NASA/CR–2008–214165

EVA Hand Tool Design Considerations, Development, and General Requirements Interpretation: A Junior Engineer's Guide

Kevin Eisenhower

October 2008

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Abstract

This paper serves as a guide to developing hand tools for use by crewmembers during extravehicular activity (EVA) in outer space. It outlines the fundamentals of EVAs and related provisions, providing a starting point and perspective for engineers unfamiliar with designing equipment to be used during manned spaceflight. Common EVA hardware constraints, which are often unclear, are interpreted and traced back to a source or justification because, as in any design field, fully understanding the basis and intent of a design requirement is needed to properly satisfy it. Lastly, miscellaneous design considerations and lessons learned in tool development are discussed. The information found within is drawn from commonly cited NASA and EVA related documents as well as from professional experiences.

1 Introduction

In human space exploration there is a saying that a single minute spent during an EVA is worth a million dollars. Whether or not this is true, it conveys the message that an astronaut crewmember's time during extravehicular activity is very busy and very valuable. As design engineers, we strive to make EVA hand tools as affective, safe and easily operable as possible for the crewmember. The intent of this document is to provide a starting point or beginner's reference for designing an EVA tool, from mechanism design and development, to meeting requirements criteria, to optimizing for human factors. The information found within will be drawn from commonly cited EVA design related documents as well as from professional experiences. By creating a reference with a large scope that does not assume the reader is already familiar with designing for EVAs and space shuttle payloads, development time and learning curves will improve for new engineers entering the EVA tool field. Just as each minute of an EVA is valuable, the time spent developing each tool is fast-paced and costly.

Hardware that flies aboard the space shuttle, including EVA tools, is considered a payload. Any payload requires proper documentation, which is governed by the "Space Shuttle Systems Payload Accommodations" document, Volume XIV of NSTS 07700. Here detailed descriptions of accommodations and integration processes can be found, as well as many top-level requirements that eventually flow down through other documents to EVA tool designs. Tool designers should familiarize themselves with NSTS 07700 Appendix 7, which deals specifically with EVA related hardware. NASA-STD-3000, "Man-Systems Integration Standards" is another top-level document to which many tool requirements can be traced. Volume 1, sections 11 and 14 address EVAs and related equipment.

Design requirements can be generic and are not always easy to interpret, so this document will explain many of the common constraints levied upon EVA hardware. In any engineering design field, fully understanding the basis and intent of a requirement can lead to proper compliance with that requirement, or in some cases proper justification for taking exception to it. Thus, in order to successfully design hardware for space, one must have a comprehension of the basics of EVAs, spacesuits, and tool related space shuttle hardware.

1.1 EVA Logistics

The spacesuit the crewmember's use, the Extravehicular Mobility Unit (EMU) is designed nominally for seven hours of EVA. Thirty minutes of this is for airlock egress/ingress, and thirty minutes is reserve, leaving only six hours of "usable" EVA time. However, ultimately the length of the EVA is very dependent on the rate at which consumables are used up. The space shuttle provides provisions for up to five two-crewmember EVAs during one mission.

1.2 Spacesuit Factors on EVA

The EMU is designed to give the wearer as much mobility as possible, but it does have limitations. Because of the design and internal pressure of the suit, motion of the arms and legs requires force exerted to overcome resistance and friction in the joints. Consequently, crewmembers are most comfortable in the "neutral body position", and the optimum work area for using an EVA tool is in front of the upper chest. To evaluate reach and access outside this work area, it is important to know how the crewmember is situated at the worksite, which is most often in a foot restraint, but in some instances the crewmember may be free floating. A free floating crewmember uses one hand to stabilize and can use one hand to actuate switches and interfaces with small forces. In a foot restraint, more complex and higher force actuations can be accomplished; however, interfaces designed for single-hand actuations keep one hand available to hold handrails for stabilization and to help apply more force. As a crewmember reaches further from the optimum work area, his or her force capabilities diminish. These are some examples of spacesuit factors that may heavy influence requirements of an EVA tool design.

1.3 Tool Stowage and Retrieval

Tool stowage accommodations on the space shuttle during launch and landing are in either the Payload Bay or the Crew Compartment. Advantages of stowage in the Crew Compartment include a more controlled environment and the ability to pre-configure tools prior to an EVA. The Payload Bay typical houses large mission related instruments and structures, but also includes containers or enclosures for tools such as the Tool Stowage Assembly (TSA). Special arrangements can be made for devices and instruments too large for these containers, however space is very limited. Items in the Payload Bay are retrieved during EVA, which impacts the EVA timeline.

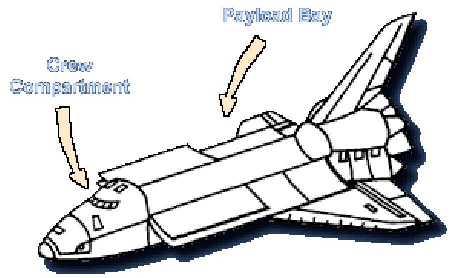


Figure 1 – Space Shuttle Payload Accomodations

(Source: http://shuttlepayloads.jsc.nasa.gov)

Items in the Crew Compartment are typically stowed in Middeck Lockers, which have a standard size and interface, and provide foam padding to protect against loads and vibrations. These tools are then staged in the shuttle airlock, and taken into EVA by the spacewalking crewmembers. This can be accomplished by temporarily stowing the tool on the Modified Mini-Workstation (MMWS, refer to Section 2.4), a supplemental attachment on the front of the EMU, or most often on a standardized Tool Board (refer to Section 2.2) that is taken into EVA.

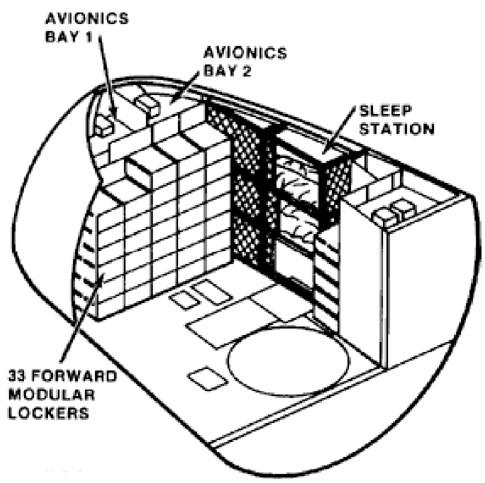


Figure 2 -- Middeck, Right Side Looking Forward

(Source: http://shuttlepayloads.jsc.nasa.gov)

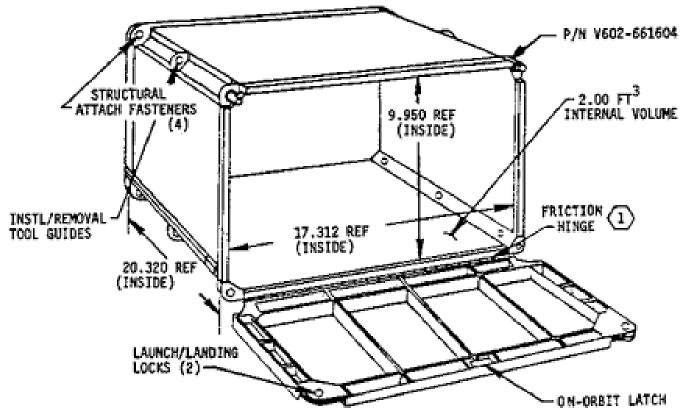


Figure 3 -- Standard Middeck Modular Locker

(Source: http://shuttlepayloads.jsc.nasa.gov)

2 Common EVA Interfaces, Tools, and Other Provisions

Just like a mechanic, NASA crewmembers are trained and equipped with a standard set of tools. Information on a majority of these tools can be found in "JSC EVA Catalog: Tools and Equipment", NASA document JSC-20466. Some of the common tools and interfaces essential to every EVA are discussed in this section.

2.1 Remote Manipulator System and Manipulator Foot Restraint

One of the most influential devices to any EVA is the Remote Manipulator System (RMS), a 50 foot long, six DOF robotic arm on the portside of the shuttle Payload Bay. It is capable of grappling the Manipulator Foot Restraint (MFR), a very effective EVA workstation. Used in concert, these items can provide adequate restraint, effortless translation, and precise positioning for a crewmember working in the Payload Bay. Movement of the RMS/MFR is done by voice link with the robotic arm operator in the crew cabin. The MFR has foot restraints and can be rotated and maneuvered into different configurations. The MFR increases the capabilities of a crewmember to perform various tasks versus free-floating. It also provides for attachment of up to four standard Tool Boards, making it the prime location for stowage and retrieval of EVA tools.

2.2 Tool Boards

The Tool Board provides temporary stowage for EVA tools. Various standardized connections allow for easy, one-handed tool retrieval. A Tool Board can be pre-configured in the crew cabin each day with the necessary equipment for that particular EVA. It can be positioned for convenient access near the worksite, such as on the MFR (See Figure 4). More information on this device can be found in the JSC EVA Catalog.

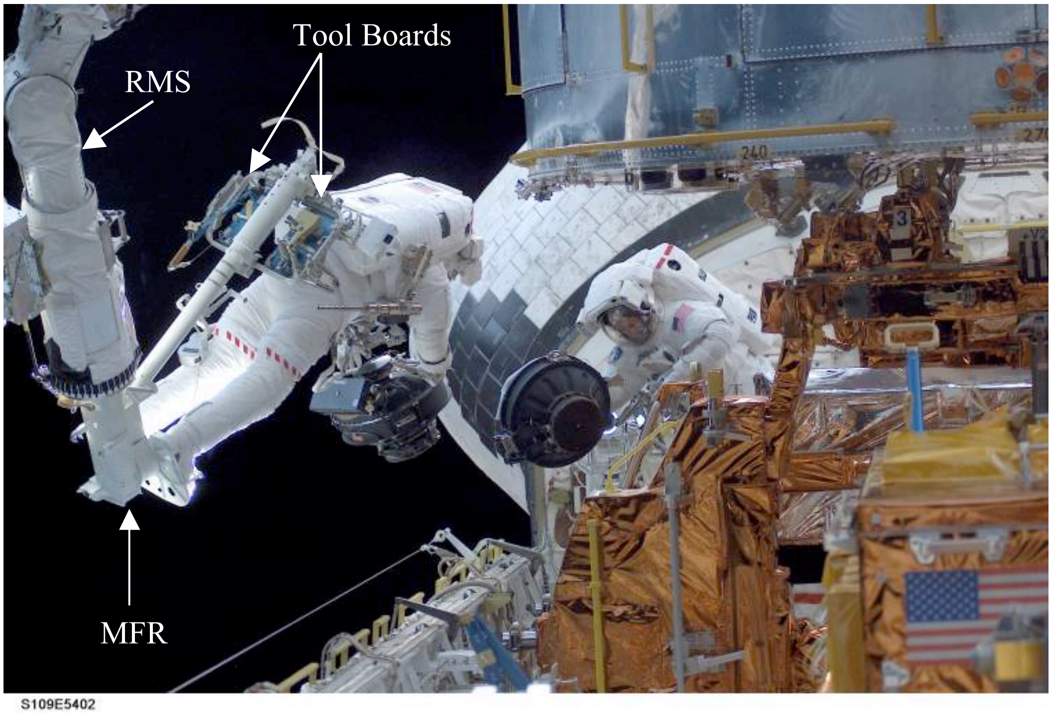


Figure 4 -- Tool Boards attached to the MFR

(Photograph Source: NASA http://spaceflight.nasa.gov/gallery)

2.3 Safety / Equipment Tethers

Each crewmember is equipped with two "safety tethers" at their waist with "equipment tether hooks" on each end, used to maintain continuous attachment to the shuttle structure. An equipment tether hook allows for one-handed actuation but also has a push-to-open lock to prevent inadvertent release. The crewmembers also have a "Payload Retention Hook (French Hook)" at the wrist to attach to hardware used during the EVA. A French Hook does not have a redundant lock-lock feature. More details can be found in the JSC EVA Catalog.

Standard tether hooks can be obtained as government furnished equipment (GFE); however, for engineering development and crew training purposes, alternative and commercially available tethers can be utilized to lower costs.

The safety tethers and equipment tethers are a fabric material and have adjustable lengths. Many other tether hooks are on the end of a steel cable. These are known as retractable tethers, as the other end of the cable goes to a spring-loaded reel.

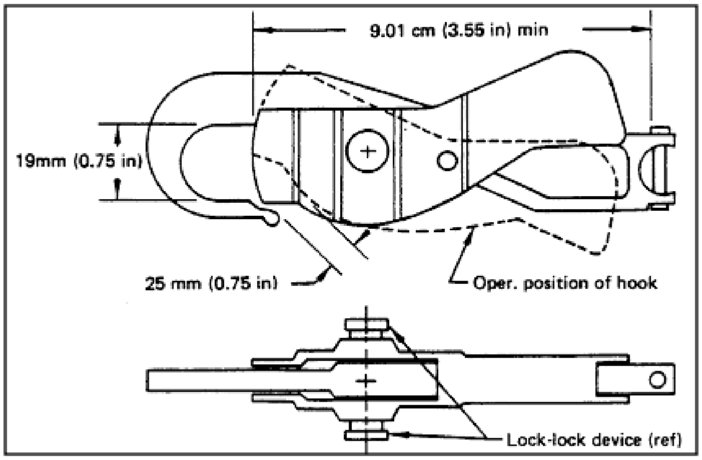


Figure 5 – Standard EVA Equipment Tether Hook
(Source: NASA-STD-3000)

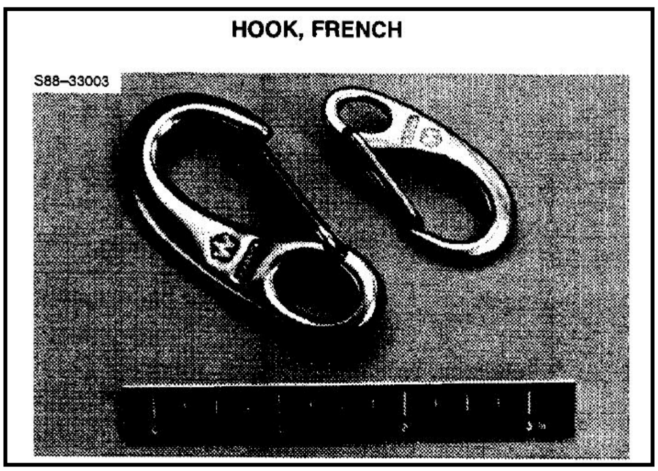


Figure 6 -- Payload Retention Hook (French Hook)
(Source: JSC EVA Catalog)

Until sufficiently attached or stowed, EVA tools must be tethered at all times to prevent inadvertent separation. A standardized receptacle for the equipment tethers, the EVA Tether Loop, should be incorporated into the design of all tools. The required receptacle dimensions to accommodate an equipment tether can be found in Figure 7. Receptacles are also required to structurally withstand crew-induced loads (e.g. inadvertently pulling on a tether hook) of up to 30 lbs in any direction (note, many internal NASA documents may provide force numbers that differs from NASA-STD-3000). The receptacle may be cleverly integrated into the tool's structure but should be easily identifiable. Crewmembers evaluation and familiarization of the receptacle's location is essential in a successful tool design. If an EVA procedure involves a tool handoff from one crewmember to another, multiple tether receptacles may be needed since both crewmembers will momentarily be tethered to the device as the same time until the handoff is completed.

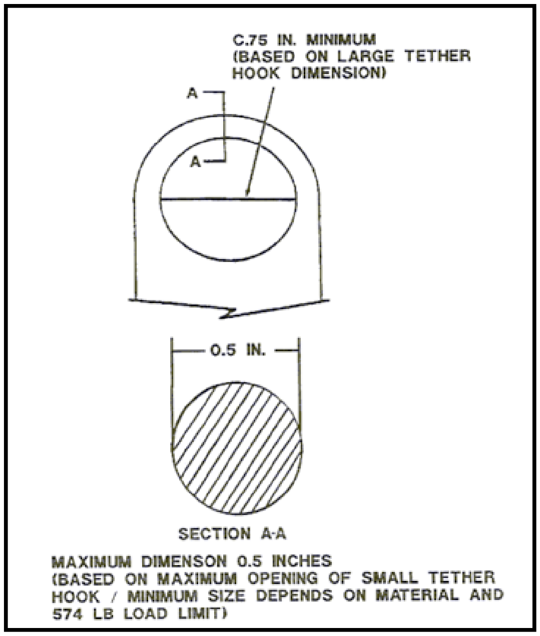


Figure 7 -- Standard EVA Tether Loop

(Source: NASA-STD-3000)

2.4 Modified Mini-Workstation

A standard device mounted to a crewmembers EMU is the Modified Mini-Workstation (MMWS). It includes a pivotal T-bar, D-rings (for attaching tether hooks), pip-pins, tethers, and various tool connection methods. The MWS can be seen on the upper torso of the EMU in Figure 8. More details can be found in the JSC EVA Catalog.

Figure 8 -- MWS on the EMU

(Source: NASA http://spaceflight.nasa.gov/gallery)

2.5 EVA Knobs

The design of a knob should rely heavily on its specific function and the tool to which it is attached. However, some standardized knobs do exist that have proven acceptable for EVA. Some of these are shown in Figure 9, and more details can be found in the JSC EVA Catalog. While typically used in rotational interfaces, a knob can also be used as a low profile, rigid handling interface in place of handles and handrails.

If a unique knob design is to be used, a few details should be kept in mind. Knobs should be large not only for structural integrity but also for ease of use by a gloved hand. Scallops should be used to provide a better grip.

It's worth noting that any rotational hand interface should be designed to require as few turns as possible. A knob can be turned approximate 90 to 135 degrees before having to let go and re-grip the knob. Multiple rotations can be excessively time consuming and exhaustive by hand. Integration of a 7/16" hex interface (common for EVA applications) into the knob allows for torque application by a wrench or power tool instead of by hand. This allows the crewmember to apply torque in whatever manner is most efficient for the task, without adding too much complication to the knob design.

KNOB, EVA

Technical Information	
Part number	SK118–030–01 (MMU FSS) 10150–20054–01 (MWS) 10176–20666–01 (PFR)
Weight	SK118–030–01 0.198 lb 10150–20054–01 0.174 lb 10176–20666–01 0.150 lb
Material/ construction	Aluminum
Load rating	
Temperature range	–150° to +250° F (operational)
Quantity flown	
Stowage	
Availability	Flight specific

Dimensional Data						
	SK118–030–01		10176–20666–01		10150–20054–01	
	inches	cm	inches	cm	inches	cm
A	2.25	5.72	2.00	5.08	3.00	7.62
B	2.00	5.08	1.50	3.81	2.12	5.38
C	0.80	2.03	0.62	1.57	1.02	2.59
D	2.25	5.72	1.60	4.06	–	–
E	1.00	2.54	1.25	3.18	–	–
F	–	–	2.69	6.83	–	–

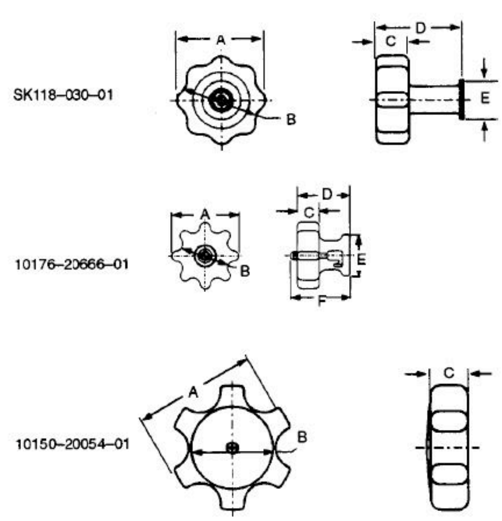


Figure 9 – A Few Standard EVA Knobs

(Source: JSC EVA Catalog)

2.6 PIP Pins

T-handled pip pins, or quick release pins, are fairly common EVA devices. They allow for release of joints by a gloved hand in a simple, easy manner. Figure 10 shows a T-handled EVA pip pin. Although on the surface they appear to be a logical choice for some applications, the NASA Mechanical Systems Working Group (MSWG), which must approve all "safety critical" mechanisms, suggests not using pip pins for safety critical applications because they have a poor track record. There is also documented history of these pins being inadvertently snagged during EVA. If used in a tool design, the MSWG suggests Avibank product part number 56789.

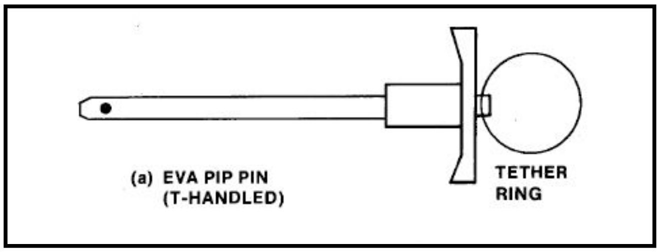


Figure 10 – EVA Pip Pin

(Source: NSTS 07700)

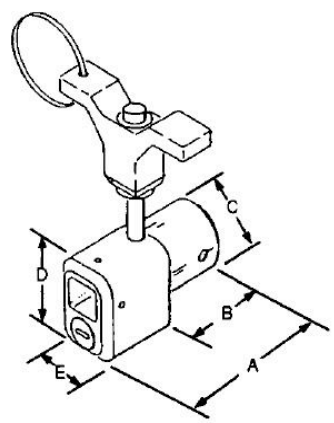
2.7 Drop-Proof Tether

A Drop-proof tether, or Mctether, is a very useful EVA device for holding a joint together yet allowing for fast and easy separation. It is designed to mate with a modified 3/8-inch square drive fitting. It allows for disconnection of the joint when a standard pip pin is inserted into a hole on the housing. If a pip pin is inserted, the joint can also be re-engaged and then locked when the pip pin is removed.

This mechanism is excellent for connecting bits, sockets and drives to EVA power tools that typically have the male square drive because it provides a secure connection with easy and quick separation. Multiple bits and drives can be joined to the same square drive interface, which can be incorporated into hand tools as well as power tools.

Technical Information	
Part number	10168–10068–01 10181–10003–**04/06**
Weight	0.184 lb (10168–) 0.100 lb (10181–)
Material/ construction	Stainless steel
Load rating	
Temperature range	–130° to +150° F
Quantity flown	
Stowage	
Availability	Flight specific

Dimensional Data						
	10168–10068–01		10181–10003			
			–01		–03	
	inches	cm	inches	cm	inches	cm
A	1.70	4.32	1.329	3.38	1.329	3.38
B	0.70	1.78	0.422	1.07	0.454	1.15
C	0.70	1.78	0.372	0.94	0.640	1.63
D	1.01	2.57	0.930	2.36	0.930	2.36
E	0.70	1.78	0.660	1.68	0.660	1.68



10168–10068–01

Figure 11 - Drop Proof Tether

(Source: JSC EVA Catalog)

2.8 Handrails

A standardized handhold design exists for EVA usage. These handrails can be found throughout the payload bay to assist crewmembers in translating from place to place, and also often on many large structures. For large EVA hand tools, a handhold may be necessary, and following this standardized design is strongly suggested when possible. Figure 12 gives the shape and dimensions for what is often referred to as the "dog-bone" handrail. It also gives the minimum clearances and length to ensure adequate access with a gloved hand. This type of handrail is most common to ISS and payload bay carriers. Handrails should be hollow to reduce mass, without reducing structural integrity below what is required. In rare cases an oval shaped handrail may be used for EVA purposes. The dimensions for this shape are 1.38" x 0.75", with full rounds on the sides.

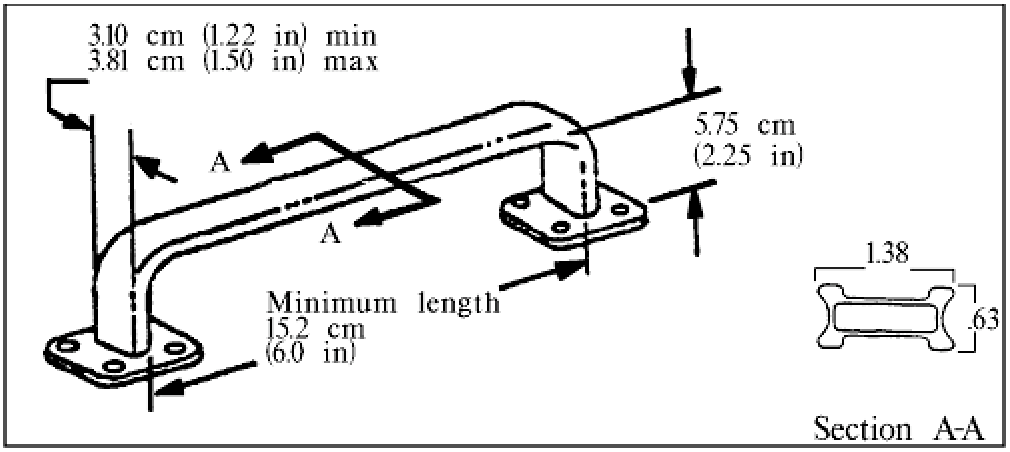


Figure 12 – Standard EVA Handrail

(Source: NASA-STD-3000)

Handrails integrated into the payload bay are rated for high impact and usage loads (220 lbs in any direction) and consequently are colored yellow for identification as such. If a handrail is not rated for these higher loads it shall not be yellow.

3 General Design Considerations – Explanations & Interpretations

There are some fundamental guidelines to always keep in mind when developing an EVA hand tool. The safety of the crewmembers comes first. This includes ensuring that tool operations don't damage the EMU's or shuttle, resulting in catastrophic hazards. From a human factors standpoint, ease of use is key, and one-handed operation is essential where possible. There are plenty of other common requirements and "desirements" at the detailed design level. Fully understanding where they come from and how they typically are implemented will lead to proper compliance with those constraints, or justification for taking exception to them.

3.1 Safety

Shuttle payloads governed by NSTS 07700 are subject to the safety requirements and policies of document NSTS 1700.7B. NASA STD-3000 also addresses some mechanical and EVA specific safety requirements. This section will highlight tool design related policies that affect the safety of the crew during EVA.

3.1.1 Sharp Edges

It is of the utmost importance to ensure there are no sharp edges or protrusions in the payload bay that could damage the crewmembers' suits. This applies not just to items that will be interfaced by the crew, but also to items and structures along translation routes in the payload bay. Consequently, there are detailed guidelines on how to design edges and corners that are on external surfaces of EVA hardware. EVA tools, after assembly, will be closely inspected for sharp edges prior to flight. This often includes passing a “swatch test”, where a trained inspector runs a polymeric swatch pad along the surfaces of the hardware to see if it catches on any protrusions or becomes scratched or torn.

To pass the swatch test, it is important that all edges of the hardware are free of burrs. Deburring often occurs at the piece part level during and after fabrication. For surfaces of mating parts that are meant to be flush, the surfaces are required to be within 0.03 inches of flat at the edges. An effective design may have the mating surfaces butted or recessed, avoiding the possibility of a protruding edge.

For general edges on EVA hand tools, an edge radius of 0.06 inches is common. Figure 13 shows the minimum requirement is 0.04 inches, however it is not unusual for a tool to need a radius smaller than this in order to do its job. Some tasks require tools with miniature parts, small protrusions, or sharp edges (to cut, for example). In these cases exception to the requirement is taken, the largest radius possible should be used, and the edges should be documented and carefully examined. Safety and design reviews may lead to a requirement that the edge be covered in some manner until the tool is actuated. This can be accomplished often with a cloth sheath or a bag. It is also good design practice for the mechanism with the sharp edge to be contained within the tool and then deployed only when it is needed. When a crewmember must go near or interact with an item having sharp edges, it is customary for ground control to iterate cautionary reminders. Requirement exceptions that might impact crew safety are often classified as “EVA considerations” or “EVA constraints” in a tool’s documentation.

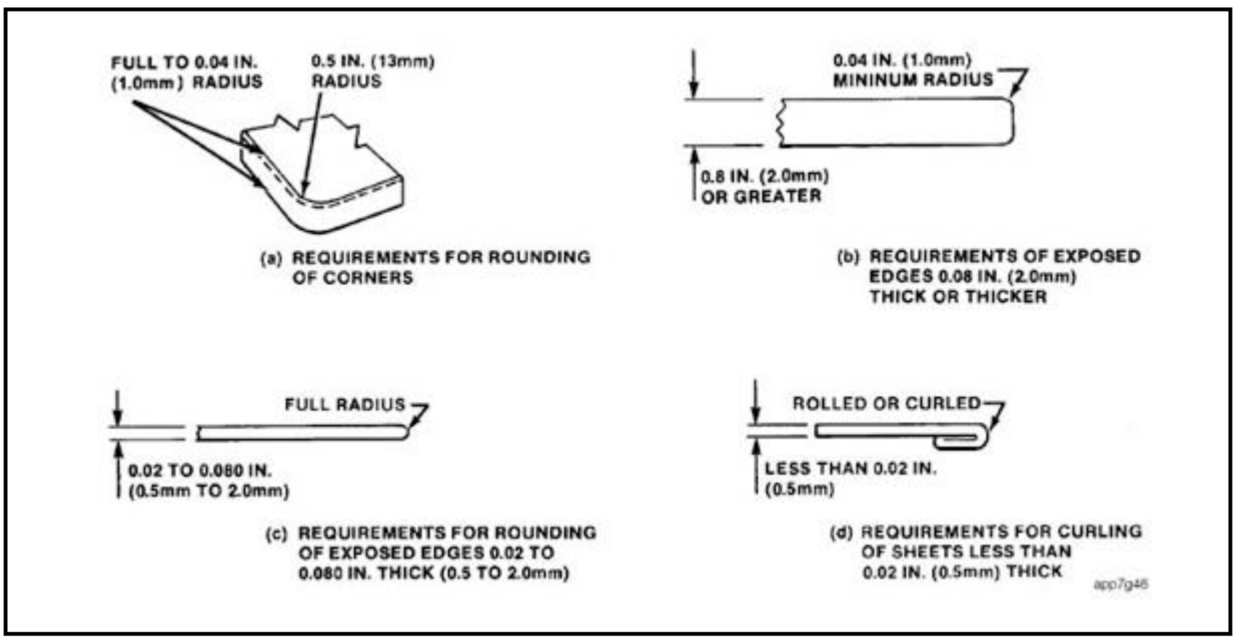


Figure 13 -- Exposed Corner and Edge Requirements

(Source: NSTS 07700)

With regards to sharp edges, extra attention is paid to fasteners because they have such small features. Fasteners used to hold parts together should not have exposed threads. Exposed threads can be covered with a nut, and in extreme circumstances covered with properly applied epoxy. Fastener heads are susceptible to the creation of sharp edges during torquing, especially small screws. The small bits used to drive these fasteners may slip out of the recess and impact the recess edges, raising a burr. It is good design practice to recess fasteners where possible, and implement allen or socket heads over torque-sets or slots. If a sharp edge is found, that fastener should be replaced prior to the mission.

3.1.2 Mechanically Stored Energy

The term "stored energy" is used to address the safety concern that a mechanism may inadvertently release or cause unsafe motion due to the existence of stored energy such as a preloaded spring. Unplanned motion in an EVA tool may create a pinching hazard or cause damage to the EMU or nearby hardware. These mechanisms should be evaluated for adequate locks and safety features to prevent inadvertent actuation.

3.1.3 Hand Clearances, Pinch Points, and Holes

Holes, slots, and recesses should be smaller than 0.4 inches or larger than 1.4 inches in size to prevent entrapment of a gloved finger. If a feature is necessary that does not satisfy this requirement, it should be documented and carefully reviewed.

Hand actuated mechanisms such as latches and levers should be carefully evaluated for pinch points. Motion of components that causes two surfaces to approach each other to a distance smaller than 1.4 inches should be avoided. An example of this can be seen in Figure 14, where the wing tab connectors are always 1.5 inches apart. The thrown or engaged position of a lever should allow adequate clearance for the crewmember's gloved hand and fingers to easily come free. Over-center mechanisms should also be carefully looked at for pinch points, as they may quickly snap or jump in to place like a stored energy mechanism.

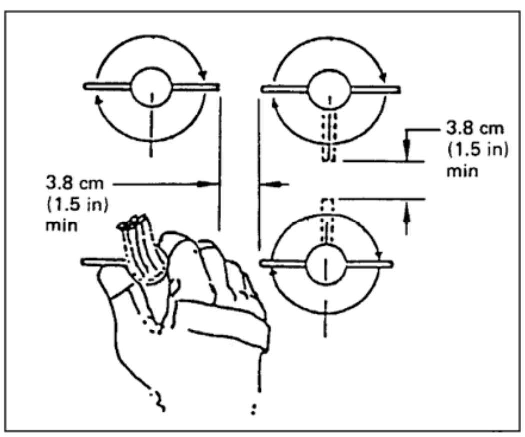


Figure 14 – Minimum Spacing Between Wing Tab Connectors

(Source: NASA-STD-3000)

3.1.4 Structural Requirements In Case of Inadvertent Contact

Perhaps one of the most influential requirements in EVA tool design is being able to withstand inadvertent contact from a crewmember. Structural requirements often drive component sizes, and material selection. All hardware must be able to withstand a 125 lbs force in any direction applied to a 0.5 inch diameter area at any location. This is often referred to as the “bump load” or “kick load” requirement. It is important to understand that the word “withstand” used here means that the resultant effect of inadvertent contact does not cause damage or harm to the crewmembers. Creation of free-floating debris is considered unsafe. A fracture in material is considered unsafe as it may create sharp edges and debris. The tool itself may consequently yield or not function properly, as long as it is still determined to be safe. It is good engineering practice to design a tool to continue to function even after such an impact. A mechanism used to capture or attach to something must not allow this inadvertent contact to disengage the mechanism, else it may become detached. See Section 3.2.4 on locks and other methods to prevent such a hazard.

It is common for a tool to need small parts to do its job that cannot meet this requirement. Material selection and redesigns should be properly evaluated and weighed against the negative trade-offs. If design reviews and EVA personnel deem it necessary, exception can be taken to the requirement and the noncompliance shall be documented, possibly as an “EVA consideration” or “EVA constraint”.

3.1.5 Rapid Return Scenario

It is essential that shuttle payloads do not inhibit rapid return of the EVA crew to the shuttle nor prevent the payload bay doors from closing. Requirements exist that mandate this rapid return and door closure must be possible within 20 minutes. EVA hand tools designed to attach to other hardware may need to take this into consideration if the tool inhibits crew translation or door closure in its attached configuration. The removal or detachment mechanisms of the tool may be subject to additional scrutiny and failure tolerance.

3.1.6 Material Selection

Safety document NSTS 1700.7B specifies that materials used in payload structures shall be rated for stress corrosion cracking (SCC) in accordance with NASA document MSFC-STD-3029. This document explains SCC as the combined action of sustained tensile stress and corrosion to cause premature failure of a susceptible material. It also classifies different materials, based on thorough testing, into categories of SCC resistance. Alloys and tempers listed in the document’s tables 1-A through 1-E are considered highly resistant to SCC. These materials are commonly called “table 1 materials”. Using a non-table 1 material (e.g. those listed in tables 2 or 3) requires submittal and approval of a Materials Usage Agreement (MUA) document because of the increased susceptibility to SCC.

NSTS 1700.7B also specifies “offgassing” requirements for structures in the shuttle payload bay. There may be additional EVA tool offgassing policies specific to various

NASA programs. Offgassing, also called outgassing, is the emanation of volatile matter or contaminants from non-metallic materials into areas where they may cause damage. Examples include silicone particulates contaminating sensitive optics, and toxic gasses entering habitable areas that could be inhaled. These contaminants may become released into the environment from materials over time. Programs have regulations on the amount or concentration of such contaminants.

Consult a materials and contamination engineer for detailed guidelines on material selection for non-metallic parts with respect to offgassing. NASA offers a useful tool for evaluating potential materials for this concern, an online database of offgassing test results that can be found at http://outgassing.nasa.gov. The materials engineer can assist with interpreting this data.

3.2 EVA Human Factors

While the tool designer has a lot of leeway in the ergonomics of a given tool, there are some very important requirements and historically proven methods that will govern the human factors domain of a design. The physical capability of a crewmember to interact with a tool depends heavily on the worksite and on the crewmember's posture and restraints. That is why evaluations of prototype hardware can be invaluable. Requirements can be modified and calculations can be voided if sufficient evidence exists from demonstrations and crewmember assessments. This section will review some of the quantitative requirements levied on tools that ensure their usability by a crewmember restricted by an EMU. It will also discuss some of the unwritten guidelines and hidden expectations that often aren't discovered until late in the design process.

3.2.1 Crewmember Applied Forces & Torques

There is a lot of documentation on what crewmembers are and are not physically capable of during EVA, however there is no better data than simulated weightless evaluations with the expected worksite configuration and EVA tool. That being said, NSTS Appendix 7 suggests that tools actuated through movement at the shoulder or elbow should require less than 20 pounds of force. Similarly, tool actuations done by the gloved hand and fingers should require less than 5 pounds of force. An example of this would be depressing a spring-loaded button, or squeezing a trigger type of mechanism. Lastly, torque type loads applied through the wrist should require no more than 35 in-lbs to actuate Common examples of this include mating and demating connectors, and turning threaded interfaces. Keep in mind, it is not uncommon to take exception to force requirements when necessitated by a tool's function or circumstance (note, many internal NASA documents may give force numbers that differs from NASA-STD-3000).

Crewmember applied forces is also highly dependent on the worksite and the manner of restraint. A free floating crewmember most easily actuates toggle and rotary switches and applies impulse type loads while holding a handrail with the other hand. A crewmember in a foot restraint has a much greater ability to push and pull with higher loads and has two hands available if needed.

Fatigue should certainly be a major design consideration. A threaded interface that must be rotated many times is an example of a design with potential for improvement. Some documents list criteria for the maximum duration of applying a particular amount of force, however these numbers should not be thought of as driving requirements. Once again, crewmember preferences through prototype evaluations will most often take precedence over any "official" numbers. Evaluations with the crewmember at the worksite restrained in a manner similar to what is expected on orbit are best for this purpose (refer to section 4.2.1 on design input from NBL).

3.2.2 Visual Alignment Indicators

A crewmember's pressurized glove can limit tactile feedback to the hand. This is a very significant difference from operating mechanisms barehanded. Even if a crewmember is able to feel a hard stop or alignment groove, they can sometimes get false positives. Consequently, all EVA tool mechanisms actuated by small motions or requiring definitive alignment should have visual feedback indicating proper actuation has been completed. This should be designed into the tool without greatly increasing the mechanism complexity or creating additional failure modes.

A great example is a wing tab connector having an alignment mark that orients the key slot with the mating receptacle. Another example is a visual depth indicator on a tool required to be flush with a mating surface in order to properly function. Also important are visual signals (such as arrows) giving reminders on which direction to actuate a moving part, and indicators displaying if a mechanism is locked or unlocked.

3.2.3 Soft Docks

Functionally and rigidly attaching an EVA tool to a piece of hardware or to another tool may be referred to as a hard dock. A non-rigid or incomplete connection might be considered a soft dock. Having a soft dock may mean additional actuations are needed to fully attach the tool, but it also allows the crewmember to temporarily let go of the tool and to verify position and visibility before hard docking.

While mention of "soft docks" might not be found in most requirements documentation, crewmembers often request such a feature. When possible, soft docks are designed so that the mechanism can restrain the weight of the attaching tool in 1-G.

An often overlooked requirement is that failure of the non-essential soft dock mechanism must not prevent full attachment, or hard dock. See Section 3.3 on failure tolerance.

3.2.4 Mechanism Locks, Preventing Inadvertent Actuation

NSTS Appendix 7 indicates that EVA tools, intrinsically designed to require easy and small actuation forces, should incorporate bump guards or locks to prevent inadvertent actuation. Essentially, the primary actions done to operate a tool should require two different motions. For example, a wing tab connector first must be slid onto its keyed receptacle, and secondly turned to achieve full engagement. Similarly, it must be deliberately turned in the opposite direction before the connector can be functionally disengaged, creating a guard against accidental disengagement.

Inadvertent actuation can also be prevented by a lock mechanism, which can be implemented in many ways. The important design consideration here is ensuring that the two required motions (or the primary motion and the unlocking) cannot be initiated by the same force vector. This means that an accidental bump on any location in any direction does not allow both motions, thus actuating the mechanism.

A "soft dock" can be considered the secondary motion when the function is attaching to something. However, this should be evaluated carefully. If it is very important that the mechanism does not accidentally detach, a mechanical lock should be used as well. Since the tool must be able to withstand accidental contact of 125 lbs for safety (see Section 3.1.4), including a lock ensures that at least the primary mechanism still functions in such a situation.

Avoiding inadvertent actuation is essential because unexpected motion can cause damage to the EMU as well as nearby hardware that can create a hazardous environment for the crew. In can lead to pinch points, creation of sharp edges, and even unrestrained hardware floating uncontrolled.

3.2.5 EVA Operable Fasteners (Hand and Tool Actuated)

Threaded interfaces and fasteners can provide a compact and efficient means to connect and disconnect joints in EVA hardware. Hand operated fasteners often have knobs or wing tabs for gripping. Tool actuated fasteners are preferred to employ a hex type interface for a socket, with size 7/16" being most common. There are many specific constraints with regards to EVA operable fasteners:

- Head or knob must be at least .75 inches tall.
- Hand actuated knobs must be at least 1.5 inches in diameter.
- Fastener must be captive or positively restrained, such that disengagement does not release it as debris.
- Fastener must be visible to verify proper seating and tool engagement.
- Torque set, recessed, Phillips, and slotted-type fasteners shall not be used. They require axial force to operate and keep the driver engaged which can sometimes back out and slip.
- If not nominally hex shaped, fastener must also include an internal or external hex shape for contingency operation.

3.3 Fault Tolerance and Design for Minimum Risk (DFMR)

NSTS 07700 Appendix 7 levies a requirement that no single mechanism failure shall result in damage to shuttle equipment or result in the use of contingency procedures. This can be considered "single-fault tolerance". It also levies a requirement that no two failures shall result in personnel injury, loss of life, or prevent safe return of the shuttle. This is "two-fault tolerance" for failure modes that are "safety-critical". These requirements pertain specifically to the safety of the crew and shuttle, however a NASA program may also have fault tolerance constraints for mission success, meaning that a mechanism failure doesn't cause the loss of a mission objective.

It is rare that an EVA tool would have a safety-critical mechanism. During shuttle launch and landing, the stowage container or mechanism that restrains the tool is responsible for keeping it safe from coming free and causing damage to the shuttle. However there may be a situation where during EVA the tool is permanently attached to or grapples another piece of hardware that is later stowed for landing. In this case, the other piece of hardware may be restrained for landing, but the attached tool is not. The tool must then be two-fault tolerant for safety and ensuring it does not detach and come free from the restrained piece of hardware.

Similarly, if a tool is meant to only *temporarily* attach to another piece of hardware, it may need to be two-fault tolerant for removal from that mating hardware. If the tool for some reason cannot detach, it may cause a safety hazard for shuttle landing. If the attachment mechanism is not two-fault tolerant, and if the stowage restraints are not designed to safely restrain both the tool and mating hardware together, then there must be certainty that the two items can be separated—through two-fault tolerance.

3.3.1 DFMR

If achieving fault tolerance through physical redundancy is impractical, a mechanism can be evaluated for DFMR status instead. DFMR is a process that allows safety-critical mechanisms to achieve one level of fault tolerance through rigorous design, analysis, testing, and inspection practices. There are strict guidelines for granting a DFMR designation. NASA's Mechanical Systems Working Group (MSWG) must review and approve a mechanism for compliance with DFMR. Granting DFMR status means that the MSWG has agreed that a rigorous development process has greatly reduced the credibility of a failure. DFMR status in some cases may be more difficult to obtain than physical redundancy, but it provides another option. More information can be found at http://mmptdpublic.jsc.nasa.gov/mswg/, including an official DFMR compliance matrix.

3.4 Integration and Testing (I&T)

Although I&T has little influence on EVA tool design, it is worth mentioning and clarifying a few keywords and policies. Every tool designed for EVA will require a "verification plan", documentation that details all the testing that the assembled tool will undergo to verify it is properly ready for the mission. Some of the common tests are listed here:

- Thermal Testing: Verifies tool functionality and stability at temperature extremes. For EVA tools, this is often done in a "thermal glove box chamber", which has interface gloves allowing mechanisms to be operated while the tool is inside. Thermocouples can be used to measure local temperatures. The chamber is at ambient pressure, not vacuum.
- Vibration Testing: Verifies quality of general workmanship of materials. Also can verify that the tool can survive launch loads in its stowage configuration.

- Life-Cycle Testing: Verifies that mechanisms will survive their expected lifetime by cycling them.
- Functional Testing: Verifies that a tool's mechanisms are working properly, or within specification. Measurements of forces and torques can be taken, as well as measurements of geometry and fit checks. A functional test is often performed before and after other verification tests.

Tool assemblies considered "flight" quality fall into one of these three categories:

- Acceptance Unit: Assembly that will be flown on a mission.
- Qualification Unit: Assembly that will not be flown on a mission, and will undergo rigorous testing beyond levels/environments expected in the mission to prove the quality of the design.
- Protoflight Unit: Assembly that is rigorously tested and also flown. The test levels are typically greater than for an acceptance unit, but not has high as a qualification unit.

4 Training EVA Crewmembers

4.1 Payload Training Overview

NASA's Mission Operations Directorate (MOD) trains the shuttle crew in payload operations and services. The Payload Training Team does this with shuttle and payload mockups, high fidelity simulators, and other methods to prepare a crew for their mission. Crew familiarization with hardware as well as detailed knowledge of EVA operations is essential to a successful mission. EVA tool engineers are often involved with this payload training, procedure development, and simulation support with respect to their designed hardware.

It is worth noting that during a shuttle mission payload customers often provide real-time support to personnel at the JSC Mission Control Center (MCC) with regards to their hardware and related procedures. This ground personnel must also be trained and made familiar with the payloads and procedures. This is done through Joint Integration Simulations (JISs), dress rehearsals or practice runs of the mission, during which a mock EVA is scripted and relayed orally, and ground personnel reacts accordingly. Because of their payload expertise, tool engineers may take part in supporting the MCC during the mission and during these simulations.

4.2 Neutral Buoyancy Lab (NBL) Simulations

A significant factor in crew training is underwater Neutral Buoyancy Lab simulations. Here a crew can practice procedures with flight-like mockups of everything from the shuttle itself to small tools. EVA protocols and timelines can be developed and optimized. NBL simulations can also be an affective input to hardware design during the development stage. Crew feedback on things such as visibility, reach, and access at worksites can lead to priceless design improvements to be incorporated by tool engineers.

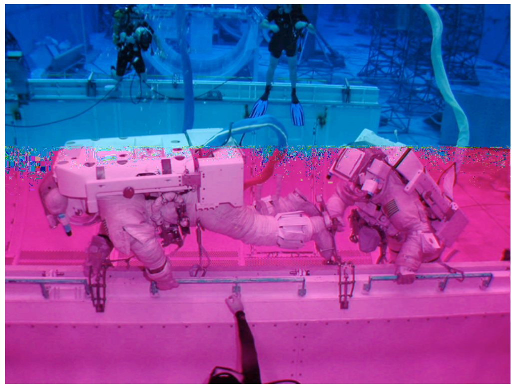


Figure 15 – Crewmembers Training at the NBL
(Source: NASA NBL Website)

Figure 16 – Training Pool Topside View
(Source: NASA NBL Website)

4.2.1 Design Inputs *from* NBL

While NBL simulations help train the crew and help develop EVA protocols, they also provide an opportunity to evaluate and critique early tool designs.

Each crewmember is equipped with wireless video cameras on top of their helmet, giving watchers almost the same view that the crewmember sees. Besides the crewmember's verbal feedback, viewing this video can give further insight into any difficulties or confusion that is encountered while operating a tool concept. SCUBA divers with underwater cameras are also on hand to photographically document the activities.

At the conclusion of an NBL evaluation, the crewmembers, systems engineers, and hardware engineers participate in a debrief meeting where tool design and performance can be discussed. The crew will elaborate on their thoughts as they recall operating a tool or performing a task. When appropriate, engineers are able to ask questions to gain input on how to modify a tool to improve crew performance and comfort. Some of the more common inputs involve clarity of labels, necessity of alignment marks, locations of tether attachment points, and preferences of tool actuation (e.g. CCW versus CW turns, force required to rotate a lever, grip locations, etc.).

Perhaps the most useful feedback from NBL is reach and access to the worksite with the tool. Only during these evaluations is the crewmember situated in foot restraints in a manner closely resembling what will be encountered on orbit. For tasks with complex interfaces, this simulates reach, access, visibility and posture much better than a tabletop evaluation of a tool. This aspect of the evaluation may make or break early tool concepts and trade studies, which is one of many reasons to have tool mockups evaluated underwater early in the development stage.

4.2.2 Designing *for* NBL

It is not always optimal to use an exact "flight-like" (meaning of the same material and configuration as the flight unit) tool for underwater NBL evaluations. For example, the water contents can be very corrosive and damaging to certain materials. Also, some material surface treatments for outer space may be useless in the water. Most importantly, because cost and schedule are always critical, alternate processes, materials and configurations can lead to cost savings and greater efficiency without compromising quality. On the other hand, there is always a negative side to training with equipment that differs from flight configuration. A crewmember may get too accustomed to the alternate operations or configurations, or they may give improper feedback and evaluation. This is referred to as negative training and should be guarded against carefully. As an example, on orbit a crewmember once almost completely let go of a tool when he finished using it because in the NBL water he was so used to handing the tool off to a SCUBA diver to swap for a lightweight version of the tool.

Underwater, crewmembers can take advantage of neutral buoyancy for simulated zero-gravity, however, the equipment that they use should also be neutrally buoyant. In orbit the tools they use will be weightless, and this should be simulated as much as possible in the NBL tools. The most common method for achieving neutral buoyancy is attaching closed cell solid foam to a tool's structure. The low density foam adds buoyancy, but it can also add volume. This additional volume might impede the function of the tool, and if it affects how the crewmember manipulates the tool it can lead to negative training.

Another way to reduce the weight of a tool is using alternate materials such as plastics and aluminum in place of steel where possible. Delrin and Ultem are commonly used. These materials also are more easily machined and thus can save costs. Light-weighting can also be accomplished by machining holes and cavities into housings and components that don't bear heavy loads.

Underwater, some standard space rated lubricants don't perform well or lack durability. Designers should investigate marine lubricants, as well as making sliding components out of materials with a lower coefficient of friction such as Delrin.

To save costs, commercial products that are similar to components used on the flight tool design should be considered, with small spring driven cable reels and quarter-turn fasteners as examples of commercially available products that closely resemble standard GFE parts common to EVA tools. Carabiners are often used in place of tether hooks. In some cases buying an off the shelf knob, handle, or bracket may suffice.

It is important to consider wear and tear on a mechanism that is used repeatedly at multiple NBLs. A tool that is design for one use on orbit may see many cycles during crew training. Easily replaceable parts may be useful. For example, a tool with a knurled surface that has the function of attaching to something else by driving those serrations into it will eventually wear down itself and the mating surface.

Lastly, it is very important to remember that crewmember's often change their minds and that not all crewmembers are the same. It is difficult to design a tool to be ergonomic until the design is mature and the EVA operations are well defined. That is why the design must be flexible to adjust for changes, especially early in the development. It also shows the value of accurate and functional mockups for use at NBL evaluations early in the design and development process.

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