or loss of life given the communication latencies, resupply challenges and evacuation constraints of NASA's Lunar and Martian DRMs.]

Rationale for Change/Comments
Moving the Maintenance definition into the rationale to keep the requirement clean with just a shall statement. Further explanation and details should go in the rationale and not clutter up the requirement statement. Additionally, a) Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity) - needs to be all inclusive and without the "e.g.,". This is a requirement statement so everything needs to be included that can be verified. Or move all the details into another place and keep the requirement statement clean as in "The human space flight program shall define and document maintenance concept of operations considering factors as described in....document....". And not list all the items here in this one requirement statement. Then it becomes a compound requirement statement instead of just verifying the contractor provided a maintenance concept of operations.

Response
Agreed.

Moved maintenance level item definition to rationale.
Added reference to SLS-SPEC-159 Cross Program Design Specification for Natural Environments (DSNE) which lists all mission work environment characteristics.

Reviewer 2 Patrick Simpkins (Consultant)

Proposed Text
"For each maintenance level item*, the human space flight program shall define and document a maintenance concept of operations considering the following factors and updated throughout the design lifecycle: a) Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity). b) Tools and support equipment available to the maintainers in-situ. c) Skill-level of the maintainers (i.e., crewmembers). d) Access needed to equipment. e) Reliability- or performance-driven preventive maintenance schedule. f) Preventative and Corrective maintenance plans."

Rationale for Change/Comments
Long-duration space flight will require both preventative to stave off avoidable equipment faults due to preventable causes as well as corrective maintenance capabilities for hardware actually experiencing faults.

Response
Agree – made suggested change.

Reviewer 3 Joe Minnow

Proposed Text
For each maintenance level item*, the human space flight program shall define and document a maintenance concept of operations considering the following factors and updated throughout the design lifecycle: a) Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity) as specified in the SLS-SPEC-159 Cross Program Design Specification for Natural Environments (DSNE). b) Tools and support equipment available to the maintainers in-situ. c) Skill-level of the maintainers (i.e., crewmembers). d) Access needed to equipment. e) Reliability- or performance-driven preventive maintenance schedule. f) Corrective maintenance plans. * Maintenance level items are assembled units or modules that are designed to be isolated from the rest of its system, removed, maintained, repaired, and/or replaced by the maintainer on-mission. Maintenance-level items are identified through the trade space analysis considering the following factors, among others: reliability, redundancy, functionality sustainment, stress reduction, derating, accessibility, modularity, and condition-based monitoring. Rationale: [If proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts to operations can be significant. NASA has been able to shift maintainability requirements from design phase to operations because ground support can be increased throughout the mission. This will not be possible to the same extent with longer lunar surface operations where vehicles and equipment will reside on the Moon. The same will be true for Mars compounded by long communication latencies that will not allow ground to provide real-time guidance and oversight for preventative and corrective maintenance tasks. In addition, environmental factors associated with surface operations, including dust, thermal extremes, day to night transitions, static electricity, dormancy, etc., will increase maintainability challenges. Standards and requirements for supportability, must be implemented early in missions beyond low-Earth orbit utilizing technologies that cannot be repaired on Earth and cannot be replaced from Earth. Impacts of not developing a Maintenance ConOps include loss of a mission or loss

of life given the communication latencies, resupply challenges and evacuation constraints of NASA's Lunar and Martian DRMs.]

Rationale for Change/Comments
Conservative design environments for NASA human flight programs to the Moon, Mars, and asteroids are specified in the SLS-SPEC-159 DSNE document. The maintenance concept of operations should use this specification to assurement consistency in program design. If special environments are required, the DSNE can be updated or tailored as necessary.

Response
Agree – made suggested changes.

Reviewer 4 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text
N/A

Rationale for Change/Comments
I think everything after the "*" should be in the rationale.

Response
Agree – made suggested changes.

Reviewer 5 Melina Naderi

Proposed Text
N/A

Rationale for Change/Comments
I would go further and say "For each Maintenance Level item and Maintenance Level subsystem" because certain subsystems are so crucial to survival, they need to be called out to possibly drive modularity and sparing of the entire assembly. Additionally, specify that the concept of operations should define aids required for the maintainer, including visual aids, color coding, task lighting etc.
ALSO ADD NEW REQT (*note: this comment does not need to be addressed in this form*)
Maintenance Level item and Maintenance Level subsystems shall be identified early in the program-no later than PDR. (note-and maybe as early as SRR)
By identifying specific and crucial subsystems as Maintenance Level, the designer begins their design with maintainability foremost in their objectives. This would be a great improvement over having bits and pieces identified as MLI/LRU post PDR and into CDR, as often happens now.
Global comment to this set of proposed requirements: Change term "preventative" to "preventive1" to be compatible with the rest of Volume 2; additionally, "preventive" is the current preferred term.

Response
Added subsystem wording to rationale, but left requirement as is because subsystems are included within the maintenance level item definition.

Added aids to list of ConOps content but stayed away from adding color coding/aid specifications to ConOps requirement, as these specifications are not in scope for a ConOps document.

Changed preventative to preventive everywhere.

Did not add in timing for identifying MLI – left to programs.

Reviewer 6 Michael Salopek

Proposed Text
N/A

Rationale for Change/Comments
General comment: This seems more like a verification method of the other maintainability requirements. This would be the program providing a data deliverable to show how it meets the maintainability standards. Std-3001 doesn't contain a verification section. However, this does seem like a good addition to the guidebook to provide suggestions on how to receive verifications of the maintainability requirements.

Alternatively, leaving in -3001 ensures that all of this data is a deliverable to the program to be used how it sees fit. If I recall sometimes verification deliverables are not always considered "data deliverables" and come with more limited rights, etc.

Response
Applicability determined by 3001 standards team.

C.3 Candidate Revision - 3001 No 03 - Preparation for Unanticipated Repairs and Maintenance

Before

All equipment shall be accessible, labeled, serviceable with the in-mission tool and test equipment set, and supply supporting information.

Rationale: [Maintainability is a vital characteristic of flight hardware, even if the equipment does not require preventative maintenance or is not anticipated, due to reliability estimates, to require corrective maintenance. Inaccuracies in reliability estimates may render preventative maintenance plans obsolete or result in unplanned corrective maintenance. Further, logistical constraints of missions BLEO will require maintenance to be performed at an intermediate level—e.g., that below the ORU level. ISS experience has shown that intermediate level maintenance is problematic if not all parts of the ORU are designed to be accessed or repaired. As sparing will be limited during extended missions without access to frequent resupply, it may also be necessary to scavenge parts from operating equipment to replace failed parts in higher priority systems. Meeting maintainability requirements allows equipment to be readily accessed, modified, or repaired when necessary. Refer to [standard] for accessibility, [standard] for labeling, [standard] for tool interfaces, and [standard] for supporting information.]

After

All flight hardware and software shall be designed to facilitate in-mission maintenance (both corrective and preventative) and check-out.

Repairs and/or replacements shall be designed to be completed within the time to effect with margin and with consideration of environmental constraints. If they cannot be so completed, alternative design strategies (e.g., redundancy) shall be utilized to maintain critical functionality.

Systems and units of equipment shall be accessible and penetrable using the on-board tool set.

Flight hardware shall include information and labeling that enables the crew to correctly locate, identify, and handle systems components.

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Requirement is vaguely worded and difficult to verify (Reviewer 1)
- ☐ Requirement is not reasonable / should not be levied on all equipment (Reviewer 3)
- ☐ Requirement should point to applicable standards and documents in the requirement (not rationale) text (Reviewer 1 & 4)
- ☐ Rationale should not include “judgment statement” on inaccurate reliability estimates (Reviewer 1)
- ☐ Requirement should specify that equipment shall be “clearly” labelled (Reviewer 2)
- ☐ Should remove “and supply supporting information” from requirement (Reviewer 5)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
All equipment shall be accessible via (specify method of accessibility here - tools or hands or suited gloves or what?), labeled (is any kind of label OK???), serviceable with the in-mission tool (what tool?) and test equipment set, and supply supporting information(this needs to be very specific so it can be verified else you are likely to get whatever the contractor interprets this be).

Rationale for Change/Comments
This is a very vaguely worded requirement - it's not prescriptive enough to verify - what does it mean to be "accessible" and what is "supporting information". The owner of this requirement is going to spend a great deal of effort negotiating and clarifying this requirement with a Contractor. Additionally, the rationale makes a judgement statement that someone is going to use inaccurate reliability estimates - this statement should be removed and just stick with an objective clarification or explanation of the motive behind the requirement.

Response
Redid requirement

Reviewer 2 Patrick Simpkins (Consultant)

Proposed Text
All equipment shall be accessible, clearly labeled, serviceable with the in-mission tool and test equipment set, and accompanied by supporting information.

Rationale for Change/Comments
Labeling is one thing, clearly labeling to enable in-flight maintenance is another. All equipment should have all attached fittings and connectors clearly labeled (thought NASA had a spec on this…or maybe in this same document?) to prevent misconnections and confusion. Added "accompanied by" and deleted "...supply..." to adjust grammar.

Response
Redid requirement

Reviewer 3 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text
N/A

Rationale for Change/Comments
I don't think this is a reasonable standard. If we want all the equipment to be accessible, then we potentially force our form/fit to be outside the envelope of what could reasonably fit inside a spacecraft. This is a trade that has to be made on a case-by-case basis. There needs to be rationale/data to support and/or justify access to every piece of hardware. However, maybe I'm interpreting "equipment" incorrectly? Is there a definition? I hear "equipment" and I think to the component level.

Response
Redid requirement

Reviewer 4 Melina Naderi

Proposed Text
All Systems in the vehicle design shall be serviceable using the pre-defined, in-mission tool and test equipment set documented in (TBD document).

Rationale for Change/Comments
This is a compound requirement- accessible, labeled, serviceable- all of which need to stand alone if they are to be verifiable. The Human Factors requirement set in 3001 should be reviewed by the author, to verify that accessibility and labeling are covered adequately there. This

requirement should be written: All Systems in the vehicle design shall be serviceable using the pre-defined, in-mission tool and test equipment set documented in (TBD document).
This is a very important requirement and needs to be set out clearly. Additionally, Add a requirement - An in-mission tool and test equipment set shall be established and defined as a part of SRR documentation. This is necessary in order to guide the designers in part selection, else the Systems requirement here is unachievable. As a part of this new requirement the rationale should state that updates/additions to this list will be considered through PDR, after which this list will be baselined.

Response
Redid requirement

Reviewer 5 Michael Salopek

Proposed Text
Remove "and supply supporting information"

Rationale for Change/Comments
Not sure what that extra phrase is doing there, was it a copy paste error? If it is intended to be there considering expanding it and making it its own requirement since the bulk of the requirement is focused on hardware and this would be information.

Response
Redid requirement

C.4 Candidate Revision - 3001 No 04 - Visual Aids

Before

For maintenance activities, visual aids shall be provided with appropriate scale, orientation, and context in order to enable crew to locate and identify components and execute the task.

Rationale: Locating and identifying all the components involved in a maintenance procedure can be time-consuming, especially when a crewmember is working with an unfamiliar system. Photos, videos, and other graphics are invaluable for providing context, and their use can accelerate pre-maintenance preparation and procedure execution. Visual aids are to be accurate to the operational environment and provide the appropriate amount of detail for the task to enable efficiency. Sparse or misleading visual cues can contribute to spatial disorientation (Bloomberg 2016) and influence astronauts' ability to accurately perform cognitive and sensorimotor tasks. (Clément et al. 2013) Appropriate visual aids are increasingly important for exploration beyond LEO, where lower-level onboard maintenance will be necessary, and oversight from the ground will be limited. Interactive visual aids that enable crew to dynamically resize and rotate should be considered to amplify crewmembers' understanding of the system context.

After

For maintenance activities, visual aids shall be provided (digitally and/or within a procedure) to enable crewmembers to locate and identify components and execute the task.

Rationale: Locating and identifying all the components involved in a maintenance procedure can be time-consuming, especially when a crewmember is working with an unfamiliar system. Photos, videos, and other graphics are invaluable for providing context, and their use can accelerate pre-maintenance preparation and procedure execution. Visual aids are to be accurate to the operational environment and provide the appropriate amount of detail for the task to enable efficiency. Sparse or misleading visual cues can contribute to spatial disorientation (Bloomberg 2016) and influence astronauts' ability to accurately perform cognitive and sensorimotor tasks. (Clément et al. 2013) Appropriate visual aids are increasingly important for exploration beyond LEO, where lower-level onboard maintenance will be necessary, and oversight from the ground will be limited. Visual aids may be provided digitally and/or within a procedure. Interactive visual aids that enable crew to dynamically resize and rotate should be considered to amplify crewmembers' understanding of the system context. Using the same visual aids in pre-mission training may be helpful to build crew familiarity with both the system and the visual aids.

Team meeting 11/16/22:

For maintenance activities, procedural aids (e.g., visual, auditory, etc.) shall be provided (digitally and/or within a procedure) to enable crewmembers to locate and identify components and execute the task.

With scale indicated

11/18/22
Way to title this aid based on what we are aiding – mobility aid, decision aid, location aid (existing one)

Maintenance aid? Procedural aid?
Could cover everything, auditory, physical

Maintenance Technical Support Aids
For maintenance activities, technical support aids (e.g., pictures, videos, auditory aids) shall be provided that include the following characteristics:

- Scaled to show the appropriate amount of detail to enable the maintenance function
- Oriented to match operational environment
- Labeled to provide context of how component fits into system

to enable crew to locate and identify components and execute the task.

Usability testing using NASA usability scale
How does somebody who isn't an engineer of the system work with it

Relevant findings from crew debriefs:

- Reasons for provision of visual aids
    - Challenge of finding the right items when doing a task for the first time
        - "It's so much easier to look at a picture... So many times had to go back between the procedure and the object to check if I really had the right object.... Will double check barcodes but pictures would be faster"
    - Figures ease communication with ground
        - "Good example of not having figures – we didn't know what the backside should look like, but were trying to explain to the ground what we were seeing, had to use inspection mirrors and lights, but a picture of the opposite view would have been really really helpful"
    - Speeds up process for crew who were not familiar with the system
        - Evidence that just-in-time video training worked well for complex procedure execution (CDRA)
- Scale
    - Scale to show appropriate level of detail for task:
        - "CDRA maintenance procedure had a lot of pictures but somehow either they were too focused on that specific hardware, or too far away for the crewmembers to see. It was a little bit hard to actually figure out exactly what hardware you needed to look at. In fact, they might have even removed a couple of screws or a bracket that they were not supposed to because they simply misunderstood what it was. Look at those procedures and look at the pictures. The NASA crewmember added that it would be helpful to have an indicator for up or a caption saying what valve it is, or at least a label for a zoomed-in picture."
    - OR enable crew to choose the level of detail themselves:
        - "Some crew preferred using iPad because they can zoom in and reorient images"
    - High enough image resolution to see details:

        - The crew took a bunch of high-resolution photos and that's what they went back to later because you can really pull them out and look at the intricate details."
        - Large / clear enough to see details (sometimes too small in PDF)
- Orientation
    - "One of the problems that they always found in procedures is when pictures are taken from different orientations, so they find themselves constantly having to orient themselves and trying to figure out where the pictures are showing"
- Context – clear labeling, shows how the component you are looking at fits in with the larger system
    - "Procedure for camera in CIGNUS was nice – had color coded connections and a figure showing how it's connected – actually thought that was pretty straightforward"
    - "There's a couple of times we were doing a T2 activity, it would show me the geometry of what I was looking for highlighting specific parts. I found that useful. CDRA is probably another example. If you can have the entire CDRA and pointing to a specific valves and things like this, it can probably help."

Alt Option - Potential New Standard:

High-fidelity mockups of flight systems with clear labels and documentation shall be provided to support training crewmembers on maintenance activities.

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☐ ~~Requirement is unverifiable as written - remove "appropriate" qualifier (Reviewer 3)~~

☐ ~~Requirement is vague and does not specify nature/location of visual aids (Reviewer 2)~~

☐ Requirement should consider and/or be paired with a requirement on training using identical flight systems (Reviewer 1)

- Added to rationale, and drafted new standard but not sure it works as a standard

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
N/A

Rationale for Change/Comments
Is there going to be a requirement for training crew on maintaining these systems? If so, then using visual aids and specifying diagrams with labeled components and orientations on boards, such as a schematic - would be helpful to train the astronauts. This requirement could be paired with another requirement requiring the Contractor to provide identical flight systems to be used in training astronauts with clear labels and schematics or drawings describing the layout of the system.

Response
Added reference to training in rationale, but as a requirement, is out of scope for 3001 – we stayed away from operational standards, as 3001 is a design standard.

Reviewer 2 Don Parker

Proposed Text
N/A

Rationale for Change/Comments
This is a vague requirement as it does not indicated where these visual aids would be located for utilization. Space Flight vehicles are obviously space confined and there is limited space for scale appropriate placards withing the spacecraft near each system. If these visual aids were to be included in a maintenance handbook, or to be provided digitally to the crew when maintenance activities are performed, that should be specified

Response
Added wording to rationale to clarify that the aids do not have to be physical placards. The means of providing the aid (e.g., digital) are to be decided by the designer.

Reviewer 3 Melina Naderi

Proposed Text
For maintenance activities, visual aids shall be provided in order to enable crew to locate and identify components and execute the task.

Rationale for Change/Comments
As written, this requirement is unverifiable. "appropriate" is not to be used in a requirement. Instead, "For maintenance activities, visual aids shall be provided in order to enable crew to locate and identify components and execute the task." The rationale can give examples of what is meant for visual aids.
The application of the Human Factors requirements will control scale/viewability. The "context" of the visual aids is something that should be required to be worked out in your "concept of operations" requirement above

Response
No changes made – verifiability to be assessed by 3001 standards team.

C. 5 Candidate Revision - 3001 No 05 - Tool & Test Equipment Commonality

Before

Systems and units of equipment shall be designed so that maintenance can be accomplished with the in-mission tool and test equipment set.

[Rationale: ISS lessons learned indicate that crews often have difficulty locating the tools and test equipment needed for a given activity, resulting in many hours spent searching for items and delayed maintenance. Tool and test equipment commonality provides redundancy and contributes to crew readiness for unplanned maintenance activities. Interchangeable tools and test equipment improve mass efficiency because common items can cover multiple types of failures. Utilizing common tools and test equipment across vendors increases in importance for missions beyond low-Earth orbit, when increasingly complex and limited resupply operations constrain the ability to replace missing or ineffective tools and test equipment while simultaneously limiting the ability to return ORUs to the ground for maintenance. Commonality helps to ensure the right tools and test equipment are available at the right time to crewmembers in-mission.]

After

Systems and units of equipment shall be designed so that maintenance can be accomplished with the set of in-mission tools and test equipment ~~set~~.

[Rationale: ISS lessons learned indicate that crews often have difficulty locating the tools and test equipment needed for a given activity, resulting in many hours spent searching for items and delayed maintenance. Tool and test equipment commonality provides redundancy and contributes to crew readiness for unplanned maintenance activities. Interchangeable tools and test equipment improve mass efficiency because common items can cover multiple types of failures. Utilizing common tools and test equipment across vendors increases in importance for missions beyond low-Earth orbit, when increasingly complex and limited resupply operations constrain the ability to replace missing or ineffective tools and test equipment while simultaneously limiting the ability to return ORUs to the ground for maintenance. Commonality helps to ensure the right tools and test equipment are available at the right time to crewmembers in-mission.]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☒ Requirement is unclear – reads as if requiring one tool (Reviewer 1)

☐ Requirement does not mention commonality in requirement text (Reviewer 2)

☐ Requirement is redundant with unanticipated repairs & maintenance requirement (Reviewers 2 and 3)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
N/A

Rationale for Change/Comments
There’s an assumption here about what this “in-mission tool” is without a detailed description of the tool. Is this a wrench or what?

Response
Fixed wording to convey that there is a set of in-mission tools, not a single in-mission tool

Reviewer 2 Patrick Simpkins

Proposed Text
"Systems and units of tools and test equipment shall be designed to as much dimension and functional commonality as possible so that maintenance of multiple systems and units can be accomplished with the in-mission tool and test equipment set."

Rationale for Change/Comments
The need to be able to maintain equipment with the in-mission tool set is already mentioned in one of the earlier requirements. The rationale for this one points to the importance of tool commonality. Suggest writing the requirement to address that aspect.

Response
Agree that commonality is the important aspect here. However, it was left out of the requirement to ensure that the requirement is verifiable.

Reviewer 3 Melinda Naderi

Proposed Text
N/A

Rationale for Change/Comments
This is a duplicate of requirement above- rewritten to say: "All Systems in the vehicle design shall be serviceable using the pre-defined, in-mission tool and test equipment set documented in (TBD document)."
If written this way, only one reqt will be needed

Response
Understood and agreed – evaluating if both requirements are needed

C.6 Candidate Revision - 3001 No 06 - Maintenance Management Information

Before

The system shall make the following maintenance management information (including maintenance triggers) available both locally and remotely:
- Real-time sensor data
- Command and status indications to/from all subsystems for the purpose of system maintenance and trouble-shooting procedures.
- Trend data acquisition and analysis.
- Status of consumables.
- Fault detection/isolation.
- Scheduled maintenance data.
- Repair/replacement information.
- Replacement unit maintenance history and maintenance checklists.

[Rationale: Maintenance management information enables maintainers to make informed decisions about when and how to perform maintenance. Real-time maintenance triggers reduce the reliance on reliability data and eliminate unnecessary preventative maintenance tasks.]

After

For preventive maintenance, the following data shall be captured/available to the crew to support autonomous procedure execution:

- Procedures
- Visual aids
- Functional state data (e.g., power, temperature, pressure, standby)
- Active indication of critical procedure step completion
- Active indication of restored functionality
- Replacement unit maintenance history
- Procedure execution records

In addition, for unexpected, corrective maintenance, the following information shall be available to the crew to support autonomous troubleshooting:
- Diagnostic sensor data
- Troubleshooting steps and decision trees
- Description of possible faults and locations
- Description of test points and normal reading ranges
- Test result interpretations and corrective action recommendations

Each maintenance level item shall produce a suggested sequence of troubleshooting steps.

OSO Note: The reasons procedures are generated on the fly is because systems are integrated. Once you mate one system with another, you have procedures that cross over. Might have a system you need to get to, but it's behind 3 other systems and had no way of knowing that when you originally designed the system.

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☐ Specify what is meant by "locally and remotely" (Reviewer 1)

☐ Add “actual/designed operating life remaining” to list of maintenance management information (Reviewer 2)

☐ Requirement may already exist in NASA software standards (Reviewer 3)

☐ Requirement should be program-specific (Reviewer 3)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
N/A

Rationale for Change/Comments
Specify locally and remotely - is this within the spacecraft itself or on the ground or?

Response
Rewrote standard, but made sure to specify that crewmembers need access to the data.

Reviewer 2 Patrick Simpkins

Proposed Text
“The system shall make the following maintenance management information (including maintenance triggers) available both locally and remotely: - Real-time sensor data - Command and status indications to/from all subsystems for the purpose of system maintenance and trouble-shooting procedures. - Trend data acquisition and analysis. - Status of consumables. - Fault detection/isolation. - Scheduled maintenance data. - Repair/replacement information. - Replacement unit maintenance history and maintenance checklists. - actual/designed operating life remaining.”

Rationale for Change/Comments
Additional rationale: Actual operating life, as well as design life remaining are essential in the planning and performance of corrective and preventative maintenance.

Response
Redid standard

Reviewer 3 Morgan Abney

Proposed Text
N/A

Rationale for Change/Comments
Does this requirement already live in another standard somewhere? I’m thinking maybe in software standards. Also – I think this type of requirement should be program-specific. Not every program is going to need all those things. And it isn’t practical that all consumables have the instrumentation to indicate status (I’m thinking LiOH cannisters for example)

Response
This standard does not live elsewhere.
Removed consumables information as data requirement.
Each program will tailor this standard to meet their specific needs.

C.7 Candidate Revision - 3001 No 07 - Condition Monitoring

Before

Equipment shall be designed to provide condition-monitoring data to an information system.

[Rationale: Monitoring is needed to optimize maintenance and improve system availability. Reliability estimates are often conservative, leading to unnecessary preventative maintenance (NASA RCM Guide, 2000). Many preventative maintenance tasks achieve nothing, while some are actively counterproductive and even dangerous (Mowbray, 1997); maintenance tasks are prone to human error, (Hobbs, 2021) and the risk of damage is increased each time a system is opened. Condition monitoring provides maintenance triggers, reducing the need for interval-based maintenance. Condition monitoring reduces the reliance on reliability data to ensure availability, ultimately improving crew safety and efficiency. New cost-effective, low-mass technologies increase the value of condition monitoring for missions beyond LEO.]

After

The system shall provide condition-monitoring data to an information system that can be accessed by the crew, either automatically or by request.

[Rationale: Monitoring is needed to optimize maintenance and improve system availability. Reliability estimates are often conservative, leading to unnecessary preventative maintenance (NASA RCM Guide, 2000). Many preventative maintenance tasks achieve nothing, while some are actively counterproductive and even dangerous (Mowbray, 1997); maintenance tasks are prone to human error, (Hobbs, 2021) and the risk of damage is increased each time a system is opened. Condition monitoring provides maintenance triggers, reducing the need for interval-based maintenance. Condition monitoring reduces the reliance on reliability data to ensure availability, ultimately improving crew safety and efficiency. New cost-effective, low-mass technologies increase the value of condition monitoring for missions beyond LEO. See 10017 for more information.]

Team meeting 12/6/22
Tina – this is more about trends – having the data to see a pattern, condition of the hardware. Bearing temp.
Shu-chieh: existing standard in 3001 on health monitoring

[V2 10017] The system shall provide system health and status information to the crew, either automatically or by request.

[Rationale: Key system parameters and off-nominal system, subsystem, and component trend data are to be available for crew viewing. System health and status information is critical for the crew to retain SA and to have the information necessary to make decisions and troubleshoot problems.]

Could combine into this ^ and add "condition monitoring"

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Requirement is vague – what is meant by "equipment?" (Reviewer 3
- ☐ Requirement should list (or point to list) of parameters/conditions to be monitored (Reviewer 1)
- ☐ Requirement does not belong in 3001 (Reviewer 2)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
N/A

Rationale for Change/Comments
Either point to where the descriptions or the condition-monitoring data are further explained or list them here in this requirement - preference is to point to another detailed list of exactly what parameters and conditions need to be monitored avoiding a compound requirement statement. This requirement as worded will require further explanation and clarification with a Contractor.

Response
Parameters may differ by program and system. Specification of the requirement left to programs.

Reviewer 2 Morgan Abney

Proposed Text
N/A

Rationale for Change/Comments
How does this fit into 3001? Again, this is an equipment/hardware/engineering standard, not a human health standard.

Response
3001 standard team to determine applicability, but specified that the condition-monitoring data needs to be provided to the crew.

Reviewer 3 Morgan Abney

Proposed Text
N/A

Rationale for Change/Comments
Need to specify to which "Equipment" this applies. Does equipment mean all subsystems or a select, critical type of equipment? As stated, this is unbounded including any program "equipment", i.e., ground servicing, launch support, etc.

Response
Replaced "equipment" with "system"

C.8 Candidate Revision - 3001 No 08 - Maintenance Activities

Before

Maintenance activities shall be designed at the skill-level of the maintainer.

[Rationale: Effectively leveraging crew capabilities is especially important for exploration beyond LEO, where intermittent and delayed communication with the ground necessitates greater crew autonomy in executing preventative and corrective maintenance tasks. Designing equipment based on the basic abilities and limitations of crew to accomplish the assigned tasks will enable increasingly Earth-independent procedure execution, with reduced guidance and oversight from the ground. In addition, the goal is to reduce errors, reduce training time, reduce workload, and decrease task execution time.]

After

Maintenance activities shall be designed at the skill-level of the crewmembers.

[Rationale: Effectively leveraging crew capabilities is especially important for exploration beyond LEO, where intermittent and delayed communication with the ground necessitates greater crew autonomy in executing preventative and corrective maintenance tasks. Designing equipment based on the basic abilities and limitations of crew to accomplish the assigned tasks will enable increasingly Earth-independent procedure execution, with reduced guidance and oversight from the ground. The skill-level of crewmembers can also be increased using "just-in-time" onboard training that is specific to the situation or system. This method may be useful in situations in which mass constraints prevent the reduction of system complexity. Designing maintenance tasks based on the capabilities of the "front-line" maintainer (as opposed to the provider) can reduce errors, reduce training time, reduce workload, and decrease task execution time.]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☐ "Skill-level" is vague and would be difficult for contractor to interpret (Reviewer 1, 2, & 3)

- Changed "maintainer" to "crewmember" - implies ASCAN training as baseline

☐ Language should be adjusted to note bidirectionality between training and skill level and discuss tradeoff between maintenance complexity and training (Reviewer 4)

- Added a few lines discussing just-in-time training as another option

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
N/A

Rationale for Change/Comments
Vaguely worded requirement and hard to verify could be misinterpreted by the Contractor without further description of exactly what skill-level is required.

Response
Changed standard to specify the skill-level of a crew member

Reviewer 2 Patrick Simpkins (Consultant)

Proposed Text
Replace requirement as written to: "Maintenance activities shall be designed at the skill-level of a qualified crew member and not to the skill-level of the LRU/ORU manufacturer or provider."

Rationale for Change/Comments
Not all crew members will be at the same skill level wrt in-flight maintenance of electrical and/or mechanical systems.

Response
Changed to skill level of a crew member

Reviewer 3 James O'Donnell (NESC Integration Office)

Proposed Text
N/A

Rationale for Change/Comments
This seems really vague to me. That being said, if skill levels of crew is something that is defined somewhere, then this makes more sense.

Response
No changes needed

Reviewer 4 Cirillo, Owens, and Piontek

Proposed Text
N/A

Rationale for Change/Comments
It seems like the core intent of this one is to require that there's a consistency between the skills required for maintenance and the skills of the maintainers. As written, the requirement reads as if the skill-level of the maintainer sets a constraint on the difficulty of maintenance activities. However, the skill level of the astronauts is also a parameter that can be adjusted via training. We recommend that the language here be adjusted to note that bidirectionality, and perhaps discuss the tradeoff between crew training and maintenance complexity. A requirement for simpler maintenance interfaces is likely to lead to higher system mass;

Response
Added content on training to the rationale

C.9 Candidate Revision - 3001 No 09 - Decision Aids

Before

For unplanned maintenance activities, decision aids shall be provided to support diagnosis, troubleshooting, and procedure execution at the skill-level of the maintainer.

[Rationale: For exploration beyond LEO, intermittent and delayed communication with the ground necessitates greater crew autonomy in managing unanticipated safety-critical vehicle anomalies. In lieu of continuous ground support simplified diagnostic aids are needed to assist crewmembers in narrowing down possible causes and making time-critical decisions in the face of uncertainty. A sequence of trouble-shooting checks is to be specified at the skill-level (e.g., training, experience) of the maintainer. To maximize the effectiveness of decision aids, the system should be designed to minimize ambiguity groups (possible failure points) and support its recommendation with relevant data (see #134).]

After

For unplanned maintenance activities, decision aids shall be provided to support diagnosis, troubleshooting, and procedure execution at the skill-level of the crewmembers.

[Rationale: For exploration beyond LEO, intermittent and delayed communication with the ground necessitates greater crew autonomy in managing unplanned corrective vehicle maintenance. In lieu of continuous ground support simplified diagnostic aids are needed to assist crewmembers in narrowing down possible causes of anomalies and making time-critical decisions in the face of uncertainty. A sequence of trouble-shooting checks is to be specified at the skill-level (e.g., training, experience) of the maintainer. To maximize the effectiveness of decision aids, the system should be designed to minimize ambiguity groups (possible failure points) and support its recommendation with relevant data (see #134).]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ ~~Requirement should specify that we want to build to skill-level of crew members (Reviewer 1)~~
- ☐ Rationale is unreasonable - cannot have complete troubleshooting and operating procedures for every possible problem (Reviewer 2)

Reviewer 1 Patrick Simpkins (Consultant)

Proposed Text
For unplanned maintenance activities, decision aids shall be provided to support diagnosis, troubleshooting, and procedure execution at the skill-level of the crew members.

Rationale for Change/Comments
I think I get what you're pulling on here but you can't predict the skill-level of one crew to the next or between crew members on the same mission so you want to make sure the decision aids, tools, etc. are NOT to the level of the manufacturer but to the level of the user/customer.

Response
Implemented suggested change

Reviewer 2 Melinda Naderi

Proposed Text
N/A

Rationale for Change/Comments
The rationale states that this reqt is necessary for "managing unanticipated safety-critical vehicle anomalies". Safety critical anomalies would not be "unplanned maintenance". That said, for other possible unplanned maintenance, it would be more reasonable to have some info available for locating the subsystem/hardware and an overview of each subsystem including drawings/schematics... but probably not complete troubleshooting and operating procedures for every possible problem.

Response
Changed to "managing unplanned corrective maintenance"
However, our data/research efforts does show that safety-critical anomalies of uncertain origin (I.e., unplanned events) do take place at a relatively high rate.

C.10 Candidate Revision - 3001 No 10 - Repair Verification

Before

The system shall provide a positive indication or measurement that verifies a repair has been made successfully and the system is functioning properly.

[Rationale: Repair activities inherently introduce risk to a system; the repair itself may be unsuccessful or maintainers may cause further damage during the repair process. Verifying a system has returned to proper functionality before returning the system to nominal operations prevents further damage or loss of operability. On missions beyond low-Earth orbit, an indication provided onboard the vehicle at the maintenance location will allow crewmembers to verify repair success without relying on ground teams. Even small communication delays (e.g., 6 to 10 seconds on the surface of the moon) reduce the ground team's ability to oversee repair activities. Crewmembers will conduct more repairs on missions beyond LEO, as the ability to send systems to the ground for detailed investigation and repair is constrained; access to repair data onboard the vehicle will facilitate successful maintenance.]

After

Preventive and corrective maintenance shall include means for verification of successful completion.

[Rationale: Verification can be provided through system self-test, external measurements, or other methods. Repair activities inherently introduce risk to a system; the repair itself may be unsuccessful or maintainers may cause further damage during the repair process. Verifying a system has returned to proper functionality before returning the system to nominal operations prevents further damage or loss of operability. On missions beyond low-Earth orbit, an indication provided onboard the vehicle at the maintenance location will allow crewmembers to verify repair success without relying on ground teams. Even small communication delays (e.g., 6 to 10 seconds on the surface of the moon) reduce the ground team's ability to oversee repair activities. Crewmembers will conduct more repairs on missions beyond LEO, as the ability to send systems to the ground for detailed investigation and repair is constrained; access to repair data onboard the vehicle will facilitate successful maintenance.]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☒ Requirement should not require self-verification capability (Reviewer 2)

☒ Unreasonable to expect every repair to provide positive indication/measurement (Reviewer 1)

Reviewer 1 Morgan Abney

Proposed Text
The system shall provide the capability for the crew to verify that a repair has been made successfully and the system is functioning properly.

Rationale for Change/Comments
Maybe this should say something more like: "The system shall provide the capability for the crew to verify that a repair has been made successfully and the system is functioning properly." Like when you have to work on your car, sometimes the check is just trying to turn it on and actively troubleshooting. I don't think it's reasonable to expect every imaginable type of repair would have a positive indication or measurement.

Response
Agreed – changed requirement to remove positive indication or measurement wording

Reviewer 2 Cirillo, Owens, and Piontek

Proposed Text
N/A

Rationale for Change/Comments
Should the system provide a self-verification capability, or can that capability be provided by tools or other diagnostic aids? Again, we like the concept of this requirement—that the crew should be able to tell whether or not a repair was successful—but our concern is that a requirement like this may result in more complex systems with self-diagnostic elements that would not otherwise be present. Every additional component in a system is just one more thing that can fail and may need maintenance. Sometimes a component enabling repair verification may be worth it, but sometimes it may lead to increased system complexity, mass, and maintenance demand that outweighs the benefits. We recommend that this requirement be reexamined to see if it can be rephrased or restructured to require the ability to verify maintenance success, rather than requiring that the system do that verification itself.

Response
Agreed – changed requirement and rationale to reflect the idea that the verification capability does not have to be built into the system.

C.11 Candidate Revision - 3001 No 11 - In-Mission Training

Before

In-Mission Training
In-mission training/refreshers shall be provided to ensure crew proficiency in performing maintenance activities.
[Rationale: Repairs are designed to be as simple as possible. However, because of the length of time between crew training and missions, providing in mission training/refreshers allows for just-in-time training. Videos and/or augmented reality are examples of training tools that may be provided.]

After

In-mission training/refreshers shall be provided to ensure crew proficiency in performing maintenance activities, including using the tools and test equipment required for the maintenance activity.

[Rationale: Repairs are designed to be as simple as possible. However, because of the length of time between crew training and missions, providing in mission training/refreshers allows for just-in-time training. Videos and/or augmented reality are examples of training tools that may be provided.]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Add more detailed success criteria for what the crew needs to be able to achieve (1)
- ☒ Change to "In-mission training/refreshers shall be provided to ensure crew proficiency in performing maintenance activities and in using the tools and test equipment required for that maintenance." (2)
- ☐ Change to "Training materials, including video of the operations, shall be provided to flight crew for primary and refresh training of maintenance activities" (3)
- ☐ Add to rationale: "videos can be of actual hardware or computer generated from CAD modeling but should include description and view of each step."

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Rationale for Change/Comments
Consider adding details to explain that the crew needs to be able to rebuild a unit completely or partially and if so what parts should be able to be replaced in order to be successful in verifying this requirement? Any old training is acceptable here? what's the criteria for success?

Response
Criteria for success to be determined at the program level

Reviewer 2 Patrick Simpkins (Retired, KSC Engineering Director)

Proposed Text
In-mission training/refreshers shall be provided to ensure crew proficiency in performing maintenance activities and in using the tools and test equipment required for that maintenance.

Rationale for Change/Comments
During flight, it will just as important to keep the crew current on the diagnostic tools and test equipment required for the maintenance operations.

Response:
Added change

Reviewer 3 Brooke Allen and Melinda Naderi, NASA Marshall

Proposed Text
Possibly use: "Training materials, including video of the operations, shall be provided to flight crew for primary and refresh training of maintenance activities".

In rationale you may want: videos can be of actual hardware or computer generated from CAD modeling but should include description and view of each step."

Response:
Method of training left to discretion of vendor/contractor

C.12 Candidate Revision - 3001 No 12 - Contamination Prevention

Before

Contamination Prevention

Maintenance tasks shall be designed to prevent environmental contamination of surface and EVA systems.

[Rationale: Planetary surface dust environments have the potential to disrupt operations on the Moon, Mars, and asteroids. Lessons learned from Apollo lunar surface missions indicate that care must be exercised to minimize environmental contaminants during maintenance.]

After

[new standard text]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Hard to ensure / verify (1, 2)
- ☐ Replace "environmental" with "dust" (3)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Rationale for Change/Comments
How would a Contractor verify this requirement?

Response:
Verification determined at a program level

Reviewer 2 Patrick Simpkins (Retired, KSC Engineering Director)

Rationale for Change/Comments
Not sure you can "prevent" environmental contamination. You can minimize and maybe do something about it if it is experienced. But it's a good stretch goal/requirement.

Response:
No changes needed

Reviewer 3 Morgan Abney (NASA ECLSS Technical Fellow)

Rationale for Change/ Comments
I think we need to replace "environmental" with "dust" in this one. Environmental can mean a lot of other things besides dust. Should just specify here, I think.

Response
Intent was to broaden beyond dust

C.13 Candidate Revision - 3001 No 14 - Cable Identification

Before

[V2 9035 suggested edits] All maintainable cables, wires, and hoses shall be uniquely and consistently identified at the maintenance point.

[Rationale: Locating and identifying the specific cable, wire, or hose needed for a maintenance activity can be time consuming. Unique identifications that enable rapid recognition among similar items reduce maintenance time. Consistency in the manner of identification across items decreases the time needed for locating and interpreting identifications. Identifications that enable rapid recognition without the use of conversion tables are less susceptible to errors. Redundant identifications give maintainers more than one opportunity to identify the item, increasing maintenance efficiency. Some conductors do not terminate in a keyed connector; they are individually attached. It is essential that the conductors be attached to the correct terminal points. All individual conductors that attach to different terminal points are to be coded. Terminal points are normally fixed and can be identified with labels and illustrations. Conductors, on the other hand, are to have identifications affixed to them. This is normally done with color coding of the insulation materials or by tagging the conductors.]

After

[V2 9035 suggested edits] All maintainable cables, wires, and hoses shall be uniquely and consistently identified at the maintenance point.

[Rationale: Locating and identifying the specific cable, wire, or hose needed for a maintenance activity can be time consuming. Unique identifications that enable rapid recognition among similar items reduce maintenance time. Consistency in the manner of identification across items decreases the time needed for locating and interpreting identifications. Identifications that enable rapid recognition without the use of conversion tables are less susceptible to errors. Redundant identifications give maintainers more than one opportunity to identify the item, increasing maintenance efficiency. Some conductors do not terminate in a keyed connector; they are individually attached. It is essential that the conductors be attached to the correct terminal points. All individual conductors that attach to different terminal points are to be coded. Terminal points are normally fixed and can be identified with labels and illustrations. Conductors, on the other hand, are to have identifications affixed to them. This is normally done with color coding of the insulation materials or by tagging the conductors. Additional design standards for cables, wires, and harnesses can be found in NASA STD 8739.4]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☒ Review / reference NASA STD 8739.4

Reviewer 1 Don Parker (NESC Principal Engineer)

Proposed Text/ Comments
Wires and cabling harness designs are governed by NASA STD 8739.4 and all additional requirements levied by this document should be in line with those contained in the engineering design standard, not in conflict, and should be appropriately referenced if applicable.

Response:
8739.4 standards on identification are not in conflict, but added reference

- 7.2.4 Methods for identifying cables, connectors, and wires shall be provided.
- 8.3.1 Temporary identification markers may be used for in-process identification requirements. All temporary markers shall be removed from completed cabling and harnessing and shall not leave a contaminating residue.
- 14.1.1 Each cable and each harness shall be permanently identified.
  - a. The identification marking shall be capable of passing all environmental testing that may be required for the projected use and remain legible.
  - b. Each connector shall be identified.
  - c. Connector identification may be placed directly on the connector or on the cable near the connector.
  - d. In all cases, identification shall resist abrasion, either as applied or with the aid of an overcoat.
  - e. All temporary identification shall be removed from each completed harness by the end of the fabrication process.
  - f. Marking tape used to position and locate harnesses and cables may be either permanent or temporary in nature.
  - g. Permanent type marking tapes shall meet environmental requirements.
  - h. Identification shall be verified visually by the responsible Quality Representative or designee for correctness, legibility, size, and proper location.

Reviewer 2 Patrick Simpkins (Retired, KSC Engineering Director)

Proposed Text/ Comments
IMHO…really good requirement and good edit to make-better.

C.14 Candidate Revision - 3001 No 15 - In-flight tool set

Before

[V2 9038 suggested edits] Each program shall establish a set of in-mission tools and test equipment necessary to maintain or reconfigure the space flight and surface systems. Also, tools are to be usable by the full range of crew sizes and strengths wearing any protective equipment (EVA suits, protective eyewear, gloves, etc.).

[Rationale: Developing requirements for tool and test equipment set design early in the program lifecycle allows for commonality across vendors. Ideally, tool and test equipment set design are to be coordinated across programs; cross-program commonality minimizes tool types, reduces training demands, and increases redundancy for a given mission. Tool set design is to be based partly on reducing the demands on the crew: selecting tools that are likely to be familiar to crewmembers and minimizing the number of different tools. Apollo and ISS lessons learned indicate that tool set design is also to consider the complement of tools and equipment needed to respond to unexpected failures and hardware workarounds. Having a comprehensive and common tool set is especially important for future long-duration missions with constrained or nonexistent resupply operations.]

After

[V2 9038 suggested edits] Each program shall establish a common set of in-mission tools and test equipment necessary to maintain or reconfigure the space flight and surface systems.

[Rationale: Developing requirements for tool and test equipment set design early in the program lifecycle allows for commonality across vendors. Ideally, tool and test equipment set design are to be coordinated across programs; cross-program commonality minimizes tool types, reduces training demands, and increases redundancy for a given mission. Tool set design is to be based partly on reducing the demands on the crew: selecting tools that are likely to be familiar to crewmembers and minimizing the number of different tools. Apollo and ISS lessons learned indicate that tool set design is also to consider the complement of tools and equipment needed to respond to unexpected failures and hardware workarounds. Having a comprehensive and common tool set is especially important for future long-duration missions with constrained or nonexistent resupply operations.]

Separate standard:
Also, tools and test equipment are to be usable by the full range of crew sizes and strengths wearing any protective equipment (EVA suits, protective eyewear, gloves, etc.).

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Requirement should be two separate requirements (Reviewer 1 & 2)
- ☒ Requirement should add in timeframe (Reviewer 2)
- ☒ Test equipment should also be usable by full range of crew sizes etc. (Reviewer 3)

Reviewer 1 Morgan Abney (NASA ECLSS Technical Fellow)

Comments
Should be two separate standards. One that establishes the in-mission tools and test equipment (though not sure why that would be in 3001) and one that establishes that it be usable by the full range of humans (should be in 3001).

Response:
Agreed – separated

Reviewer 2 Brooke Allen and Melinda Naderi, NASA Marshall

Comments / Proposed Text
ADD timeframe
An in-mission tool and test equipment set shall be established and defined as a part of SRR documentation.
This is necessary in order to guide the designers in part selection. If not provided at SRR, the designers will have no guide for part selection.
As a part of this new requirement the rationale should state that updates/additions to this list will be considered through PDR, after which this list will be baselined.

The second statement, ""Also, tools are to be usable..."", should be a separate rqmt but may be covered under the current 3001 rqmt, V2 9047 ""Physical work access envelopes shall accommodate the crew, required tools, and any protective equipment needed to perform maintenance."""

Response:
Made second statement separate standard, but did not add in timeframes. Timeframes to be determined at the program level

Reviewer 3 Michael Salopek

Proposed Text
From: Also, tools are to be usable…
To: Also, tools and test equipment are to be usable…

Response:
Changes made

C.15 Candidate Revision - 3001 No 16 - Tool Clearance

Before

9.7.3.5 Tool Clearance

[V2 9050] The system shall provide tool clearances for tool installation and actuation for all tool interfaces during in-mission maintenance.

[Rationale: Tools to be used for in-mission maintenance are to be identified by the hardware developer, and clearance for application is to be accommodated to ensure that maintenance tasks can be performed.]

(Note – all we changed on this existing 3001 standard was in-flight to in-mission)

After

(No changes)

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☐ Doesn't fit in 3001 (Note: it is in 3001 already)

☐

Reviewer 1 Morgan Abney (NASA ECLSS Technical Fellow)

Comments / Proposed Text
Not clear why this would be in 3001. Maybe if rewritten as "The system shall provide tool and hand clearances for tool installation and actuation for all tool interfaces during in-mission maintenance." And the rationale describe that we can't cause harm to the crew hand/ergonomics. That would seem to fit in 3001.

Response:
Already in 3001 – decision on inclusion to be made by 3001 standards team

C.16 Candidate Revision – 3001 No 17 – Maintenance Time

Before

9.7.2.1 Maintenance Time

[V2 9039] Planned maintenance for systems and associated hardware and equipment **shall** be capable of being performed within the allotted crew schedule while wearing the most encumbering equipment and clothing anticipated.

[Rationale: Maintenance and servicing are directly related to the amount of time available for mission goals. Reduction in the time devoted to maintenance and servicing means more crew time devoted to achieving mission goals. Also, because of the complexity of space missions and the interdependency of many factors (equipment, supplies, weather, solar flares, political considerations, etc.), designs are to be self-sufficient and minimize reliance on outside maintenance support. Designs are to provide the tools and mechanisms (including cleaning), parts (as modular units where possible), supplies, training, and documentation necessary for crews to maintain efficient and safe operations. Crew schedule allotted for planned maintenance should include time associated with dust management and cleaning.]

After

*[Rationale: Maintenance and servicing are directly related to the amount of time available for mission goals. Reduction in the time devoted to maintenance and servicing means more crew time devoted to achieving mission goals. Also, because of the complexity of space missions and the interdependency of many factors (equipment, supplies, weather, solar flares, ~~political considerations,~~ **changes in mission design and objectives,** etc.), designs are to be self-sufficient and minimize reliance on outside maintenance support. Designs are to provide the tools and mechanisms (including cleaning), parts (as modular units where possible), supplies, training, and documentation necessary for crews to maintain efficient and safe operations. Crew schedule allotted for planned maintenance should include time associated with dust management and cleaning.]*

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☒ Requirement contains potentially politicized language (Reviewer 1)
- ☐ Requirement contains objectives that may not be feasible in practice (Reviewer 2)
- ☐ Requirement does not specify the number of crew (Reviewer 3)
- ☐ The intent of the Requirement is unclear; specifically, whether it is really to promote design options that minimize maintenance time (Reviewer 3)

Reviewer 1 Patrick Simpkins (Retired, KSC Engineering Director)

Proposed Text
Do you really want to mention "political considerations" in a document about extended human space flight? Maybe "…many factors (equipment, supplies, weather, solar flares, changes in mission designs and objectives, etc.),…

Rationale for Change/Comments
Important to focus on the technical and mission performance factors while keeping an eye towards possible mission scope changes.

Reviewer 2 James O'Donnell (NESC Integration Office)

Proposed Text/Comments
"Planned maintenance for systems and associated hardware and equipment shall be capable of being performed within the allotted crew schedule while wearing the most encumbering equipment and clothing anticipated." Again, this makes sense, but my first thought when reading it is, "What if, for a given necessary maintenance activity, this is not possible?" (This one is probably OK, because I can see if the first cut at designing something results in maintenance activities that would take too long, the correct answer is probably, "Redesign it so that the maintenance doesn't take as long or can be split up into shorter, discrete parts."

Reviewer 3 Brooke Allen and Melinda Naderi, NASA Marshall

Comments
"allotted crew schedule" does this mean within one crew working shift?

Typically, Planned maintenance has a predicted time to complete and the timeliner/scheduler schedules the crew to perform the procedure in small planned blocks of time, in total or in total across two or more different crew on continuous shifts.
Perhaps the real intent is to design systems to minimize maintenance times by using modular components, qd's and the like? If this is so, the requirement verbiage needs to indicate this clearly.

C.17 Candidate Revision – 3001 No 19 – Extreme Environment

Before

Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to sustain extreme environmental conditions in components and areas where such conditions can induce failures.

[Rationale: Space environment can present extreme environmental (EE) conditions in pressure, temperature, radiation, and chemical or physical corrosion. Certain planned mission operations can also induce EE conditions in heat flux and deceleration during entry, descent, and landing (EDL) phases (Balint et al., 2008). Exposure of space hardware to EE conditions, if not designed and built to sustain, can lead to malfunctions and consequently higher spare requirements and frequent maintenance and servicing needs. Increase in both equipment failures and maintenance and servicing needs means less crew time devoted to achieving mission goals. Designs are to prevent EE conditions from negatively impacting mission objectives and operations.]

Balint, T. S., Cutts, J. A., Kolawa, E. A., & Peterson, C. E. (2008). Extreme environment technologies for space and terrestrial applications. Space Exploration Technologies, 6960, 36–47. https://doi.org/10.1117/12.780389

After (Based on Proposed Text by Joe Minow)

Equipment, including tools and instruments, that ~~operates and/or~~ is maintained on the planetary surface shall be designed to meet all performance requirements specified in NASA-STD-5017A Design and Development Requirements for Mechanisms during and after exposure to the expected environmental conditions specified in the SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE)

[Rationale: Space environment can present extreme environmental (EE) conditions in pressure, temperature, radiation, and chemical or physical corrosion, as well as acidity and dust. Certain planned mission operations can also induce EE conditions in heat flux and deceleration (g-loading) during entry, descent, and landing (EDL) phases (Balint et al., 2008). Contamination with lunar dust can affect the function of equipment and instrumentation by degrading seals and valves, breaking down lubricants, jamming moving parts, and creating flow blockages (Cain, 2010). Exposure of space hardware to EE conditions, if not designed and built to sustain, can lead to malfunctions and consequently higher spare requirements and frequent maintenance and servicing needs. Increase in both equipment failures and maintenance and servicing needs means less crew time devoted to achieving mission goals. Designs are to prevent EE conditions from negatively impacting mission objectives and operations.]

Balint, T. S., Cutts, J. A., Kolawa, E. A., & Peterson, C. E. (2008). Extreme environment technologies for space and terrestrial applications. Space Exploration Technologies, 6960, 36–47. https://doi.org/10.1117/12.780389

Cain, J. R. (2010). Lunar dust: The Hazard and Astronaut Exposure Risks. Earth, Moon, and Planets, 107(1), 107–125. https://doi.org/10.1007/s11038-010-9365-0

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☒ Requirement is vague (Reviewer 1)

☐ Requirement should be deleted (Reviewer 2)

☒ Requirement should point to a descriptive and specific environments requirement document (Reviewer 1, Reviewer 3, Reviewer 4)
☐ Requirement is not verifiable (Reviewer 4)
☐ Requirement is not suitable for 3001 (Reviewer 5)
☒ Requirement should inherit from existing NASA mechanism design requirement (Reviewer 6)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to survive and operate in the environmental conditions as described in ….insert environment description

Rationale for Change/Comments
This requirement statement is vague and should just point to a descriptive and specific environments requirements documents. All hardware shall survive and be able to operate in the environments as described in….program doc here….. That other environments document will describe the dust environment, thermal ranges, radiation exposure, etc. and other relevant environments for space operations.

Reviewer 2 Patrick Simpkins (Retired, KSC Engineering Director)

Proposed Text
Recommend delete requirement. Design and Construction standards require the need for products to perform and survive the expected environmental extremes plus margins.

Rationale for Change/Comments
N/A

Reviewer 3 Joe Minow (NASA Technical Fellow for Space Environments)

Proposed Text
"Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to meet all performance requirements during and after exposure to the environmental conditions specified in the SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE)"

Rationale for Change/ Comments
"A requirement that equipment be designed to operate in extreme environments can drive the cost, technical, and schedule for the equipment. Without specifying the severity of the environment the requirement cannot be verified. NASA crewed missions to the Moon and Mars are designed to withstand the conservative space environments specified in the SLS-SPEC-159 DSNE document.

Lunar surface environments are specified in Section 3.4 of the DSNE. There are reserved sections in the DSNE for surface environments on Mars (Section 3.10), moons of Mars (Section 3.11), and near Earth asteroids (Section 3.12). These sections will be updated in the future to contain the necessary planetary surface design environments.

There is likely also a document specifying induced environments for lunar missions (GP 10057 Gateway Space Induced Environments Requirements does this for Gateway, check to see if there is a similar requirements document for HLS and xEVA).”

Response
Thank you!!!

Cross-Program Design Specification for Natural Environments (DSNE)
SLS-SPEC-159, Revision F (Effective May 8, 2019)
https://ntrs.nasa.gov/api/citations/20190027643/downloads/20190027643.pdf

Gateway Space Induced Environments Requirements
GP10057, Revision A (Effective May 6, 2021)
(Available via https://moon2mars.ndc.nasa.gov/gateway/)

Reviewer 4 Brooke Allen and Melinda Naderi, NASA Marshall

Proposed Text
“Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to sustain extreme environmental conditions, described in program environmental specifications, in components and areas where such conditions can induce failures”

Rationale for Change/ Comments
This requirement is not verifiable. The specific environmental conditions have to be specified or a document that contains that info must be referenced in the requirement text to direct the designer and for use in verification. IF this requirement is intended to apply to programs on multiple planets then write the requirement to generalize:

Reviewer 5 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text
N/A

Rationale for Change/ Comments
Why in 3001?

Reviewer 6 Don Parker (NESC Principal Engineer)

Proposed Text
N/A

Rationale for Change/ Comments
Tool and equipment functionality should be covered by the NASA STD 5017 for mechanisms and would include design tolerances for force margins in the relevant environment. These requirements should be in line with those and should be referenced as to not have vague competing requirements

Same comments as below, NASA STD 5017 for Mechanism Design in the relevant environment should be the parent and this should either reference that appropriate requirement or provide rationale as to why this is in addition to or a clarification of that mechanism design requirement

Response
Agreed and revised accordingly

NASA-STD-5017
Design and Development Requirements for Mechanisms
https://standards.nasa.gov/sites/default/files/standards/NASA/w/CHANGE-1/1/NASA-STD-5017A-Revalidated-w-Change-1.pdf

Response from Team discussion
Dave – should continue to look for more relevant standards. Leave it in in the meantime.
Put 5017 in parking lot until Mark returns

Tony – does 5017 include lifetime?
Dave – yes

Consult with Mark to see where this requirement better fits

NEW – Michael Salopek Comments

Proposed Rewording:
From: Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to sustain extreme environmental conditions in components and areas where such conditions can induce failures
To: Equipment, including tools and instruments that operate and/or are maintained on the planetary surface, shall be designed to mitigate failures due to the extreme environmental conditions of the planetary surface.

C.18 Candidate Revision - 3001 No 20 - Dust Prevention [MERGED With No. 19]

Before

Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to prevent dust intrusion into components and areas where dust accumulation can induce failures.

[Rationale: Contamination with lunar dust can affect the function of equipment and instrumentation by degrading seals and valves, breaking down lubricants, jamming moving parts, and creating flow blockages (Cain, 2010), leading to malfunctions and consequently higher spare requirements and frequent maintenance and servicing needs. Increase in both equipment failures and maintenance and servicing needs means less crew time devoted to achieving mission goals. Designs are to prevent dust from negatively impacting mission objectives and operations.]

Cain, J. R. (2010). Lunar dust: The Hazard and Astronaut Exposure Risks. Earth, Moon, and Planets, 107(1), 107–125. https://doi.org/10.1007/s11038-010-9365-0

After

Equipment, including tools and instruments, that ~~operates and/or~~ is maintained on the planetary surface shall be designed to prevent dust intrusion into components and areas where dust accumulation can ~~induce failures~~ lead to failing performance requirements specified in NASA-STD-5017A Design and Development Requirements for Mechanisms

Synthesis of Comments (Checkmarks represent comments addressed in revision)

☐ Requirement is a duplicate of the one on extreme environment (Reviewer 1)

☐ Requirement is not suitable for 3001 (Reviewer 2)

☒ Requirement should inherit from existing NASA mechanism design requirement (Reviewer 3)

☐ Requirement is difficult to verify (Reviewer 4)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
N/A

Rationale for Change/Comments
This is a duplicative requirement if the above is re-worded to specify survival under all environments as described in a program document. - the environments needs to be captured as requirements in a separate document.

Reviewer 2 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text
N/A

Rationale for Change/ Comments
Why in 3001?

Reviewer 3 Don Parker (NESC Principal Engineer)

Proposed Text
N/A

Rationale for Change/ Comments
Tool and equipment functionality should be covered by the NASA STD 5017 for mechanisms and would include design tolerances for force margins in the relevant environment. These requirements should be in line with those and should be referenced as to not have vague competing requirements

Same comments as below, NASA STD 5017 for Mechanism Design in the relevant environment should be the parent and this should either reference that appropriate requirement or provide rationale as to why this is in addition to or a clarification of that mechanism design requirement

Response
Agreed and revised accordingly

NASA-STD-5017
Design and Development Requirements for Mechanisms
https://standards.nasa.gov/sites/default/files/standards/NASA/w/CHANGE-1/1/NASA-STD-5017A-Revalidated-w-Change-1.pdf

Reviewer 4 Brooke Allen and Melinda Naderi, NASA Marshall

Proposed Text
N/A

Rationale for Change/ Comments
Totally prevent dust intrusion? How do you verify this? Is there a spec?

Team Discussion comments
Requirement belongs to engineering

Also reference
Cross-Program Design Specification for Natural Environments (DSNE)
SLS-SPEC-159, Revision F (Effective May 8, 2019)
https://ntrs.nasa.gov/api/citations/20190027643/downloads/20190027643.pdf

Tina – from maintainability aspect, there needs to be consideration on dust, separate from performance requirements

Dave – maybe there should be reference to SLS-SPEC-159. Be able to maintain in the expected environment; that may be the standard we need

Nancy – there is a relocatable requirement candidate

Tina – engineering does not have a maintainability standard

Tony – they should all be candidates. Some for Safety and Engineering. A lot will need to be replicated elsewhere.

Dave – one document for everything? What we want the intent to be. Maintainability design environment?

Alonso – make both about maintenance.

Dave – agreed.

Tina – maybe consider combining with the one on dust tolerance

Dave
a. Equipment operates in expected environment
b. Be able to maintain in the expected environment

Tony – whether lifetime is part of performance requirements

Dave – meet requirements over lifetime

NEW – Michael Salopek Comments

Proposed Text

From: Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to prevent dust intrusion into components and areas where dust accumulation can induce failures.

To: Equipment, including tools and instruments that operate and/or are maintained on the planetary surface, shall be designed to mitigate failures and performance degradation below minimum specifications due to dust or other particulate contamination from the planetary surface.

Rationale for change
Suggested re-wording. One could make the argument that dust/particulates are part of the extreme environmental conditions of the planetary surface, however I like addressing them separately to avoid confusion.

C.19 Candidate Revision - 3001 No 21 - Dust Tolerance

Before

Dust Tolerance

Dust shall not reduce tool and equipment functionality below minimum performance specifications.

[Rationale: Planetary surface dust environments have the potential to disrupt operations on the Moon, Mars, and asteroids. Composition and transport mechanisms may vary, but in general, dust can cause thermal management, erosion, binding, and other issues with equipment, as well as affect crew health. Both active (e.g., cleaning or protecting through external forces) and passive (e.g., pretreating to reduce attraction) technologies may be used to mitigate dust effects. If such technologies are unable to eliminate dust intrusion, then its consequences must be anticipated and controlled. Equipment and tools that cannot be completely protected from dust should be made robust to the dust environment and tolerant of dust effects such that functionality is not adversely compromised.]

After

[new standard text]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☐ Overlaps with #20 [*Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to prevent dust intrusion into components and areas where dust accumulation can induce failures.] (1, 6, 8)*
- ☐ Could be unavoidable (2) and unverifiable (6)
- ☐ Rewrite requirement in terms of meeting performance requirements when exposed to dust environments specified in DSNE (3)
- ☐ Rewrite as a cleanliness standard? (4)
- ☐ Compare to NASA STD 5017 (5)
- ☐ Add " and lifetime" specifications to end of requirement (6)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Comments
This is a duplicative requirement if the above *[Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to prevent dust intrusion into components and areas where dust accumulation can induce failures.]* is re-worded to specify survival under all environments as described in a program document. - the environments needs to be captured as requirements in a separate document.

Reviewer 2 James O'Donnell (NESC Integration Office)

Proposed Text/Comments
"Dust shall not reduce tool and equipment functionality below minimum performance specifications." My only comment about this one is that I can imagine there being a tool or equipment where this is unavoidable and the correct answer would be to plan for this by having an adequate supply of them when they wear out or break.

Response:
Agree, tailoring and/or waiving of this requirement will be handled by programs

Reviewer 3 Joe Minow (NASA Technical Fellow for Space Environments)

Proposed Text
Tool and equipment functionality shall meet all performance requirements during and after exposure to dust environments as specified in the SLS-SPEC-159 DSNE.

[Rationale: Planetary surface dust environments have the potential to disrupt operations on the Moon, Mars, and asteroids. Composition and transport mechanisms may vary, but in general, dust can cause thermal management, erosion, binding, and other issues with equipment, as well as affect crew health. Both active (e.g., cleaning or protecting through external forces) and passive (e.g., pretreating to reduce attraction) technologies may be used to mitigate dust effects. If such technologies are unable to eliminate dust intrusion, then its consequences must be anticipated and controlled. Equipment and tools that cannot be completely protected from dust should be made robust to the dust environment and tolerant of dust effects such that functionality is not adversely compromised.]

Rationale for change
Rewrite requirement in terms of meeting performance requirements when exposed to dust environments specified in DSNE. Lunar dust environments are specified in Section 3.4.2 of the DSNE. There are reserved sections in the DSNE for surface environments on Mars (Section 3.10), moons of Mars (Section 3.11), and near Earth asteroids (Section 3.12). These sections will be updated in the future to contain the necessary dust design environments.

Response:
Change made

Reviewer 4 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text/Comments
Maybe this one can be rewritten as a cleanliness standard? Something like: "Tools and equipment shall be designed to prevent failure caused by environmental exposure." The rationale could then describe the dust, water vapor, thermal, etc. risks to tool failure.

Response:
Proposing separate cleaning standard

Reviewer 5 Don Parker (NESC Principal Engineer)

Comments
Tool and equipment functionality should be covered by the NASA STD 5017 for mechanisms and would include design tolerances for force margins in the relevant environment. These requirements should be in line with those and should be referenced as to not have vague competing requirements

Reviewer 6 Brooke Allen and Melinda Naderi, NASA Marshall

Comments
how does this relate to the last requirement? *[Equipment, including tools and instruments, that operates and/or is maintained on the planetary surface shall be designed to prevent dust*

intrusion into components and areas where dust accumulation can induce failures.]
How would you verify this--what does it take to meet this?

Reviewer 7 Tony DiVenti

Proposed Text/Comments
Add performance "and lifetime" specifications to requirement. Enforces concept that lifetime expectations and requirements need to be defined (and coupled with) performance because items often can not work infinitely without some level of degradation. Lifetime should help projects better scope their costs and efforts needed to meet this important requirement.

Response:
We discussed in meeting and agreed to keep as is

Reviewer 8 Michael Salopek

Proposed Text
Delete

Rationale for Change/Comments
I think this can be combined with the previous requirement using my suggested re-wording.

C.20 Candidate Revision – 3001 No 22 – Dust Removal

Before

Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable and withstand cleaning using planned cleaning methods.

[Rationale: The cohesive properties of lunar dust in a vacuum, augmented by electrostatic properties, tend to make it adhere to anything it contacts. Upon attaining gravity, some of the lunar dust floats up in the pressurized environment atmosphere and becomes widely dispersed. During Apollo missions, dust brought into pressurized environments (lunar modules, command modules) was found to cause irritation to the eyes and lungs of the astronauts, potentially compromising crew health (Gaier, 2005). An efficient plan is to be designed and implemented for removing dust from any item exposed to planetary surface dust before entering the airlock. Such items are to withstand cleaning using planned cleaning methods, including not sustaining scratches by the abrasiveness of lunar dust in the cleaning process]

Gaier, J. R. (2005). The Effects of Lunar Dust on EVA Systems During the Apollo Missions (NASA Technical Memorandum NASA/TM-2005-213610). Glenn Research Center. https://history.nasa.gov/alsj/TM-2005-213610.pdf

After

Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable and withstand cleaning using planned cleaning methods.

[Rationale: The cohesive properties of lunar dust in a vacuum, augmented by electrostatic properties, tend to make it adhere to anything it contacts. Upon attaining gravity, some of the lunar dust floats up in the pressurized environment atmosphere and becomes widely dispersed. During Apollo missions, dust brought into pressurized environments (lunar modules, command modules) was found to cause irritation to the eyes and lungs of the astronauts, potentially compromising crew health (Gaier, 2005). An efficient plan is to be designed and implemented for removing dust from any item exposed to planetary surface dust before entering the airlock. Program requirements on cleaning methods and cleanliness level are to be established pursuant to Surface Cleanliness Level – Generally Clean as specified in JPR 5322.1 Contamination Control Requirements Manual Table 3-1, or equivalent. ~~Such items are to withstand cleaning using planned cleaning methods, including not sustaining scratches by the abrasiveness of lunar dust in the cleaning process~~]

Synthesis of Comments (Checkmarks represent comments addressed in revision)

- ☒ Requirement should specify a “clean to” level (Reviewer 1, Reviewer 3)
- ☐ Requirement should specify cleaning methods (Reviewer 1, Reviewer 4)
- ☐ Requirement could be combined with dust tolerance requirement candidate (Reviewer 2)
- ☐ Requirement is vague (Reviewer 3)
- ☒ Requirement provides no metric to verify (Reviewer 3)
- ☒ Requirement should inherit from existing NASA standard on contamination control requirements (Reviewer 3)
- ☐ Requirement may be considered in corresponding Planetary Protection requirements (Reviewer 5)
- ☐ Requirement could be a candidate in Safety and Engineering parking lot (Reviewer 5)

Reviewer 1 Heather Koehler (NASA Technical Fellow for Flight Mechanics)

Proposed Text
Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable (to XX level) and withstand cleaning using planned cleaning methods (what planned methods - are any methods acceptable ?If not specify which exact methods so it can be verified).

Rationale for Change/Comments
This requirement should specify a "cleaned to level" so it's easy to verify. Need to specify exact methods or this statement will require further clarification with a contractor.

Reviewer 2 Morgan Abney (NASA ECLSS Technical Fellow)

Proposed Text
N/A

Rationale for Change/ Comments
Could be combined with proposed 21 rewrite above.
(note: 21 refers to dust tolerance requirement candidate)

Reviewer 3 Don Parker (NESC Principal Engineer)

Proposed Text
N/A

Rationale for Change/ Comments
This requirement is vague. There are specific standards and specifications for cleaning and contamination control (i.e. NASA SN-C-0005) for operational spacecraft environments and these requirements listed here should not be in conflict with or augment other requirements without additional rationale and reference to those applicable requirements. Also, these particular requirements are vague and do not have metrics to verify compliance. Cleaned is a relative term typically defined by an associated level and particulate tolerance and none is specified or referenced.

Response
Space Shuttle Contamination Control Requirements
NASA-SN-C-0005, Revision D (July 20, 1998)
http://everyspec.com/NASA/NASA-JSC/NASA-JSC-General/SN-C-0005D_3509/

Similar requirements
JPR 5322.1H Contamination Control Requirements Manual
https://imlive.s3.amazonaws.com/Federal%20Government/ID442073314433735474660840042908205934 38/JPR5322.1_Rev_H.pdf

Contamination Control Requirements Manual	JPR No.	5322.1H
	Effective Date:	01/25/2016
	Expiration Date:	01/25/2021
	Page Number	Page 21 of 57

TABLE 3-1	SURFACE CLEANLINESS LEVELS	
A. CLEANLINESS LEVELS AND DESCRIPTIONS		
LEVEL	**NAME**	**DESCRIPTION**
GC	**Generally Clean** [*1]	Hardware shall be free of visible manufacturing residue, dirt, oil, grease, processing debris, or other extraneous contamination. Customer requirements may preclude usage of GC.
VC	**Visibly Clean** [*2]	Hardware shall meet the requirements of the GC Level, and qualitatively verified to be free of all particulate and non-particulate material when viewed from a specified distance with normal unaided (or corrected-to normal) vision with a specified illumination level.
VC+UV	**Visibly Clean + Ultraviolet** [*3]	Hardware shall meet the requirements of the specified VC Level, and qualitatively verified by inspection under UV light (3,200 to 3,800 angstroms) to be free of surface film residue.
PC	**Precision Clean**	Hardware shall meet the requirements of the specified VC Level, and quantitatively verified as clean by direct or indirect sampling using particle counting and/or Non-Volatile Residue (NVR) analysis.

Also maybe relevant
IEST-STD-CC1246E: Product Cleanliness Levels – Applications, Requirements, and Determination

(Note: IEST • Institute of Environmental Sciences and Technology)
This standard provides methods for specifying and determining product cleanliness levels for contamination-critical products. The emphasis is on contaminants that can impact product performance.
https://www.iest.org/Standards-RPs/Recommended-Practices/IEST-STD-CC1246

Reviewer 4 Brooke Allen and Melinda Naderi, NASA Marshall

Proposed Text
N/A

Rationale for Change/ Comments
Need to define planned cleaning methods before you can verify this requirement.

Reviewer 5 Tony DiVenti

OK with this change. However, brings up topic of consideration relating to potential standardization of this requirement with what may (or may not) be required in corresponding Planetary Protection requirements. Also add as a Parking Lot consideration item for Safety & Eng.

Reviewer 6 Michael Salopek – NEW

Proposed Text
From: Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable and withstand cleaning using planned cleaning methods.

To: Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable and withstand cleaning using planned cleaning methods prior to entering the pressurized environment.

Rationale for Change/Comments
Based on rationale, assume we want this cleaned prior to entering the habitat. Could argue that is covered by the "planned cleaning method" however I was thinking it may be worth pointing out specification because this would imply that the tool or equipment must be able to be cleaned while the crew is wearing pressurized gloves/suits.

Appendix D. Candidate Standards Submitted for STD 3001, Vol 2 Recommendations

22-01739 NASA Exploration Systems Maintainability Standards for Artemis and Beyond

*Edits to existing 3001 standards in red

D.1 General

D.1.1 Maintenance Concept of Operations

For each maintenance-level item, the human space flight program shall define and document a maintenance concept of operations considering the following factors and updated throughout the design lifecycle:

a. Mission work environment (e.g., dust, lighting, heating, atmosphere, gravity) as specified in the SLS-SPEC-159 Cross Program Design Specification for Natural Environments (DSNE).
b. Tools, aids, and support equipment available to the maintainers in-situ.
c. Skill-level of the maintainers (i.e., crewmembers).
d. Access needed to equipment.
e. Reliability- or performance-driven preventive maintenance schedule.
f. Preventive and corrective maintenance plans.

[Rationale: Maintenance level items are assembled units or modules that are designed to be isolated from the rest of its system, removed, maintained, repaired, and/or replaced by the maintainer on-mission. Certain subsystems are so crucial to survival they need to be identified to drive modularity and sparing of the entire system. Maintenance-level items and subsystems are identified through the trade space analysis considering the following factors, among others: reliability, redundancy, functionality sustainment, stress reduction, derating, accessibility, modularity, and condition-based monitoring. If proper attention and emphasis is not placed on supportability concerns and issues, particularly early in a program, the potential impacts to operations can be significant. NASA has been able to shift maintainability requirements from design phase to operations because ground support can be increased throughout the mission. This will not be possible to the same extent with longer lunar surface operations where vehicles and equipment will reside on the Moon. The same will be true for Mars compounded by long communication latencies that will not allow ground to provide real-time guidance and oversight for preventive and corrective maintenance tasks. In addition, environmental factors associated with surface operations, including dust, thermal extremes, day to night transitions, static electricity, dormancy, etc., will increase maintainability challenges. Standards and requirements for supportability, must be implemented early in missions beyond low-Earth orbit utilizing technologies that cannot be repaired on Earth and cannot be replaced from Earth. Impacts of not developing a Maintenance ConOps include loss of a mission or loss of life given the communication latencies, resupply challenges and evacuation constraints of NASA's Lunar and Martian DRMs.]

D.1.2 Availability of Critical Systems

Repairs and/or replacements shall be designed to be completed within the time-to-effect with margin and with consideration of operational factors. *If they cannot be so completed, alternative design strategies (e.g., redundancy) shall be utilized to maintain critical functionality.*

[Rationale: Mission success is dependent on the availability of the critical systems that keep the crew alive and enable completion of mission objectives. System reliability is one approach to assuring availability. If reliability cannot be guaranteed, corrective maintenance and contingency plans are needed to assure system operation. Repair and replacement activities may be time constrained depending on availability requirements. Operational factors, including available onboard resources, crew capabilities, and environmental constraints, affect the design and feasibility of corrective maintenance activities.

D.1.3 Damage Prevention

The system shall be designed to prevent collateral and inherent damage during maintenance.

[Rationale: Maintenance activities can lead to increased failures because there is risk to the subject system and proximate systems each time the system is opened or disturbed, especially when systems are not designed for maintainability. Designing the system to the physical capabilities and limitations of the maintainer prevents damage when proper procedures are followed. Designing systems to contain failure effects, minimize failure propagation, and minimize interaction with proximate systems also reduces the risk of damage during maintenance. Designs and maintenance strategies should be analyzed (e.g., failure/process analysis) for feasibility and risk prior to incorporation.]

D.1.4 In-mission Maintenance

All flight hardware and software shall be designed to facilitate in-mission maintenance (both preventive and corrective) and check-out.

[Rationale: Crew and vehicle health and the ability to meet mission objectives require that maintenance and check-out activities be achieved with efficiency and accuracy. Design considerations, e.g., tool interfaces, can significantly impact the performance of these activities. Maintainability and its characteristics are to be considered in the design trade space.]

D.2 Accessibility

D.2.1 Access Using Available Tools

Systems and units of equipment shall be accessible and serviceable using the in-mission tool set.

[Rationale: Accessibility is a key characteristic of system maintainability, and therefore to system availability. Even if the equipment does not require *preventive* maintenance, or is not anticipated, due to reliability estimates, to require *corrective* maintenance, it may need to be accessed and opened due to unforeseen events. Further, logistical constraints of missions BLEO will require maintenance to be performed at an intermediate level—e.g., that below the ORU level. ISS experience has shown that intermediate level maintenance is problematic if not all parts of the ORU are designed to be accessed or repaired. As sparing will be limited during extended missions without access to frequent resupply, it may also be necessary to scavenge parts from operating equipment to replace failed parts in higher priority systems.]

D.2.2 Module Access – Edits to Existing Standard

[V2 9045 original] The system shall locate maintenance items so that the maintenance task does not require the removal or disabling of other systems or components.

[V2 9045 suggested edits] The system shall ensure access to maintenance items so that the maintenance task does not require the removal or disabling of other systems or components (excluding access panels).

[Edits to existing rationale: Location of items depends on many factors (physical room, interface with other items, manufacturing considerations, etc.), and maintenance can be easily overlooked. It is important, therefore, that, early in a design, system developers identify those items that require frequent and/or critical maintenance. Deintegrating and demating is a source of risk during maintenance. Accessibility to critical items and those items requiring frequent servicing is a priority. Required electrical and pressure and fluid system safing are exempt from this requirement. ~~Accessibility to those items then becomes a higher priority in selecting the location of these items.~~]

D.3 Visibility and Identifiability

D.3.1 Component Identification

Flight hardware shall include information and labeling that enables the crew to correctly locate, identify, and handle systems components.

[Rationale: It is critical to provide an accurate representation of the interior of any flight hardware unit that can be opened, both to ensure crew safety and to prevent damage to the system. Information and labeling are especially important for unplanned corrective maintenance tasks that require crewmembers to open an unfamiliar unit and locate, identify, and handle the components inside. Well-designed labeling enables crewmembers to contextualize the components within the system and understand subsystem interactions. Additionally, potentially hazardous items are clearly labeled to protect crewmembers from injury.

D.3.2 Cable Identification – Edits to Existing Standard

[V2 9035 original] All maintainable cables, wires, and hoses shall be uniquely identified.

[V2 9035 suggested edits] All maintainable cables, wires, and hoses shall be uniquely and consistently identified at the maintenance point.

[Rationale: Locating and identifying the specific cable, wire, or hose needed for a maintenance activity can be time consuming. Unique identifications that enable rapid recognition among similar items reduce maintenance time. Consistency in the manner of identification across items decreases the time needed for locating and interpreting identifications. Identifications that enable rapid recognition without the use of conversion tables are less susceptible to errors. Redundant identifications give maintainers more than one opportunity to identify the item, increasing maintenance efficiency. Some conductors do not terminate in a keyed connector; they are individually attached. It is essential that the conductors be attached to the correct terminal points. All individual conductors that attach to different terminal points are to be coded. Terminal points are normally fixed and can be identified with labels and illustrations. Conductors, on the other hand, are to have identifications affixed to them. This is normally done with color coding of the insulation materials or by tagging the conductors. Additional design standards for cables, wires, and harnesses can be found in NASA STD 8739.4.]

D.3.3 Visual Aids for Maintenance

Visual aids for both preventive and corrective maintenance shall be provided with appropriate scale, orientation, and context to enable crew to locate and identify components.

[Rationale: Locating and identifying all the components involved in a maintenance procedure can be time-consuming, especially when a crewmember is working with an unfamiliar system. Photos, videos, and other graphics are invaluable for providing context, and their use can accelerate pre-maintenance preparation and procedure execution. Visual aids are to be accurate to the operational environment and provide the appropriate amount of detail for the task to enable efficiency. Sparse or misleading visual cues can contribute to spatial disorientation (Bloomberg 2016) and influence astronauts' ability to accurately perform cognitive and sensorimotor tasks. (Clément et al. 2013) Appropriate visual aids are increasingly important for exploration beyond LEO, where lower-level in-mission maintenance will be necessary, and oversight from the ground will be limited. Visual aids may be provided digitally and/or within a procedure. Interactive visual aids that enable crew to dynamically resize and rotate should be considered to amplify crewmembers' understanding of the system context. Using the same visual aids in pre-mission training may be helpful to build crew familiarity with both the system and the visual aids.]

Bloomberg, J.J., Reschke, M.F., Clément, G.R., Mulavara, A.P., Taylor, L.C. (2016). Evidence Report: Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight. (NASA Evidence Report). Lyndon B. Johnson Space Center. https://ntrs.nasa.gov/api/citations/20150018603/downloads/20150018603.pdf

Clément G, Skinner A, Lathan C (2013) Distance and size perception in astronauts during long-duration space flight. Life 3: 524-537. https://doi.org/10.3390%2Flife3040524

D.4 Tools & Test Equipment

D.4.1 In-Mission Tool Set – Edits to Existing Standard

[V2 9038 original] Each program shall establish a set of in-flight tools necessary to maintain or reconfigure the space flight system. Also, tools are to be usable by the full range of crew sizes and strengths wearing any protective equipment (EVA suits, protective eyewear, gloves, etc.).

[V2 9038 suggested edit part 1] ~~Each mission program shall establish~~ A common set of in-mission tools and test equipment necessary to maintain or reconfigure the space flight and surface systems shall be established.

[Rationale: Establishing a common set of tools with which all mission systems can be maintained minimizes mass and complexity, reduces training demands, and increases redundancy for a given mission. Tool set design is to be based partly on reducing the demands on the crew: selecting tools that are likely to be familiar to crewmembers and minimizing the number of different tools. IVA and EVA tools generally differ due to the unique requirements imposed by the EVA environment, therefore a common set of IVA and a common set of EVA tools with as much overlap as possible is a primary goal of this requirement. The other primary goal of this requirement is to have a common set of tools for all phases of the mission to be used across all elements of the mission (e.g., transportation vehicle, orbital outpost, lander, surface habitat, and surface systems should all use the same common toolkit.) Apollo and ISS lessons learned indicate that tool set design is also to consider the complement of tools and equipment needed to respond to unexpected failures and hardware workarounds. Having a comprehensive and common tool set is especially important for future long-duration missions with constrained or nonexistent resupply operations.]

[V2 9038 suggested edit part 2] Tools and test equipment shall be usable by the full range of crew sizes and strengths wearing any protective equipment (EVA suits, protective eyewear, gloves, etc.)

[Rationale: Crew members of varying size and strength need the capability to conduct maintenance activities under a variety of conditions. Ensuring tools and test equipment are usable under the most encumbering circumstances reduces maintenance time and complexity.]

D.4.2 Tool and Test Equipment Commonality

Systems and units of equipment shall be designed so that maintenance can be accomplished with the set of in-mission tools and test equipment.

[Rationale: ISS lessons learned indicate that crews often have difficulty locating the tools and test equipment needed for a given activity, resulting in many hours spent searching for items and delayed maintenance. Tool and test equipment commonality provides redundancy and contributes to crew readiness for unplanned maintenance activities. Interchangeable tools and test equipment improve mass efficiency because common items can cover multiple types of failures. Utilizing common tools and test equipment across vendors increases in importance for missions beyond low-Earth orbit, when increasingly complex and limited resupply operations constrain the ability to replace missing or ineffective tools and test equipment while simultaneously limiting the ability to return ORUs to the ground for maintenance. Commonality helps to ensure the right tools and test equipment are available at the right time to crewmembers in-mission.]

D.4.3 Tool Clearance – Edits to Existing Standard

[V2 9050 original] The system shall provide tool clearances for tool installation and actuation for all tool interfaces during in-flight maintenance.

[V2 9050 suggested edit] The system shall provide tool clearances for tool installation and actuation for all tool interfaces during in-mission maintenance.

[Rationale: Tools to be used for in-mission ~~in-flight~~ maintenance are to be identified by the hardware developer, and clearance for application is to be accommodated to ensure that maintenance tasks can be performed.]

D.5 Data

D.5.1 Condition Monitoring

The system shall be designed to provide condition-monitoring data to an information system that can be accessed by the crew, either automatically or by request. (See also 10.1.6.1 System Health and Status.)

[Rationale: Monitoring is needed to optimize maintenance action plans and improve system availability. Reliability estimates are often conservative, leading to unnecessary preventive maintenance (NASA RCM Guide, 2000). Many preventive maintenance tasks achieve nothing, while some are actively counterproductive and even dangerous (Mowbray, 1997); maintenance tasks are prone to human error, (Hobbs, 2021) and the risk of damage is increased each time a system is opened. Condition monitoring provides maintenance triggers, reducing the need for interval-based maintenance. Condition monitoring reduces the reliance on reliability data to ensure availability, ultimately improving crew safety and efficiency. New cost-effective, low-mass technologies increase the value of condition monitoring for missions beyond LEO.]

D.5.2 Maintenance Management Information

For preventive maintenance, the following data shall be captured/available to the crew to support autonomous procedure execution:

a. Procedures
b. Visual aids
c. Functional state data (e.g., power, temperature, pressure, standby)
d. Active indication of critical procedure step completion
e. Active indication of restored functionality
f. Replacement unit maintenance history
g. Procedure execution records

In addition, for unexpected, corrective maintenance, the following information shall be available to the crew to support autonomous troubleshooting:

a. Diagnostic sensor data
b. Troubleshooting steps and decision trees
c. Description of possible faults and locations
d. Description of test points and normal reading ranges
e. Test result interpretations and corrective action recommendations

[Rationale: Maintenance management information enables maintainers to make informed decisions about when and how to perform maintenance. Real-time maintenance triggers reduce the reliance on reliability data and eliminate unnecessary preventive maintenance tasks.]

D.6 Diagnosis and Troubleshooting

D.6.1 Maintenance Activities

Maintenance activities shall be designed at the skill-level of the crewmembers.

[Rationale: Effectively leveraging crew capabilities is especially important for exploration beyond LEO, where intermittent and delayed communication with the ground necessitates greater crew autonomy in executing preventive and corrective maintenance tasks. Designing equipment based on the basic abilities and limitations of crew to accomplish the assigned tasks will enable increasingly Earth-independent procedure execution, with reduced guidance and oversight from the ground. The skill-level of crewmembers can also be increased using "just-in-time" in-mission training that is specific to the situation or system. This method may be useful in situations in which mass constraints prevent the reduction of system complexity. Designing maintenance tasks based on the capabilities of the "front-line" maintainer (as opposed to the provider) can reduce errors, reduce training time, reduce workload, and decrease task execution time.]

D.6.2 Maintenance Decision Aids

For unplanned maintenance activities, decision aids shall be provided to support diagnosis, troubleshooting, and procedure execution at the skill-level of the crewmembers.

[Rationale: For exploration beyond LEO, intermittent and delayed communication with the ground necessitates greater crew autonomy in managing unanticipated unplanned vehicle maintenance. In lieu of continuous ground support simplified diagnostic aids are needed to assist crewmembers in narrowing down possible causes of anomalies and making time-critical decisions in the face of uncertainty. A sequence of trouble-shooting checks is to be specified at the skill-level (e.g., training, experience) of the maintainer. To maximize the effectiveness of decision aids, the system should be designed to minimize ambiguity groups (possible failure points) and support its recommendation with relevant data (see #134).]

D.7 Testing

D.7.1 Verification of Repair

Preventive and corrective maintenance shall include means for verification of successful completion.

[Rationale: Verification can be provided through system self-test, external measurements, or other methods. Repair activities inherently introduce risk to a system; the repair itself may be unsuccessful or maintainers may cause further damage during the repair process. Verifying a system has returned to proper functionality before returning the system to nominal operations prevents further damage or loss of operability. On missions beyond low-Earth orbit, an indication provided at the maintenance location (e.g., onboard the vehicle) will allow crewmembers to verify repair success without relying on ground teams. Even small communication delays (e.g., 6 to 10 seconds on the surface of the moon) reduce the ground team's ability to oversee repair activities. Crewmembers will conduct more repairs on missions beyond LEO, as the ability to send systems to the ground for detailed investigation and repair is constrained; crew access to repair data will facilitate successful maintenance.]

D.8 Training

D.8.1 In-Mission Training

In-mission training/refreshers shall be provided to ensure crew proficiency in performing maintenance activities, including using the tools and test equipment required for maintenance.

[Rationale: Repairs are designed to be as simple as possible. However, because of the length of time between crew training and missions, providing in mission training/refreshers allows for just-in-time training. Videos and/or augmented reality are examples of training tools that may be provided.]

D.9 Lunar Environment

D.9.1 Maintenance Time – Edits to Existing Standard

[V2 9039] Planned maintenance for systems and associated hardware and equipment **shall** be capable of being performed within the allotted crew schedule while wearing the most encumbering equipment and clothing anticipated.

[Suggested edits to rationale: Maintenance and servicing are directly related to the amount of time available for mission goals. Reduction in the time devoted to maintenance and servicing means more crew time devoted to achieving mission goals. Also, because of the complexity of space missions and the interdependency of many factors (equipment, supplies, weather, solar flares, changes in mission design and objectives, etc.), designs are to be self-sufficient and minimize reliance on outside maintenance support. Designs are to provide the tools and mechanisms (including cleaning), parts (as modular units where possible), supplies, training, and documentation necessary for crews to maintain efficient and safe operations. Crew schedule allotted for planned maintenance is to include time associated with dust management and cleaning.]

D.9.2 Mobility Aid Provision – Edits to Existing Standard

[V2 8042] Mobility aids shall be provided to support all expected suited and unsuited tasks.

[Suggested edits to rationale: Mobility aids must support all ~~IVA~~ tasks, which may be suited or unsuited. Design of mobility aids are to consider the entire range of crewmember activities. Because of the limited maneuverability of a suited crewmember, mobility aids are required to allow crewmembers to safely and efficiently ingress and egress the vehicle in both microgravity and on the surface. Without predefined mobility aids, personnel may use available equipment that may be damaged from induced loads. Mobility aids are to be designed to accommodate a pressurized-suited crewmember by providing clearance, non-slip surfaces, and noncircular cross sections.

Microgravity considerations: Experience in the Skylab program showed the problems of movement in microgravity. Stopping, starting, and changing direction all require forces that are best generated by the hands or feet. Mobility aids such as handholds and foot restraints allow crewmembers to efficiently move from one location to another in microgravity, as well as reduce the likelihood of inadvertent collision into hardware that may cause damage to the vehicle or injury to the crew. Appropriately located mobility aids make this possible. Mobility aids for ~~EVA~~ microgravity suited operations must be provided along the expected translation paths of suited crewmembers at an interval that accommodates the suited crewmember's reach.

Surface operations considerations: Experience in the Apollo program showed the problems of movement in partial gravity due to the lack of reaction forces which caused issues ambulating and utilizing tools that provided torque. Mobility aids will be required when ingressing and egressing a vehicle as well as to protect crewmembers from a fall when descent from height is necessary to reach surface for EVAs. Multi-purpose mobility aids could help reduce the number of items required (e.g., a surface EVA mobility aid may serve as a cart for ICR transport, provide additional lighting, and be a UHF/wifi-repeater).]

D.9.3 Contamination Prevention

Maintenance tasks shall be designed to prevent environmental contamination of maintenance target and EVA systems.

[Rationale: Planetary surface environments have the potential to disrupt operations on the Moon, Mars, and asteroids. Lessons learned from Apollo lunar surface missions indicate that care must be exercised to minimize dust contaminants during maintenance. Maintenance tasks should be analyzed before application by maintainers to ensure appropriate contamination provisions are in place within procedures. Note: For celestial body in-situ conditions preservation see NASA-STD-8719.27, Planetary Protection Standard.]

D.9.4 Extreme Environment

Equipment, including tools and instruments, that is maintained on the planetary surface shall be designed to meet all performance requirements specified in NASA-STD-5017A Design and

Development Requirements for Mechanisms during and after exposure to the expected environmental conditions specified in the SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE).

[Rationale: Space environment can present extreme environmental (EE) conditions in pressure, temperature, radiation, and chemical or physical corrosion, as well as acidity and dust. Certain planned mission operations can also induce EE conditions in heat flux and deceleration (g-loading) during entry, descent, and landing (EDL) phases (Balint et al., 2008). Contamination with lunar dust can affect the function of equipment and instrumentation by degrading seals and valves, breaking down lubricants, jamming moving parts, and creating flow blockages (Cain, 2010). Exposure of space hardware to EE conditions, if not designed and built to sustain, can lead to malfunctions and consequently higher spare requirements and frequent maintenance and servicing needs. Increase in both equipment failures and maintenance and servicing needs means less crew time devoted to achieving mission goals. Designs are to prevent EE conditions from negatively impacting mission objectives and operations.

Balint, T. S., Cutts, J. A., Kolawa, E. A., & Peterson, C. E. (2008). Extreme environment technologies for space and terrestrial applications. Space Exploration Technologies, 6960, 36–47. https://doi.org/10.1117/12.780389

Cain, J. R. (2010). Lunar dust: The Hazard and Astronaut Exposure Risks. Earth, Moon, and Planets, 107(1), 107–125. https://doi.org/10.1007/s11038-010-9365-0

D.9.5 Dust Tolerance

When designs cannot prevent its intrusion, dust shall not reduce tool and equipment functionality below minimum performance specifications as specified in the SLS-SPEC-159 DSNE.

[Rationale: Planetary surface dust environments have the potential to disrupt operations on the Moon, Mars, and asteroids. Composition and transport mechanisms may vary, but in general, dust can cause thermal management, erosion, binding, and other issues with equipment, as well as affect crew health. Both active (e.g., cleaning or protecting through external forces) and passive (e.g., pretreating to reduce attraction) technologies may be used to mitigate dust effects. If such technologies are unable to eliminate dust intrusion, then its consequences must be anticipated and controlled. Equipment and tools that cannot be completely protected from dust are to be robust to the dust environment and tolerant of dust effects such that functionality is not adversely compromised.]

D.9.6 Dust Removal

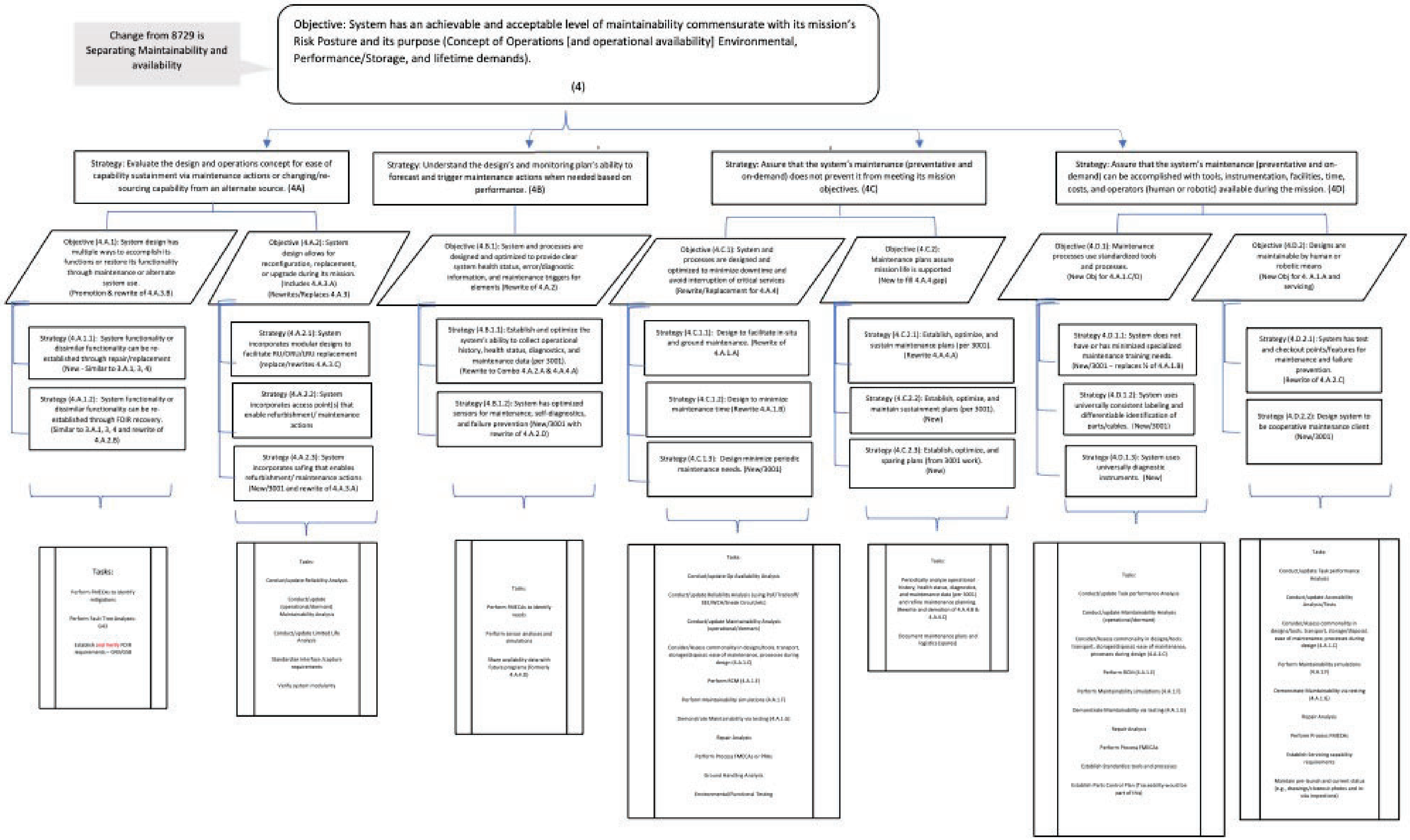
Any item exposed to planetary surface dust that must be brought into pressurized environments shall be cleanable and withstand cleaning using planned cleaning methods.

[Rationale: The cohesive properties of lunar dust in a vacuum, augmented by electrostatic properties, tend to make it adhere to anything it contacts. Upon attaining gravity, some of the lunar dust floats up in the pressurized environment atmosphere and becomes widely dispersed. During Apollo missions, dust brought into pressurized environments (lunar modules, command modules) was found to cause irritation to the eyes and lungs of the astronauts, potentially compromising crew health (Gaier, 2005). An efficient plan is to be designed and implemented for removing dust from any item exposed to planetary surface dust before entering the airlock. Program requirements on cleaning methods and cleanliness level are to be established pursuant

to Surface Cleanliness Level – Generally Clean as specified in JPR 5322.1 Contamination Control Requirements Manual Table 3-1, or equivalent.]

Gaier, J. R. (2005). The Effects of Lunar Dust on EVA Systems During the Apollo Missions (NASA Technical Memorandum NASA/TM-2005-213610). Glenn Research Center. https://history.nasa.gov/alsj/TM-2005-213610.pdf

Appendix E. Notional Revision for NASA-STD-8729.1A Maintainability Objectives Hierarchy



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Appendix A Glossary and Acronyms

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14. ABSTRACT
This assessment was requested by the NASA Engineering and Safety Center (NESC), which, based on findings from the NESC study “Safe Human Expeditions Beyond Low Earth Orbit (LEO)” (Valinia et al., 2022), determined its topic to be an underrecognized critical and urgent Agency need, due to impending Artemis vehicle procurements. The principal objective of this assessment was to review and update current Agency-level maintainability requirements for space systems to support crew on expeditions beyond LEO in both preventive and corrective maintenance. This report contains the results of the NESC assessment.

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