NASA-STD-3001 Technical Brief

Design for Maintainability

OCHMO-TB-036

Executive Summary

Maintenance in a hostile, microgravity environment is a complex and undesirable task for humans. It also constitutes a large portion of a system lifecycle and can consume significant time during a mission. NASA-STD-3001 levies several technical requirements that provide guidance for designing equipment and systems to facilitate maintenance and ensure proper maintainability. Reduction in the time devoted to maintenance and servicing means more crew time devoted to achieving mission goals. Design for maintainability is about improving the ability to perform preventive and corrective maintenance. For crew to be able to preserve the vehicle and their own health and to meet mission objectives, maintenance and check-out activities need to be executed effectively and efficiently. Maintainability should be considered an integral part of hardware design and a life-cycle systems engineering approach should be employed from the earliest design phases throughout flight operations.

Relevant Technical Requirements

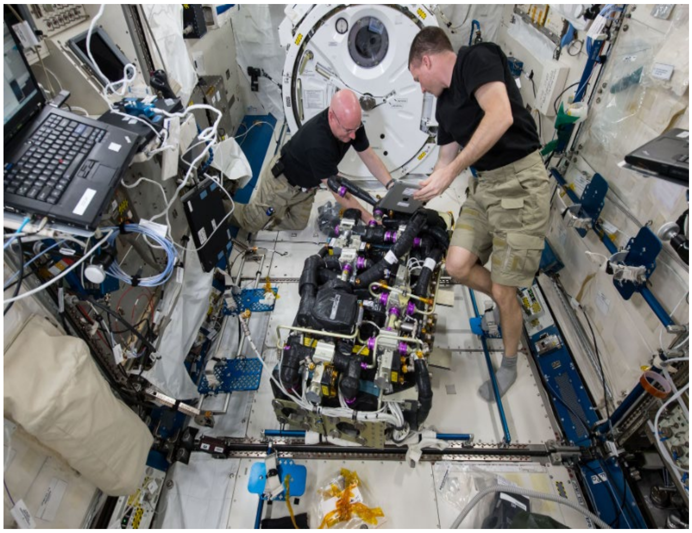
NASA-STD-3001 Volume 1, Rev C

[V1 3004] In-Mission Medical Care

NASA-STD-3001 Volume 2, Rev D

[V2 3006] Human-Centered Task Analysis
[V2 3102] Human Error Analysis
[V2 9003] Routine Operation
[V2 9004] Training Minimization
[V2 9110] In-Mission Training
[V2 9111] Maintenance Concept of Operations
[V2 9112] Availability of Critical Systems
[V2 9113] Damage Prevention
[V2 9114] In-Mission Maintenance
[V2 9033] Mating, Demating Hazards
[V2 9035] Cable Identification
[V2 9036] Design for Maintenance
[V2 9037] Commercial Off-the-Shelf (COTS) Equipment Maintenance
[V2 9038] In-Mission Tool Set
[V2 9115] Maintenance Tools Usability
[V2 9116] Tool and Test Equipment Commonality
[V2 9050] Tool Clearance
[V2 9039] Maintenance Time
[V2 9042] Captive Fasteners
[V2 9043] Minimum Number of Fasteners – Item

Executive Summary (continued)



Carbon Dioxide Removal Assembly (CDRA) Maintenance. Photo: NASA (2015)

Related OCHMO Technical Briefs:

1. OCHMO-TB-007 Mission Duration
2. OCHMO-TB-001 Artemis Lighting Considerations
3. OCHMO-TB-011 Lunar Dust
4. OCHMO-TB-017 Automated and Robotic Systems
5. OCHMO-TB-016 Behavioral Health and Performance
6. OCHMO-TB-032 Cognitive Workload
7. OCHMO-TB-002 Environmental Control & Life Support System (ECLSS)
8. OCHMO-TB-005 Usability, Workload, & Error

Relevant Technical Requirements

NASA-STD-3001 Volume 2, Rev D

[V2 9044] Minimum Variety of Fasteners – System
[V2 9117] Access Using Available Tools
[V2 9045] Maintenance Item Location
[V2 9046] Check and Service Point Accessibility
[V2 9047] Maintenance Accommodation
[V2 9048] Visual Access for Maintenance
[V2 9118] Component Identification
[V2 9119] Visual Aids for Maintenance
[V2 9051] Fault Detection
[V2 9052] Failure Notification
[V2 9120] Condition Monitoring
[V2 9121] Maintenance Management Information
[V2 9122] Fault Management Information
[V2 9123] Maintenance Activities
[V2 9124] Maintenance Decision Aids
[V2 9125] Verification of Repair
[V2 9126] Contamination Prevention
[V2 9127] Extreme Environment (EE)
[V2 9128] Dust Tolerance
[V2 10151] Labeling Plan and Icon Library
Section 10: Crew Interfaces

Background

For the past 60 years, crewed spacecraft have either been non-reusable, maintained on Earth, or maintained with system-level Maintenance Items (MI) delivered to orbit as needed. NASA-STD-3001 provides guidance in designing equipment and systems to facilitate maintenance and ensure proper maintainability to support crew in routine operations and conditions requiring critical repairs. ***NASA-STD-3001 Volume 2, Section 9.7 Design for Maintainability***

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, 1997: Designing and Developing Maintainable Products and Systems. Report No. MIL-HDBK-470A*).

Reduction in the time devoted to maintenance and servicing can mean 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, etc.), designs are to minimize reliance on outside maintenance support.

Designs are to provide the tools, parts, supplies, training, and documentation necessary for crews to maintain efficient and safe operation.
NASA-STD-3001 Volume 2 [V2 9036] Design for Maintenance

The most successful NASA programs have been those that include maintainability features in all facets of the life cycle. The frequency of maintenance for a given time highly depends on that item's reliability.

Corrective maintenance and contingency plans are needed to ensure continued system operation if reliability cannot be guaranteed.

Reliability ↑ *Frequency of maintenance* ↓

<u>On-Orbit Maintenance Types</u>

- **Preventive Maintenance:** Regularly performed on a system to lessen the likelihood of failure. Preventive maintenance can be time-based, meaning the maintenance is performed routinely on a fixed schedule, or condition-based, meaning the maintenance is performed on contingency, depending upon the condition of the equipment or system. The crew trains for preventive maintenance prior to an assigned mission. ***Refer to NSA-STD-3001 Volume 2 Appendix C: Definitions***

- **Corrective Maintenance:** Involves repairing or replacing equipment that has stopped working or is damaged. Corrective maintenance activities include identifying, isolating, and rectifying a fault to restore the failed equipment, machine, or system to an operational condition. ***Refer to NASA-STD-3001 Volume 2 Appendix C: Definitions***

Reference the NASA Human Integration Design Handbook (HIDH) Section 9.3 Maintainability for additional information

Background

Maintenance Concept of Operations

Maintainability should be considered an integral part of hardware design and a life-cycle systems engineering approach from the earliest design phases throughout flight operations. Human spaceflight programs need to define and document a **Maintenance Concept of Operations** considering the following factors, at minimum, and updated throughout the design lifecycle:

a. Mission work natural environment (e.g., dust, lighting, heating, atmosphere, gravity) as specified in program requirements for natural environments (e.g., 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 – considering mission-criticality, urgency of repair, anticipated frequency of servicing, and complexity of approach.

e. Reliability- or performance-driven preventive maintenance schedule.

f. Preventive and corrective maintenance plans.

g. Total crew time and number of crew needed.

Developing a plan is crucial for 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 the ground to provide real-time guidance and oversight for preventive and corrective maintenance tasks. ***NASA-STD-3001 Vol 2 [V2 9111] Maintenance Concept of Operations.***

In addition, environmental factors associated with surface operations, including dust, thermal extremes, day-to-night transitions, static electricity, dormancy, etc., will increase maintainability challenges.

Maintenance: All actions necessary to retain equipment in (or restore it to) a serviceable condition. Maintenance includes servicing, repair, modification, modernization, overhaul, inspection, condition determination, corrosion control, and initial provisioning of support items.
Modified based on MIL-HDBK-1908B, Definitions of Human Factors Terms.

A7-L Pressure Suit with lunar dust Apollo 11. Photo: National Air and Space Museum

For additional information, reference NASA OCHMO-TB-011 Lunar Dust and OCHMO-TB-017 Automated and Robotic Systems.

Background

<u>Maintenance Levels</u>

Depot: Extensive overhauls or repairs are conducted at sites with specialized equipment not typically located at operating locations.

Orbital Replacement Unit (ORU): Repair through in-situ replacement of whole, large-scale packages of components. When ORUs are used, each spare package replacement removes the specific item that failed, and any other items packaged within the same ORU. This strategy can minimize maintenance and repair time but can also increase logistics mass.

Sub-ORU (intermediate): Repair or replacement at lower-level assemblies. Reduces total spare mass but increases the difficulty of fault isolation and access.

Unit/Component (piece part): Repair or replacement at component level. Tracing a fault to a component is typically more difficult than isolating it to an ORU, and replacing a component can be more intricate and time-consuming than replacing an ORU.

JAXA astronaut Soichi Noguchi and ESA astronaut Thomas Pesquet during ISS spacesuit maintenance training. Photo: NASA (2020)

<u>Maintainability Design Factors</u>

Visibility: Visibility is an element of maintainability design that provides the system maintainer visual access to a system component for maintenance action(s). Designing for visibility significantly reduces maintenance times.

Accessibility: Accessibility is the ease of access to an item during maintenance. When accessibility is poor, other failures are often caused by removal/disconnection and incorrect re-installation of other items that hamper access, causing rework.

Testability: Testability is a measure of the ability to detect system faults and to isolate them at the lowest replaceable component(s). The speed with which faults are diagnosed can greatly influence downtime and maintenance costs.

Simplicity: System simplicity relates to the number of subsystems that are within the system, the number of parts in a system, and whether the parts are standard or special purpose. System simplification reduces spare investment, enhances the effectiveness of maintenance troubleshooting, and reduces the overall cost of the system while increasing reliability.

Interchangeability: Interchangeability refers to a component's ability to be replaced with a similar component without a requirement for recalibration. This flexibility in design reduces the number of maintenance procedures and consequently lowers maintenance costs.

Background

Lessons Learned from ISS Operations

In the first five years of ISS Maintenance Operations, crews spent over 4,000 hours performing preventive and corrective intra-vehicular maintenance tasks. That averages 1.9 hours or more per workday and 1.8 hours per rest day performing ISS maintenance tasks, which exceeds the time estimated by vehicle design.

Much of the ISS equipment was designed before a complete operational plan was available for how it would be used, which led to designs that are difficult to access for repairs and maintenance (access panels) and hardware and systems that are not durable and maintainable.

ISS Crewmember Feedback

Challenge of maintaining systems that were originally not designed to be maintained onboard.

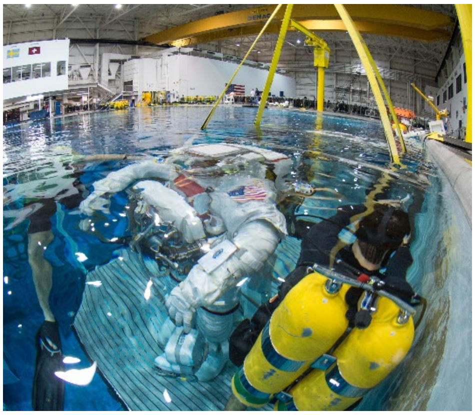
Reliability data is often limited and inaccurate for complex systems in extreme environments. Systems flown to ISS sometimes require unanticipated maintenance tasks that were never intended to be performed onboard. Crewmembers and system engineers alike reported challenges maintaining systems that were not originally designed to be maintainable. A common problem is accessibility, especially at the sub-ORU level. Another challenge is ambiguous failures that require trial-and-error of replacing multiple components to determine where the failure had occurred.

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

Crewmembers and trainers alike reported that high-fidelity mockups are critical for crewmembers to get familiar with system functionality, especially when working with complex systems or an unfamiliar task.

Visual aids can improve task efficiency and situation awareness.

When crewmembers work complex procedures, a lot of time may be spent up-front getting familiar with the task before starting (identifying parts, getting resources together) unless the crewmember is already very familiar with the system and task. Crew comments emphasized the need for robust visual aids that help identify the right components and where they go.



Expedition 42/42 crew members Terry Virts and Barry Wilmore during ISS EVA Maintenance 7 training at the NBL. Photo: NASA (2013)

Chris Hadfield replacing a low-temperature cooling valve on the ISS. Photo: Canadian Space Agency (2020)

Lessons learned summary: Plan for maintainability and integrate it in the overall design from the beginning stages. Design for ease of diagnosis and prevention of human error in maintenance

Application

<u>Design for Maintainability Considerations</u>

The following factors should be considered when designing for maintainability:

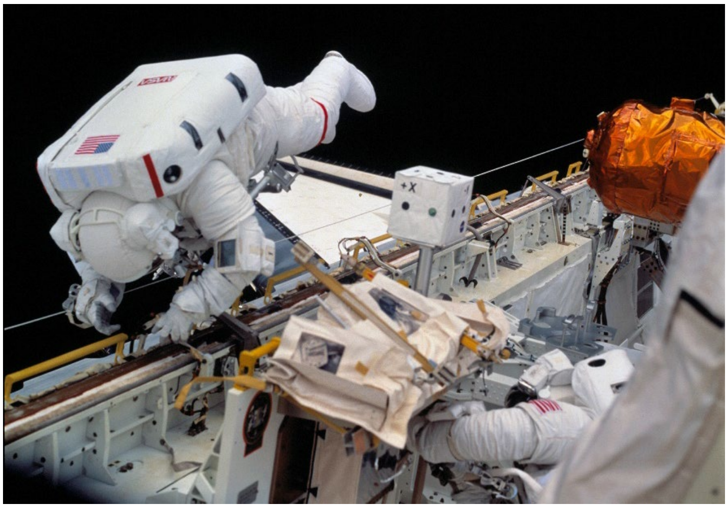
a. Non-Interference of Preventive Maintenance - Preventive maintenance should be minimized and require as little crew time as feasible.

b. Flexible Preventive Maintenance Schedule - Preventive maintenance schedules should be sufficiently flexible to accommodate changes in the schedule of other mission activities.

c. Redundancy - If maintenance is necessary and system operations will be interrupted, redundant installations should be considered to permit maintenance without interrupting system operations.

d. Goals of Designing for Maintainability – The following are goals for optimizing crew involvement in preventive and corrective maintenance:
   1. Reduce training requirements of crew.
   2. Reduce certain skill requirements of crew.
   3. Reduce time spent on preventive and corrective maintenance.
   4. Increase maintenance capabilities during the mission (especially corrective maintenance).

e. Corrective Maintenance - The following factors should be considered when designing corrective maintenance tasks:
   1. The benefit gained from repair should be worth the time and effort expended on repair.
   2. The time and effort involved in corrective maintenance should be weighed against the cost and feasibility of carrying replacement units.
   3. Required calibration, alignment, or adjustment should be easily and accurately accomplished.
   4. Automate fault detection and isolation tasks whenever possible.



NASA astronauts James Voss and Michael Gernhardt work together at the EVA Assembly and Maintenance Task Board in the Space Shuttle Endeavour's cargo bay. The EVA task board helped the two space walkers evaluate work that will be done in the relatively near future on the ISS. Photo: NASA (1995)

Mission success is dependent on the availability of the critical systems that keep the crew safe and enable the completion of mission objectives. System reliability is one approach to assuring availability. Corrective maintenance and contingency plans are needed to assure system operation if reliability cannot be guaranteed. ***NASA-STD-3001 Vol 2 [V2 9112] Availability of Critical Systems***

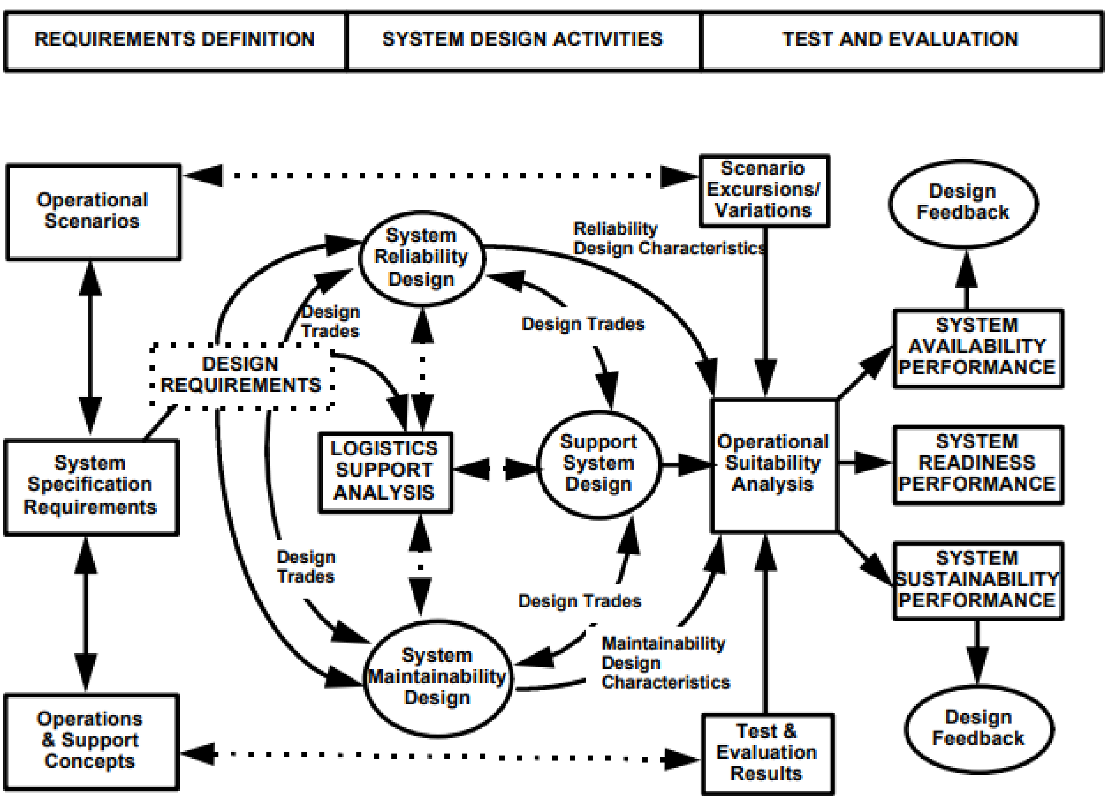
Application

Design for Maintainability Requirements

Design for maintainability is about improving the ability to perform preventive and corrective maintenance. It involves system-level optimization for parts, analyzing the resulting ergonomics, and considering tools and information as part of the design. Resilient systems are not necessarily failure-proof but recoverable through maintenance. **NASA-STD-3001 Volume 2 Section 9.7 Design for Maintainability** levies several technical requirements that provide guidance for designing equipment and systems to facilitate maintenance and ensure proper maintainability.

The design of equipment and systems greatly affects how they are maintained in terms of complexity, duration, frequency, and safety. The crew needs to safely and efficiently perform routine service, maintenance, and anticipated unscheduled maintenance activities while wearing the most encumbering equipment and clothing anticipated. ***NASA-STD-3001 Vol 2 [V2 9111] Maintenance Concept of Operations.***

Human factors design requirements should also be applied to ensure proper design considerations. Early evaluation during concept development can ensure the early application of anthropometric considerations. ***NASA-STD-3001 Vol 2 [V2 3006] Human-Centered Task Analysis; OCHMO-HB-004: Anthropometry, Biomechanics, and Strength***



System Reliability, Maintainability, and Support Relationships (typical)

From: NASA Lesson Number 831 – Maintainability Program Management Considerations (1994)

Application

Volume is to be provided to allow the size extremes of the crewmembers performing the tasks using proper tools and protective equipment within the prescribed times.

Providing volume will not be possible to the same extent with longer lunar surface operations where vehicles and equipment will reside on the Moon.

In addition, environmental factors associated with surface operations, including dust, thermal extremes, day-to-night transitions, static electricity, dormancy, etc., will increase maintainability challenges.

Exposure of space hardware to extreme environmental (EE) conditions can lead to malfunctions and, consequently, higher spare requirements and frequent maintenance and servicing needs. Designs are to prevent EE conditions from negatively impacting mission objectives and operations.

For celestial body in-situ conditions preservation, maintenance tasks should be analyzed before application by maintainers to ensure appropriate contamination provisions within procedures.

<u>Design for Maintainability Guidance</u>

Maintenance-level items and subsystems need to be identified through the trade space analysis considering the following factors: reliability, redundancy, functionality sustainment, stress reduction, derating, accessibility, modularity, and condition-based monitoring. Designs and maintenance strategies should be analyzed (e.g., failure/process analysis) for feasibility and risk before incorporation. ***NASA-STD-3001 Vol 2 [V2 9113] Damage Prevention***

Tools and Equipment Considerations: Maintenance activities are primarily where tools and fasteners are used. The need for tools should be considered early in system design since their use can have an impact on crew training and flight operations. Since many tools are used with fasteners, tool design depends greatly on fastener design.

Maintenance level Items are assembled units or modules designed to be isolated from the rest of its system and removed, maintained, repaired, and/or replaced by the maintainer on-mission.

NASA-STD-8719.27 Planetary Protection Standard

NASA-STD-3001 Volume 2 *[V2 9111] Maintenance Concept of Operations, [V2 9038] In-Mission Tool Set, [V2 9126] Contamination Prevention, [V2 9127] Extreme Environment (EE), [V2 9128] Dust Tolerance, [V2 9129] Dust Removal*

Application

Tool selection: Tool selection for planned and unplanned or contingency maintenance activities is crucial. When determining the tool complement for space missions, consider the following:

- Standardization – Tools must be standardized. This includes a need for a commonality of measurement system. ***Refer to NASA-STD-3001 Volume 2 Section 9.1 Standardization and Section 10 Crew Interfaces***

- Minimal Tool Set – The system should be maintainable and reconfigurable using a minimum set of tools that are common and feasible with the other systems. A minimum set of tools, common to more than one system, allows many maintenance tasks to be performed without a proliferation of unique tools.

- Multipurpose Tools – A tool kit should include multipurpose and multi-size tools, as there are often unexpected needs.

- Power tools should be used to accomplish repetitive manual tasks, such as disengaging captive fasteners or operating mechanical drive systems. ***Refer to Section 9.4.3 Power Tools of the HIDH for additional information.***

CDRA Maintenance
Photo: NASA (2015)

Apollo and ISS lessons learned indicate that toolset design must also consider the complement of tools and equipment needed to respond to unexpected failures and hardware workarounds. Having a comprehensive and common toolset is especially important for future long-duration missions with constrained or nonexistent resupply operations

Application

Tools labeling and identification: 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.

This is normally done by color-coding the insulation materials or by tagging the conductors. ***NASA-STD-3001 Vol 2 [V2 10151] Labeling Plan and Icon Library, [V2 9118] Component Identification, [V2 9035] Cable Identification***

It is important to accurately represent the interior of any flight hardware unit that can be opened to ensure crew safety and prevent system damage.

Tool and tool stowage labeling and identification requirements must comply with the labeling guidance defined in ***NASA-STD-3001 Vol 2 [V2 10151] Labeling Plan and Icon Library.***

Clear and informative labeling can streamline this process and help the crew properly contextualize the components within the larger system. Unique identifications that enable rapid recognition among similar items reduce maintenance time.

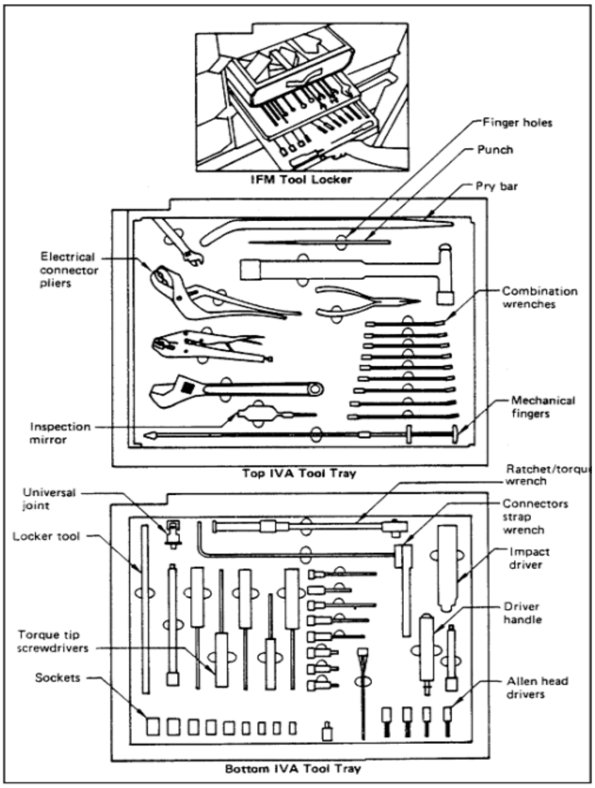
Placement labels should be provided for each tool in a stowage container. It should be obvious if a tool is outside its storage location.

For example, toolboxes that use different colors of foam, such as a yellow layer of foam beneath a blue layer. By providing the different colors of foam, it is easy to determine that a tool has yet to be returned. Tools unaccounted for can become hazardous to hardware and personnel.

[V2 9118] Component Identification
Flight systems **shall** include information and labeling that enables the crew to correctly locate, handle, and identify the systems components.

[V2 10151] Labeling Plan and Icon Library
The system **shall** provide labels that are consistent with a Labeling Plan and Icon Library as established by the program.

From: NASA-STD-3001 Volume 2



Shuttle hand tool stowage. Photo: JSC-12770 (1985)

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

Application

Tools stowage: Specialized tools should be located close to where they will be used. General-purpose tools should be stowed in one specific area. The stowage location of tool kits should be optimized for accessibility to workstations and/or maintenance workbenches. A systematic approach to the arrangement of tools in the tool kit should be applied.

Tool and test equipment commonality: It is important to have a common set of tools for all mission phases to be used across all mission elements (e.g., transportation vehicle, orbital outpost, lander, surface habitat, and surface systems). Commonality provides redundancy and contributes to crew readiness for unplanned maintenance activities. ***NASA-STD-3001 Vol 2 [V2 9116] Tool and Test Equipment Commonality***

A comprehensive and common toolset is especially important for future long-duration missions with constrained or nonexistent resupply operations. Designers need tools and test equipment usable under the most encumbering circumstances to reduce maintenance time and complexity. ***NASA-STD-3001 Vol 2 [V2 9115] Maintenance Tools Usability***

Establishing a common set of tools for maintaining all mission systems minimizes mass and complexity, reduces training demands, and increases redundancy for a given mission. ***NASA-STD-3001 Vol 2 [V2 9004] Training Minimization, [V2 9110] In-Mission Training***

Designing equipment based on the basic abilities and limitations of the crew to accomplish the assigned tasks will enable increasingly Earth-independent procedure execution, with reduced guidance and oversight from the ground.

The crewmember's skill level can also be increased using "just-in-time" onboard training specific to the situation or system. ***NASA-STD-3001 Volume 2 Section 4 Physical Characteristics and Capabilities, [V2 9123] Maintenance Activities***

Captive fasteners: All fastener components intended for crew interaction should be captive. A captive fastener is one that is automatically retained in a workpiece when it is not performing its load-bearing job and, therefore, does not require the crew to restrain and store them during maintenance.

Crew should have a minimum selection of fasteners to help reduce crew time devoted to maintenance activities. The commonality of fasteners can also reduce the time to access and the need for different tools. ***NASA-STD-3001 Vol 2 [V2 9042] Captive Fasteners, [V2 9043] Minimum Number of Fasteners-Item, [V2 9044] Minimum Variety of Fasteners-System***

For additional information, refer to: OCHMO-TB-017 Automated and Robotic Systems and OCHMO-TB-007 Mission Duration.

Application

<u>Accessibility</u>

Inspecting, removing, and replacing equipment may need to be done during any phase of flight, in which the spacecraft may be in different gravity conditions and by individuals wearing protective clothing and equipment that may limit mobility. Equipment should be designed so that the elements to be maintained are visible and physically accessible**.**

System designers need to consider crewmembers' physical capabilities and the environmental factors (e.g., limited gravity, physical space) when assessing accessibility. ***NASA-STD-3001 Vol 2 [V2 9048] Visual Access for Maintenance***, ***[V2 9117] Access Using Available Tools***

Accessibility to items requiring frequent and/or critical servicing is a priority. System developers must identify items requiring frequent and/or critical maintenance. De-integrating and demating is a source of risk during maintenance. ***NASA-STD-3001 Vol 2 [V2 9033] Mating, Demating Hazards***

Designing the system to the physical capabilities and limitations of the maintainer (e.g., ensuring parts are accessible by hand) prevents collateral and inherent damage when proper procedures are followed. ***NASA-STD-3001 Vol 2 [V2 0913] Damage Prevention***

STS-133 NASA astronauts Alvin Drew and Steve Bowen installed the J612 power extension cable, moved a failed ammonia pump module to the external stowage platform 2 on the Quest Airlock for return to Earth later, and installed a camera wedge and extensions to the mobile transporter rail. Photo: NASA (2011)

Reference NASA HIDH Section 9.4 Tools and 9.6 Connectors for additional information.

Application

<u>Physical Accessibility Design Requirements</u>

Adequate access and working space are needed to allow personnel to efficiently access equipment to minimize the potential for human error or system damage. When designing for physical access, consider the following:

- Priority of Access – Items that are most critical to system operation and require rapid maintenance must be most accessible. When relative criticality is not a factor, items requiring the most frequent access must be most accessible. Easy access must be provided for frequently failed components (e.g., lamps and fuses).
- Access dimensions – Access openings for two hands, one hand, and fingers should accommodate the dimensions shown in Figure 9.3-1. from the HIDH. In the case where access to openings is required by a suited crewmember, the suit glove dimensions, tactility, and dexterity characteristics should be considered.

Minimal one-hand access openings without visual access

	Height x Width	
Empty hand, to wrist		
Bare hand, rolled	95 mm (3.75 in.) sq or dia	
Bare hand, flat	55 mm (2.25 in.) × 100 mm (4 in.) or 100 mm (4 in.) dia	
Clenched hand, to wrist		
Bare hand	95 mm (3.75 in.) × 125 mm (5.0 in.) or 125 mm (5.0 in.) dia	
Arm to elbow		
Light clothing	100 mm (4.0 in.) × 115 mm (4.5 in.)	
Arm to shoulder		
Light clothing	125 mm (5.0 in.) sq or dia	

Minimal finger access to first joint

Push-button access		
Bare hand	32 mm dia (1.26 in.)	
Two-finger twist access		
Bare hand	object plus 50 mm (1.97 in.)	

Minimum sizes for access openings for one hand and fingers without visual access (MIL-STD -1472F) Figure 9.3-1 HIDH

Application

- Component Removal – Access to inspect or replace a component (e.g., an ORU) should not require the removal of other component(s) that are not the subject of the maintenance activity
- Access Covers – Access covers that are not completely removable should be self-supporting in the open position. Access to inspect or replace a component should not require the removal of more than one access cover. Access covers should not require the removal of many fasteners and, if accessed frequently, should not require a tool. Closures and covers should be quickly and easily removed to allow equipment maintenance.
- Check Points and Service Points – Checkpoints and service points for systems must be in accessible locations. Access points should not be located near electrical, mechanical, or other hazards to protect the crew and ground personnel. If this is not possible, other means of hazard protection should be provided.
- Cables – Cables should be routed to be accessible for inspection and repair. Cables should have sufficient slack for the removal of connectors. Common cable interfaces would result in more efficient operations and better maintenance access. Cables must be clearly labeled to indicate the equipment and connectors to which the cables mate. All replaceable wires and cables must be uniquely identified in accordance with the labeling plan. ***NASA-STD-3001 Vol 2 [V2 10151] Labeling Plan and Icon Library, Appendix F: Display Standard***

Astronaut Raja Chari tests using tools while wearing a spacesuit glove. Photo: NASA (2022)

Application

Visibility and Identifiability

Designers need to locate and design equipment such that it is directly visible during task performance. Direct line-of-sight visual access reduces the likelihood of human error***. NASA-STD-3001 Volume 2 Section 9.7.5 Visibility and Identifiability, Section 10.4.2 Displays [V2 9048] Visual Access for Maintenance.***

When designing for visual access, consider the following:

Visual-Only Access – Only visual access is required. The following practices should be followed with the order of preference as given:

1. Provide an opening with no cover except where this might degrade system performance.
2. Provide a transparent window if dirt, moisture, or other foreign materials might create a problem.
3. Provide a quick-opening metal cover if a transparent cover will not meet other requirements.

Visual and Manual Access – If a crewmember needs to see the equipment to perform a maintenance task, the access must be large enough to allow simultaneous visual as well as physical access; otherwise, a separate window should be provided for visual access to monitor task performance.

Labeling – Each access should be labeled to indicate items visible or accessible through it, including a number, letter, or other symbol directly cross-referenced to maintenance procedures. Cables, fluid lines, and shields protecting other subsystems should also be labeled or otherwise coded to allow positive identification. ***NASA-STD-3001 Volume 2 Section 10.4.3 Labels [V2 10151] Labeling Plan and Icon Library, [V2 9118] Component Identification, [V2 9035] Cable Identification.***

Cosmonaut Valery Korzun and astronaut Peggy Whitson perform maintenance on the Treadmill Vibration Isolation System (TVIS) in the Zvezda Service Module on the ISS. Photo: NASA (2002)

Application

<u>Maintenance Data Design Requirements</u>

- Condition Monitoring: Fault management information enables maintainers to make informed decisions about when and how to perform maintenance. Using real-time maintenance triggers (as opposed to performing preventive maintenance at scheduled intervals determined by reliability analysis) can eliminate unnecessary preventive maintenance tasks and make more efficient use of spare parts. Therefore, condition-based maintenance is advantageous for long-duration exploration missions (LDEMs) with reduced ground support. ***NASA-STD-3001 Vol 2 [V2 9120] Condition Monitoring**, **[V2 9122] Fault Management Information***
- Maintenance management information: Systems must alert the crew when flight-critical equipment has failed and is not operating within tolerance limits without removing the affected equipment. Automatic alerting of equipment failure expedites troubleshooting and ensures that the crew has adequate situational awareness of the functionality that has been lost. Efficient equipment design must minimize the amount of time required for maintenance. ***NASA-STD-3001 Vol 2 [V2 9121] Maintenance Management Information, [V2 9052] Failure Notification***

<u>Maintenance Decision Aids</u>

- Visual Aids for Maintenance: 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. Appropriate visual aids are increasingly important for exploration beyond Low Earth Orbit 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. ***NASA-STD-3001 Vol 2 [V2 9124] Maintenance Decision Aids***
- Properly designed aids for fault detection and isolation can also reduce crew training requirements. Interactive visual aids that enable the crew to resize and rotate dynamically should be considered to amplify crewmembers' understanding of the system context. ***NASA-STD-3001 Vol 2 [V2 9119] Visual Aids for Maintenance, [V2 9121] Maintenance Management Information, [V2 9052] Failure Notification***
- Simplified decision aids are needed to assist crewmembers in identifying possible causes of anomalies and making time-critical decisions. A sequence of troubleshooting checks is to be specified at the crew skill level.
- To maximize the effectiveness of decision aids, the system needs to be designed to minimize ambiguity groups (possible failure points) and support its recommendation with relevant data**. *NASA-STD-3001 Vol 2 [V2 9121] Maintenance Management Information, [V2 9124] Maintenance Decision Aids, [V2 10170] Decision Aid Clarity, [V2 10171] Decision Aid Failure Notification***

Reference OCHMO-TB-005 Usability, Workload, & Error for additional information.

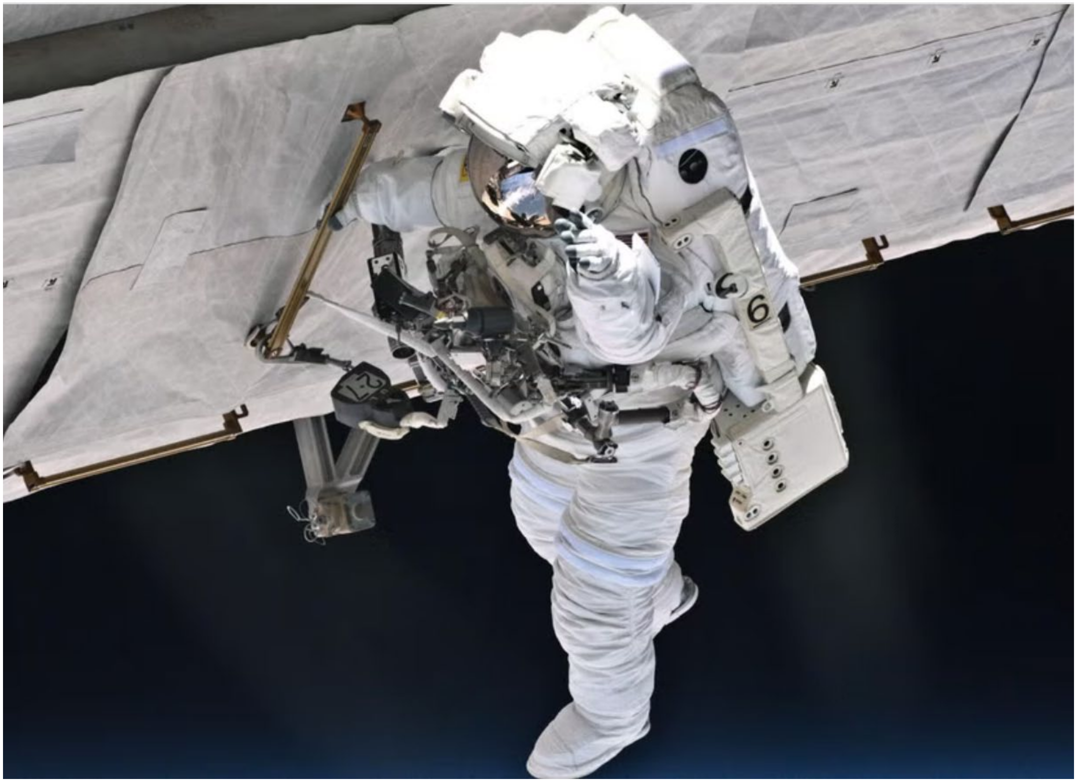
Application

Verification

The system needs to include verification methods through system self-test, external measurements, or other methods. On missions beyond low-Earth orbit (LEO), an indication provided onboard the vehicle at the maintenance location will allow crewmembers to verify repair success without relying on ground teams.

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. ***NASA-STD-3001 Vol 2 [V2 9125] Verification of Repair***

Testing: Integrated system testing on the ground prior to deployment may reveal unanticipated failure modes and prevent in-mission corrective maintenance. See [OCHMO-TB-018 Human-in-the-Loop (HITL)].



NASA Astronaut Garett Reisman makes repairs to the ISS during a spacewalk. Photo: NASA (2010)

Back-Up

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

Referenced Technical Requirements

NASA-STD-3001 Volume 1 Revision C

[V1 3004] In-Mission Medical Care All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, individual crewmember needs, clinical practice guidelines, flight surgeon expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses consider the needs and limitations of each specific vehicle and design reference mission (DRM) with particular attention to parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, and behavioral care, are to include, but are not limited to: (see NASA-STD-3001, Volume 1 Rev C for full technical requirement list).

NASA-STD-3001 Volume 2 Revision D

[V2 3006] Human-Centered Task Analysis Each human spaceflight program or project shall perform a human-centered task analysis to support systems and operations design.

[V2 3102] Human Error Analysis Each human spaceflight program or project shall perform a task-based human error analysis (HEA) to support systems and operations design.

[V2 9003] Routine Operations Worksites shall be designed to provide rapid access to needed tools and equipment for routine / nominal operations.

[V2 9004] Training Minimization Hardware and equipment with which crew interacts shall minimize the time required for training.

[V2 9110] In-Mission Training In-mission training/refreshers, including using tools and test equipment required for maintenance, shall be provided to ensure crew proficiency in performing maintenance activities

[V2 9111] Maintenance Concept of Operations For each maintenance-level item, the human spaceflight program shall define and document a maintenance operational concept considering the following factors, as a minimum, and updated throughout the design lifecycle:

a. Mission work natural environment (e.g., dust, lighting, heating, atmosphere, gravity) as specified in program requirements for natural environments (e.g., 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 – considering mission-criticality, urgency of repair, anticipated frequency of servicing, and complexity of approach.
e. Reliability- or performance-driven preventive maintenance schedule.
f. Preventive and corrective maintenance plans.
g. Total crew time and number of crew needed.

[V2 9112] Availability of Critical Systems System repairs and/or replacements shall be designed to be completed within the time-to-effect margin.

[V2 9113] Damage Prevention The system shall be designed to prevent damage during maintenance.

[V2 9114] In-Mission Maintenance The program shall design all flight hardware and software to facilitate in-mission preventive and corrective maintenance and check-out.

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

Referenced Technical Requirements

NASA-STD-3001 Volume 2 Revision D

[V2 9033] Mating, Demating Hazards The system shall not subject personnel and equipment to hazards, including spills, electrical shocks, and the release of stored energy during mating or demating

[V2 9036] Design for Maintenance The system shall provide the means necessary for the crew to safely and efficiently perform routine service, maintenance, and anticipated unscheduled maintenance activities while wearing the most encumbering equipment and clothing anticipated.

[V2 9037] Commercial Off-the-Shelf (COTS) Equipment Maintenance Maintenance for commercial off-the-shelf equipment shall be suitable to the spaceflight environment.

[V2 9038] In-Mission Tool Set The program shall establish a common set of in-mission tools and test equipment for spaceflight and surface systems.

[V2 9115] Maintenance Tools Usability tools and test equipment shall be usable by the full range of crew sizes and strengths wearing any personal protective equipment (PPE).

[V2 9116] 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.

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

[V2 9039] Maintenance Time 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.

[V2 9042] Captive Fasteners Fasteners used by the crew during maintenance shall be captive.

[V2 9043] Minimum Number of Fasteners – Item For items that may be serviceable by the crew, the number of fasteners used shall be the minimum required to meet structural engineering integrity requirements.

[V2 9044] Minimum Variety of Fasteners – System The system shall be serviceable with a common set of fasteners that meet structural integrity requirements.

[V2 9117] Access Using Available Tools Systems and units of equipment that require maintenance shall be accessible and openable during the mission using the on-board tool set.

[V2 9045] Maintenance Item Location The system shall ensure maintenance access to the items prioritized [V2 9111] Maintenance Concept of Operations, so that the maintenance task does not require the removal or disabling of other systems or components (excluding access panels).

[V2 9046] Check and Service Point Accessibility Check points and service points for systems, hardware, and equipment shall be directly accessible while wearing the most encumbering equipment and clothing anticipated.

[V2 9047] Maintenance Accommodation Physical work access envelopes shall accommodate the crew, required tools, and any protective equipment needed to perform maintenance.

[V2 9048] Visual Access for Maintenance Maintenance tasks that require visual feedback shall be directly visible during task performance while wearing the most encumbering equipment and clothing anticipated.

[V2 9118] Component Identification Flight systems shall include information and labeling that enables the crew to correctly locate, handle, and identify the systems components.

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

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

Referenced Technical Requirements

NASA-STD-3001 Volume 2 Revision D

[V2 9119] Visual Aids for Maintenance 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.

[V2 9051] Fault Detection Unit of equipment undergoing maintenance shall provide rapid and positive fault detection and isolation of defective items.

[V2 9052] Failure Notification The system shall alert the crew when critical equipment has failed or is not operating within tolerance limits.

[V2 9120] Condition Monitoring The system shall be designed to provide condition-monitoring data to an information system that can be accessed by the crew, to maintenance data systems or mission control. (See also 10.2.1 System Health and Status).

[V2 9121] Maintenance Management Information For each maintenance-level item, as a minimum, the following data shall be captured and made/ available to the crew: 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.

[V2 9122] Fault Management Information For maintenance-level items experiencing off-nominal performance, the following data shall be made available to the crew in real-time:

a. Live 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.

[V2 9123] Maintenance Activities Maintenance activities shall be designed to the skillset common to all crewmembers at the time of maintenance.

[V2 9124] Maintenance Decision Aids For corrective maintenance activities, decision aids shall be provided to support diagnosis, troubleshooting, and procedure execution at the expertise-level common to all crewmembers.

[V2 9125] Verification of Repair Preventive and corrective maintenance shall include means for verification of successful completion.

[V2 9126] Contamination Prevention For planetary surface missions, maintenance tasks shall be designed to prevent environmental contamination (e.g., dust) of maintenance items and EVA systems**.**

[V2 9127] Extreme Environment (EE) Equipment, including tools and instruments, that are 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 natural environmental conditions specified in the SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE).

[V2 9128] Dust Tolerance Tool and equipment functionality shall not reduce below minimum performance specifications due to dust exposure when designs cannot prevent its intrusion.

[V2 10151] Labeling Plan and Icon Library The system shall provide labels that are consistent with a Labeling Plan and Icon Library as established by the program.

Reference List

1. Bertels, C. (2006, June 19). Crew Maintenance Lessons Learned from ISS and Considerations for Future Manned Missions. SpaceOps 2006 Conference. SpaceOps 2006 Conference, Rome, Italy. https://doi.org/10.2514/6.2006-5952
2. Evans, W. A., DeWeck, O., Laufer, D., & Shull, S. (2006). Logistics Lessons Learned in NASA Space Flight (Technical Report NASA/TP-2006-214203). John F. Kennedy Space Center, National Aeronautics and Space Administration. https://ntrs.nasa.gov/citations/20110022528
3. Owens, A. C., & de Weck, O. L. (2018). International Space Station Operational Experience and its Impacts on Future Mission Supportability. Proceedings of the 48th International Conference on Environmental Systems. 48th International Conference on Environmental Systems, Albuquerque, NM. https://ttu-ir.tdl.org/bitstream/handle/2346/74165/ICES_2018_198.pdf?sequence=1&isAllowed=y
4. Apollo Lunar Surface Journal. (2018). https://history.nasa.gov/alsj/
5. Apollo Flight Journal. (2019). https://history.nasa.gov/afj/index.html
6. Johnson, G. W. (2018). Lessons Learned from 50+ Years in Human Spaceflight and Safety (Contractor Report JSC-E-DAA-TN62036). SAIC. https://ntrs.nasa.gov/citations/20190028301
7. Sullivan, T. A. (1994). Catalog of Apollo Experiment Operations (NASA Reference Publication 1317). National Aeronautics and Space Administration. https://www.hq.nasa.gov/alsj/RP-1994-1317.pdf
8. Winterhalter, D., Levine, J. S., Kerschmann, R. L., & Brady, T. K. (2020). Lunar Dust and Its Impact on Human Exploration: A NASA Engineering and Safety Center (NESC) Workshop (NASA/TM−2020-5008219 NESC-RP-19-01469). https://ntrs.nasa.gov/citations/20205008219
9. Winterhalter, D., Levine, J. S., & Kerschmann, R. (2018). The Dust in the Atmosphere of Mars and Its Impact on the Human Exploration of Mars: A NESC Workshop (NASA/TM-2018-220084 NESC-RP-17-01263). https://ntrs.nasa.gov/citations/20180006321
10. 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
11. Wagner, S. (2006). The Apollo Experience Lessons Learned for Constellation Lunar Dust Management (NASA/TP-2006-213726). Johnson Space Center. https://ntrs.nasa.gov/citations/20060050035
12. 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
13. NASA Handbook 5300.4(1E) prohibiting maintainer body movement, and "Maintainability Program Requirements for also identifies requirements necessary to Space Systems," March 10, 1987, NASA provide an efficient workspace for Headquarters.
14. NASA Handbook 7120.5, "Management of drawings or sketches before detailed Major Systems and Projects," November 1993, NASA Headquarters
15. Air Force Design Handbook 1-9 anthropometric considerations. Use of these "Maintainability (for Ground Electronic evaluations results leads to improved designs Systems)," Second Edition, Revision 7, February 25, 1988, United States Air Force Division.
16. NASA/SP-2010-3407 the Human Integration Design Handbook (HIDH)
17. NASA-STD-3000. DESIGN FOR MAINTAINABILITY (nasa.gov)

Reference List

18. "Maintainability Program Management Considerations". Technique PM 2. [PFP#680142611] (nasa.gov)
19. "Maintainability Engineering Design and time to effect repairs, lower maintenance Cost of Maintainability," Revision II, January 1975, Rome Air Development Center.
20. Reliability, Maintainability, and Supportability (RMS) Guidebook, Second Edition, 1992, Society of Automotive Engineers G-11 International RMS Committee.
21. MIL-STD-470B "Maintainability Program for Systems and Equipment," May 30, 1989, Department of Defense
22. Reliability, Maintainability, and Quality Assurance Division, NASA Headquarters. (1987). Maintainability Program Requirements for Space Systems (NHB-5300.4(1E)). https://ntrs.nasa.gov/citations/19940003824
23. NASA Reliability and Maintainability Steering Committee. (1994). Recommended techniques for effective maintainability. A continuous improvement initiative of the NASA Reliability and Maintainability Steering Committee (NASA-TM-4628). https://ntrs.nasa.gov/citations/19950025109