Using Life-Cycle Human Factors Engineering to Avoid Costs:

Lessons Learned from NASA's Human Factors Verification Process for Space Payloads

Presented by:

S. Richard Ellenberger

Juan Davaloz

ISS Flight Crew Integration Deputy System Manager

Habitability and Human Factors Branch (SF3)

NASA Johnson Space Center, Houston Texas

Topics

- A few words on Human Systems Integration (HSI)
- The Promise of HSI
- HSI Success Story
- Program Lifecycle costs
- Elements of HSI at NASA
- What is Human Factors and how do we do it?
- Why Human Factors?
- Designing hardware for microgravity environment
- ISS Human Factors Implementation Team (HFIT)
- Examples of HFIT’s positive impact on design
- Examples of unfortunate design choices
- HFIT’s role in Cost Avoidance
- Human Factors Requirements News

What is Human System Integration?

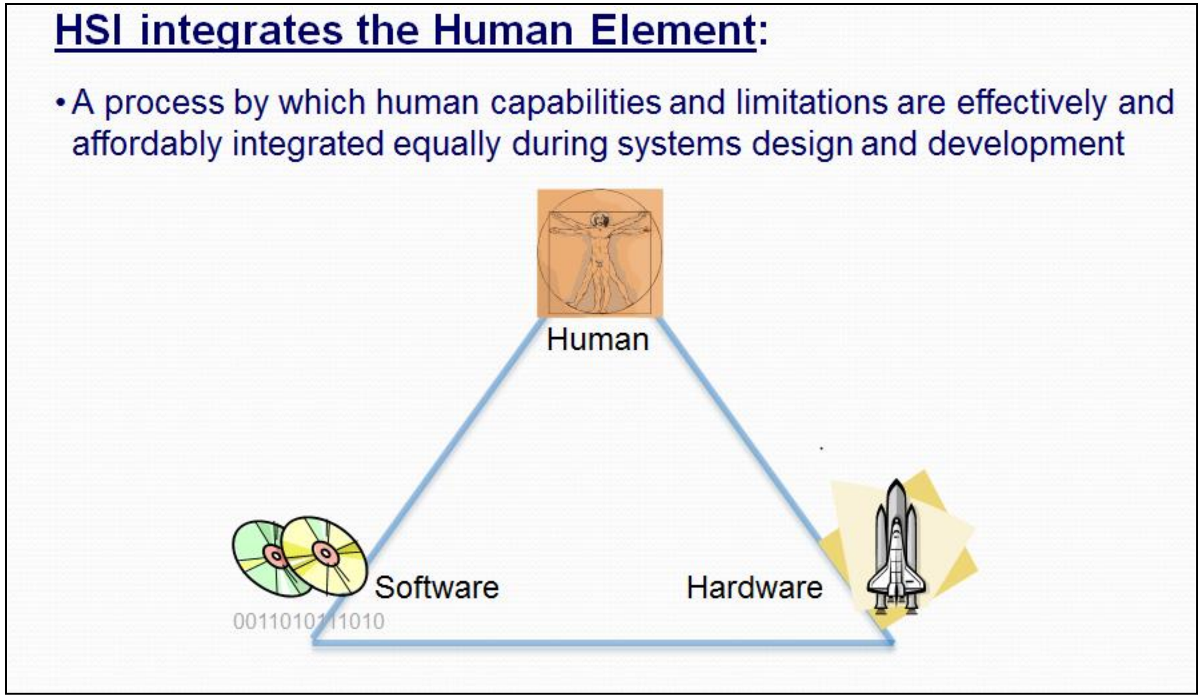
Human Systems Integration:

An interdisciplinary and comprehensive management and technical process that focuses on the integration of human considerations into the system acquisition and development processes to enhance human system design, reduce life-cycle ownership cost, and optimize total system performance (NPR 7123.1B).

NPR 7123.1B defines the system as

hardware + software + humans

…but says very little on how to integrate humans and systems.

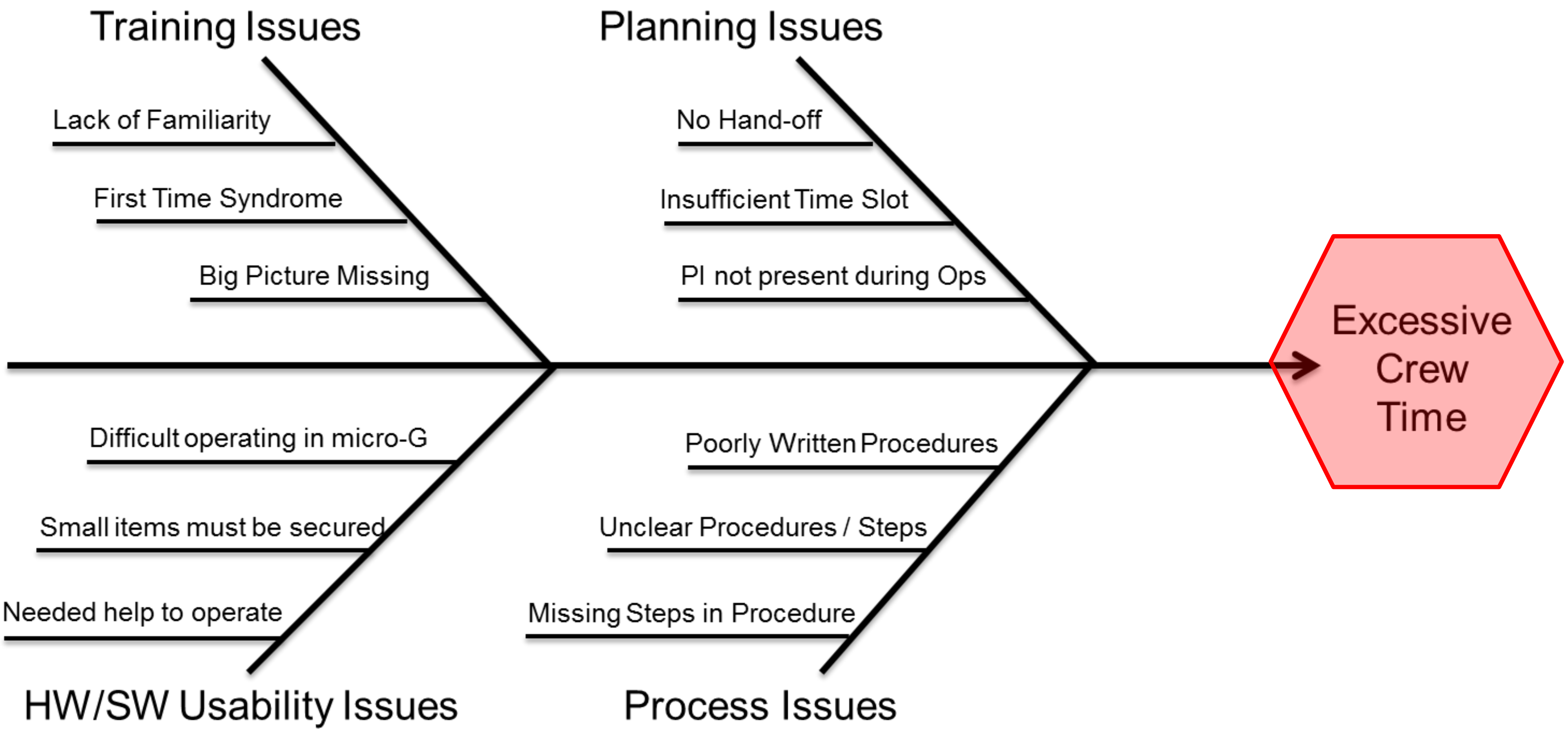


The Promise of HSI

- System Optimization due to:
  - Reduced manpower numbers
  - Simplified requirement for personnel skills
  - Reduced training needs
  - Simplified maintenance and logistics
  - Mishap avoidance
  - Avoidance of system rework costs

- Designs that are focused on the needs of operators, maintainers, and other support personnel
- Demonstrates "return on investment" of HSI in human spaceflight through engagement of all domains and organizations
  - Stakeholders and domains are engaged early and often in the lifecycle
- Promotes total system performance (increased effectiveness and efficiency)

Why early? Reduce Risk & Optimize Performance

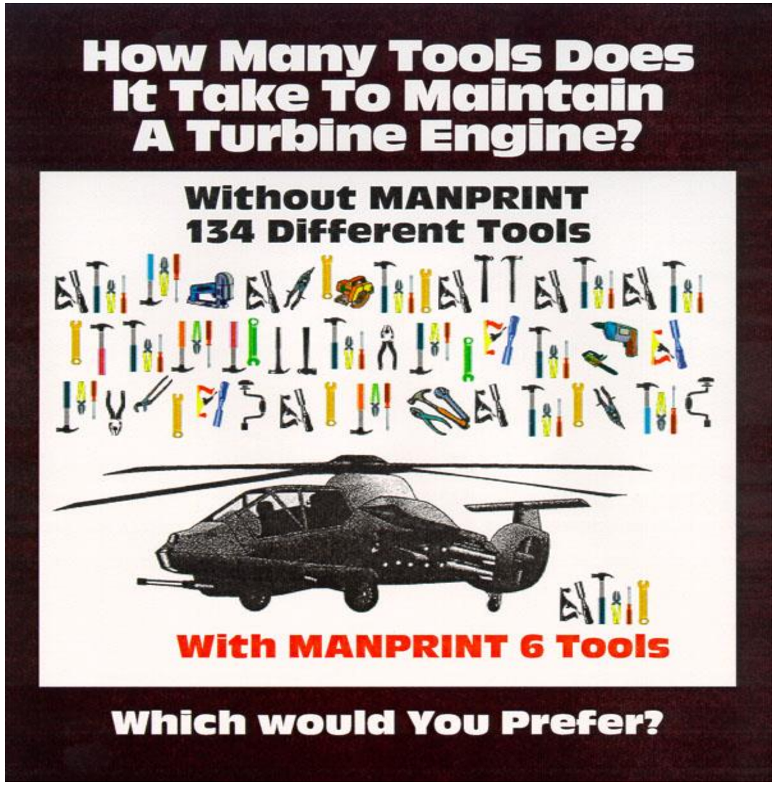


Ref: Categorical example; Grouping of the 109 payload-related crew notes per Dr. Beard/NASA-Ames

Why HSI? A DoD HSI Success Story

Comanche Tool Kit

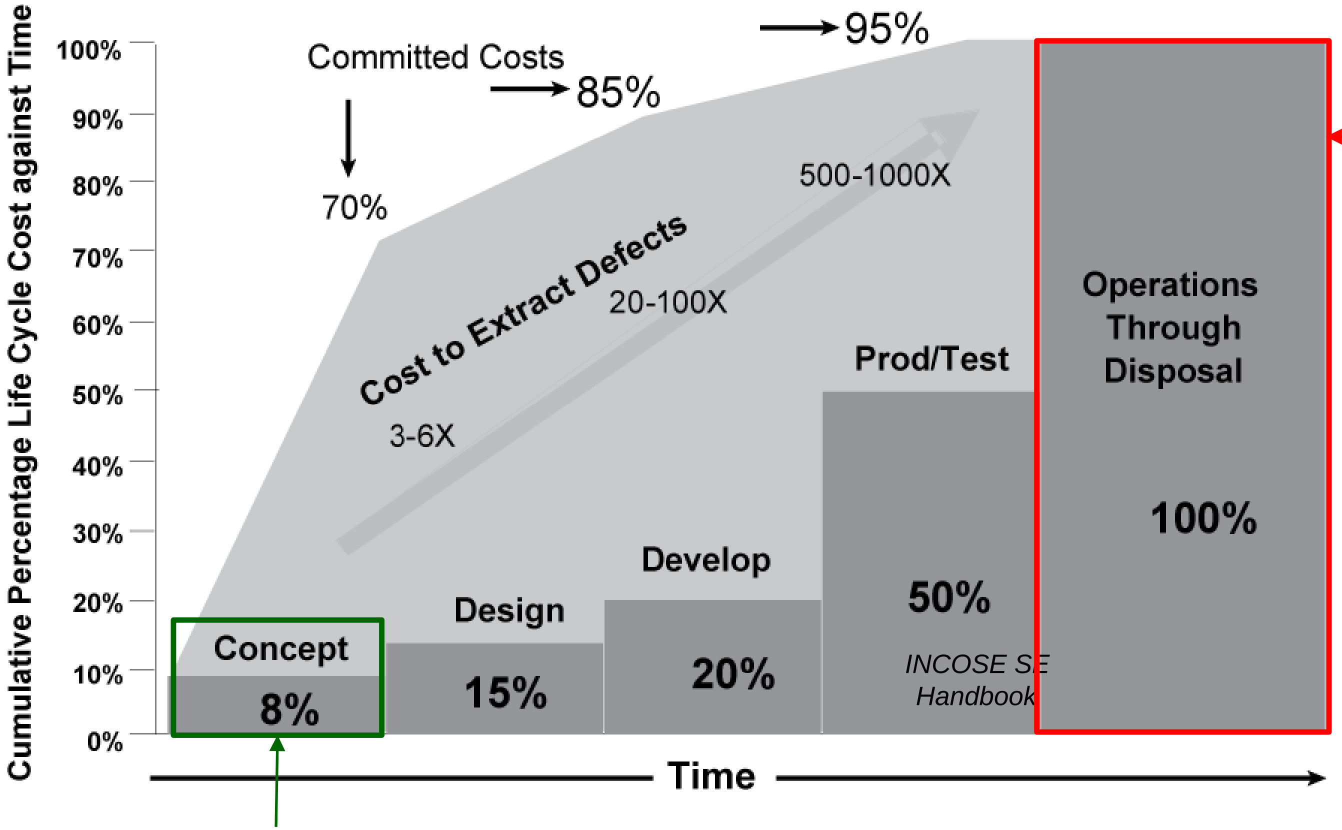
- The tool box for the T-53 series helicopter turbine engine (Huey & Iroquois) had 134 different tools.
- Because of the Department of Defense tool MANPRINT (Manpower & Personnel Integration), and its inclusion of HSI in the design process, the tool KIT for the T-800 for the Comanche has **six** tools instead of 134.
  - And the tools are inexpensive & commercially available
- Result:
  - Fewer tools
  - Less burden on the supply system
  - Less training and inventory time
  - Increased combat readiness



6

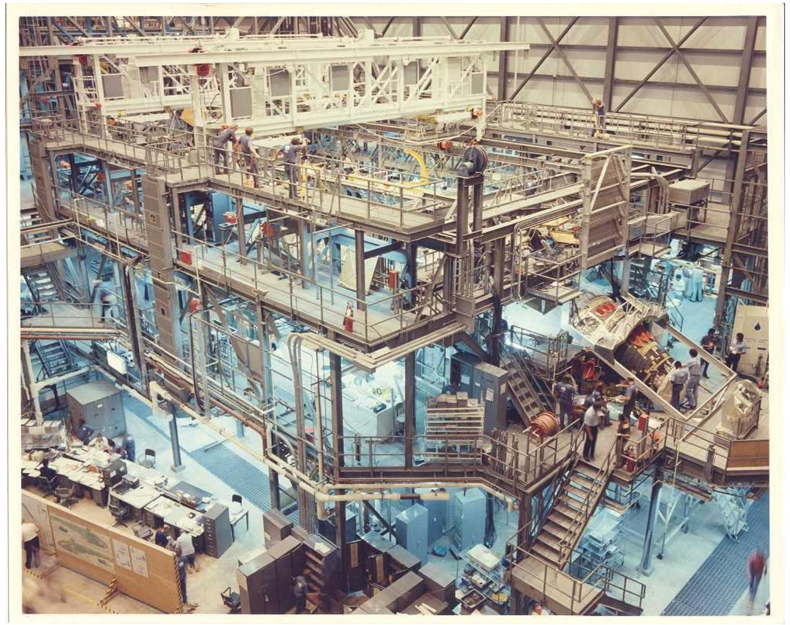
How do we know HSI matters? Cost.

- Lifecycle cost reduction is the goal that drives HSI
- Based upon analyses by the DoD and by INCOSE (International Council on Systems Engineering) 80% of new systems' costs occur after development
- These major operations phase costs are human-related:
  - Manpower, Personnel, Training
  - Rework of human interfaces
  - Logistics and maintenance
  - Poor human /system performance



- To make a difference, HSI <u>must</u> engage at program/project outset
- Once operational, it is extremely expensive--typically prohibitively--to rework systems for human/system efficiency and effectiveness

Example: The Shuttle Concept vs. Reality



Concept
- "Jet aircraft" style hanger
- 5 weeks turnaround time
- 40 flights per year for fleet of 3 vehicles

Reality
- Elaborate scaffolding
- Large number of service workers required
- ~4 flights per year, average

Classic Problems
- Insufficient definition of Ops requirements
- Focus on Performance
- Developers not responsible for Operational Costs
- Very few incentives for addressing turn-around time or maintainability

Source: Bo Bejmuk, Space Shuttle Integration (Lessons Learned Presentation)
See HSIPG Appendix C section 2 for more details

Elements of HSI at NASA

Human Systems Integration encompasses all these areas at NASA

Habitability and Human Factors Branch (SF3)

Human Health & Performance
- Human-Centered Standards
- Human Factors
- Environmental Factors
- Habitability
- Training
- Occupational Health &
- Flight Medicine

Mission Operations
- Operations Experience
- Maintenance & Logistics
- Training
- Personnel & Manpower

Astronaut Office
- Astronaut Support
- Flight Crews Summaries
- Anecdotal Evidence

HSI

Budgeting
- Full-cost Accounting
- Life Cycle Cost Estimates

Legal & Contracts
- Acquisition Strategy

Engineering
- Design
- Systems Engineering
- Program Management
- Training

Safety & Mission Assurance
- Safety
- Human-Rating
- Human Reliability
- Survival Analyses
- Maintainability
- Supportability
- Probabilistic Risk Assessment

Ground Operations
- Logistics
- Personnel & Manpower

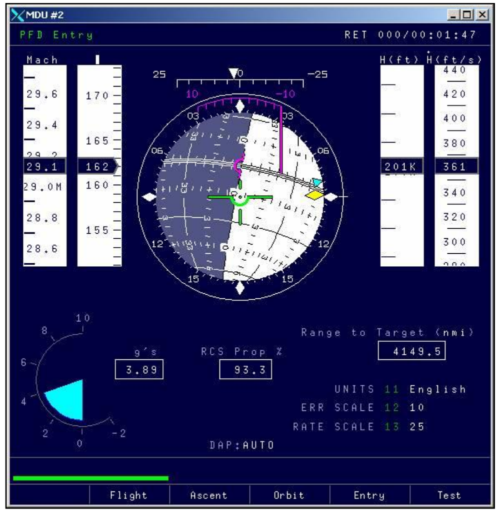
What is Human Factors?

Human Factors in design:

- Design for the human/system interface and account for both cognitive and physical limits.

Key Measures/Goals

- Improve effectiveness
- Improve efficiency
- Improve safety
- Improve situational awareness
- Reduce errors
- Reduce workload
- Reduce fatigue
- Reduce the training demand
- Ensure operability and usability
- Improve satisfaction
- Meet user's needs and wants
- Improve user's perception of product



Early involvement is key: "You can use an eraser on the drafting table or a sledgehammer on the construction site." – Frank Lloyd Wright

How do we do Human Factors?

Human Factors is composed of a number of **unique disciplines** including:

- Cognitive Psychology
- Industrial Psychology
- Biomechanics
- Human/Computer Interaction
- Industrial Design
- Architecture
- Other Engineering and Science specialty domains

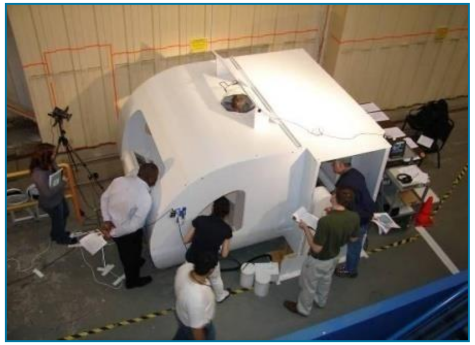
Human Factors practitioners develop, apply, and verify according to:

- Spaceflight Human Systems Standard *(NASA-STD-3001 Volume 2)*
- Human Integration Design Handbook *(SP-2010-3407)*
- Human Systems Integration Practitioner's Guide *(SP–2015-3709)*
- NASA Institutional Review Board processes
- Program-specific requirements and processes

Iterate

Understand

User, Task, & Environment



Design

Solutions

Evaluate

Designs

Human Factors **processes** ensure that the design meets the users' intent and capabilities / limitations

Why Human Factors?

- These humorous examples make the point of why Human Factors is needed.
- Some say that Human Factors is “common sense”. While there is a degree of truth to that, not all Human Factors design challenges are as obvious as below.

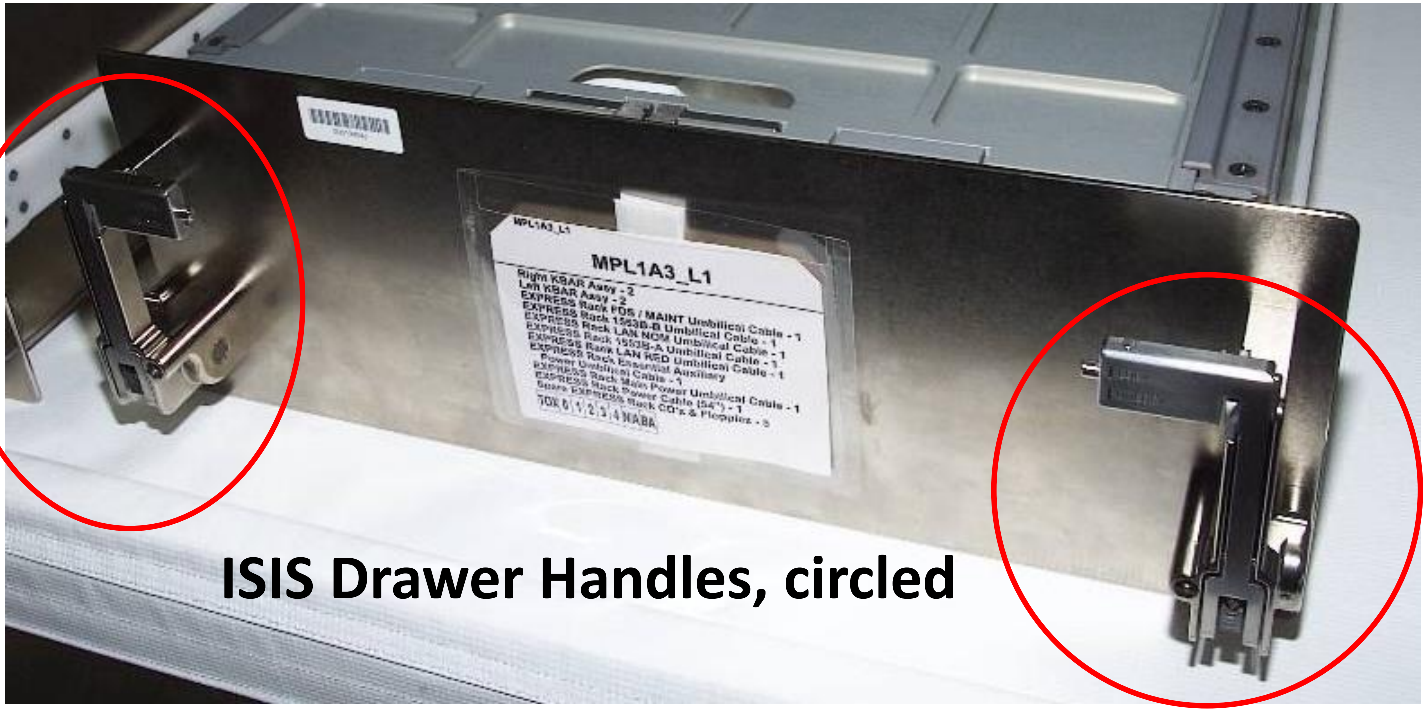
Designing hardware for microgravity environment

- When designing for microgravity operations, consider the ways in which the lack of gravity can both help and hurt the ability of crew to perform tasks.
- Some tasks like moving large objects is considerably easier in microgravity. Objects have mass, but they don't have weight, which means maneuvering them can be easier. However, stopping objects from moving can be challenging.
- Some tasks are harder in microgravity. Because of lack of gravity, crew does not have the same leverage when manipulating objects, such as torqueing a connector or fastener.
  - That's the rationale behind the one-handed operation guideline, because while the crew is manipulating the object with their dominant hand, their other hand is used to stabilize themselves to provide leverage.
  - Certain major operations, like glovebox tasks, can require two hands, in which case the crew will decide to restrain their feet, using a handle rail, or foot restraint. Two-handed operations should be limited to operations where there is no other choice.

Two-handed glovebox operation with foot restraint

Designing hardware for microgravity environment

- Cautionary Note: There can be unanticipated consequences of microgravity's effect on hardware. For example, International Subrack Interface Standard (ISIS) locker handles have a spring effect that is more severe in space than in 1G. They have pinched multiple crew members' fingers causing pain or minor injury.
  - This effect was not discovered during ground testing.
  - The lesson is when designing mechanical devices where stored energy is part of their function, take steps to eliminate pinch hazards.



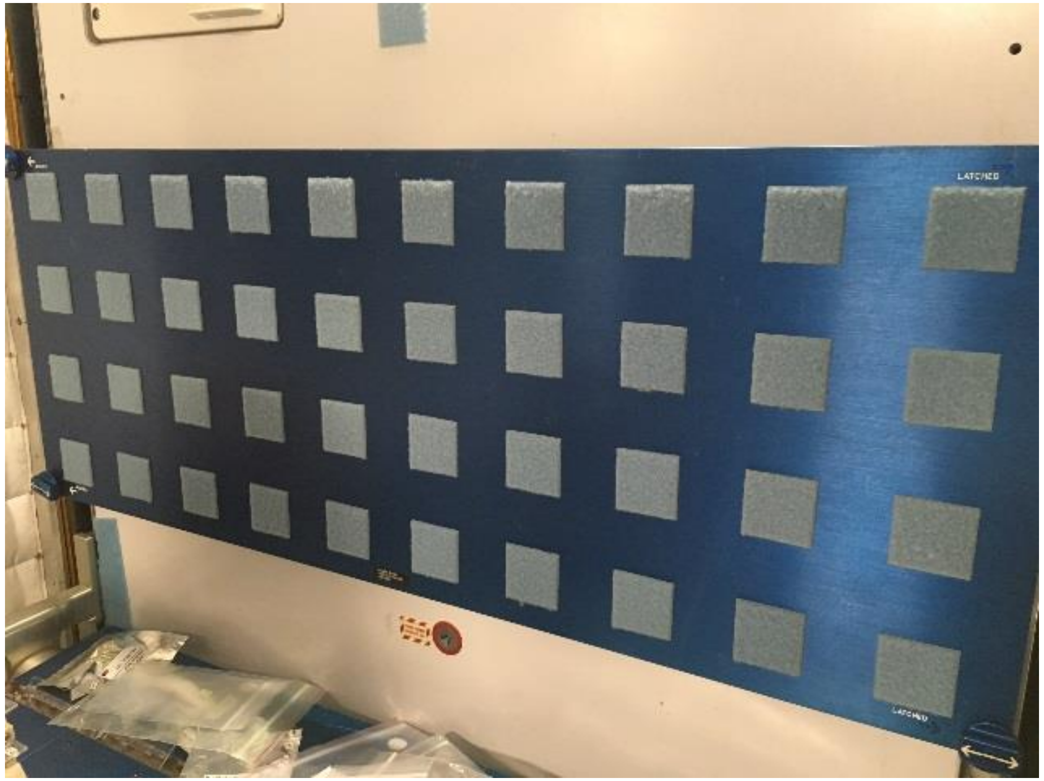
ISIS Drawer Handles, circled

Designing hardware for microgravity environment

- Lack of gravity means objects float away easily and do not stay nicely arranged, such as when we arrange objects on a table in 1G.
  - The captive parts requirement is meant to prevent objects from floating away and causing crew injury, or getting stuck in filters, fans, or other mechanisms causing hardware damage.
  - Bags of science samples, tools, etc. should have Velcro on the back to allow the crew to temporarily stow them nearby on a rack or work area, keeping them organized and restrained.
    - Caution: ISS doesn’t allow long unbroken strings of Velcro due to flammability concerns. Maximum Velcro for a surface area is 2 inch (50mm) squares separated by 2 inches (50mm) vertically or horizontally away from other Velcro, as in this picture of the Maintenance Work Area (MWA) mockup.

Maintenance Work Area:

Example of maximum Velcro per area



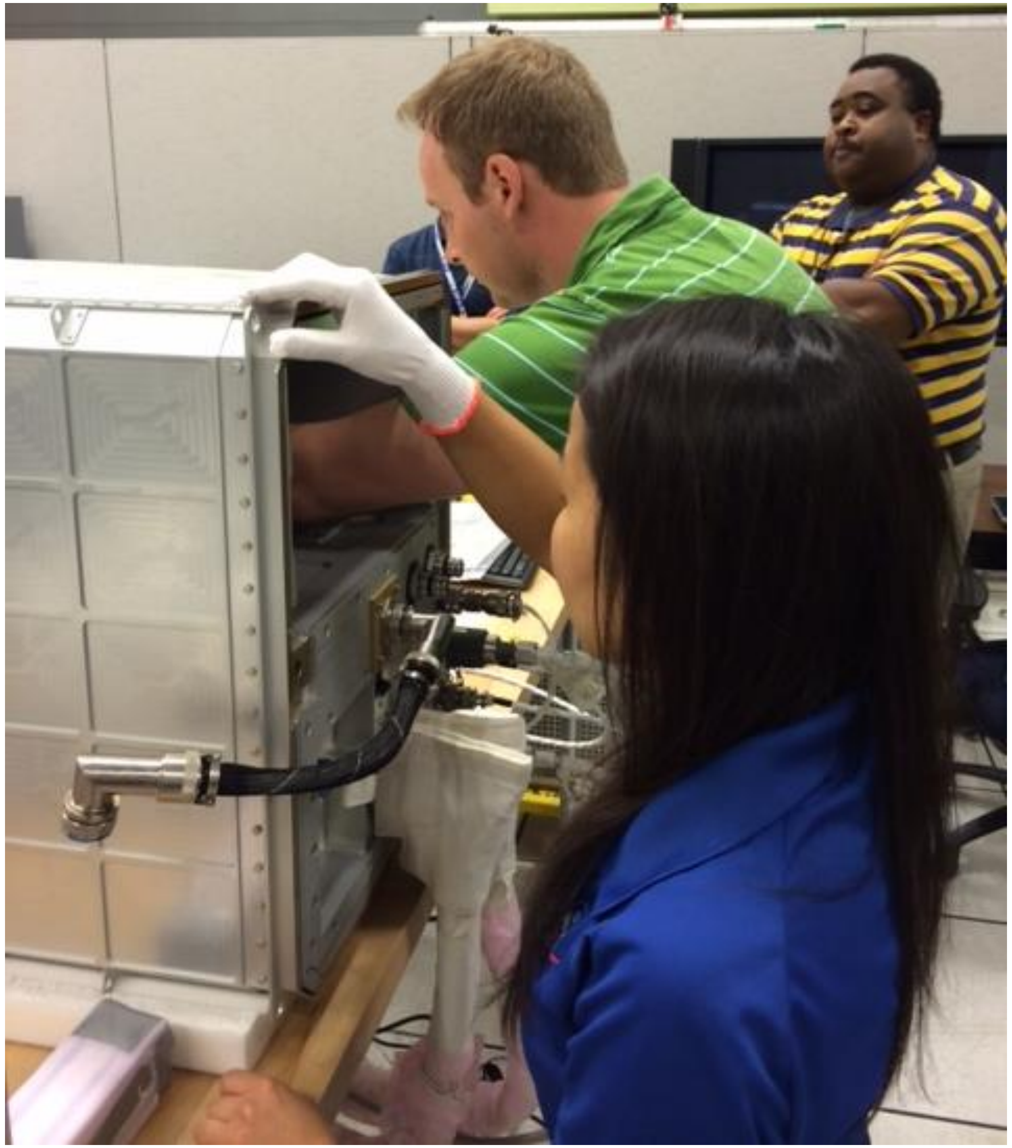
ISS Human Factors Implementation Team (HFIT)

- The ISS Human Factors Implementation Team (HFIT) is an optional service that provides hardware developers guidance in designing flight hardware crew interfaces that meet the Human Factors requirements and guidelines (SSP 50005 for ISS Systems, SSP 57000 for ISS Payloads).
- The requirements are meant to prevent crew injury and avoid damage to neighboring hardware, and the guidelines are meant to facilitate mission success.
- HFIT is available to U.S. Payloads, some ISS Systems, and International Partner (IP) Payloads in the U.S. Lab module
- HFIT crew interface labeling review support is available to all ISS Payloads, upon request, and should occur no later than CDR timeframe.

ISS Human Factors Implementation Team (HFIT)

- **Nominal Human Factors Implementation Team (HFIT) process:**
  - **Assign HFIT rep** at Payload Kickoff
  - **Determine Applicable Human Factors Requirements** (at/near System Requirements Review)
  - **Perform Initial HFIT Evaluation** (at or soon after PDR):
    - Assess prototype or mockup hardware for crew interfaces and labeling against applicable Human Factors requirements.
    - Identify issues early when it is more cost effective to influence design.
    - Provide recommendations on how the payload can comply with requirements.
  - Between evaluations: **Support the Payload Developer** as needed
    - Negotiate solutions to requirements-design conflicts.
  - **Perform Final HFIT evaluation** (after CDR or when flight hardware available).
    - Verify flight hardware meets requirements.
    - HFIT and Astronaut Office approve pre-coordinated, non-safety related non-compliances.
    - HFIT provides Certification of Compliance (CoC) after all issues closed.

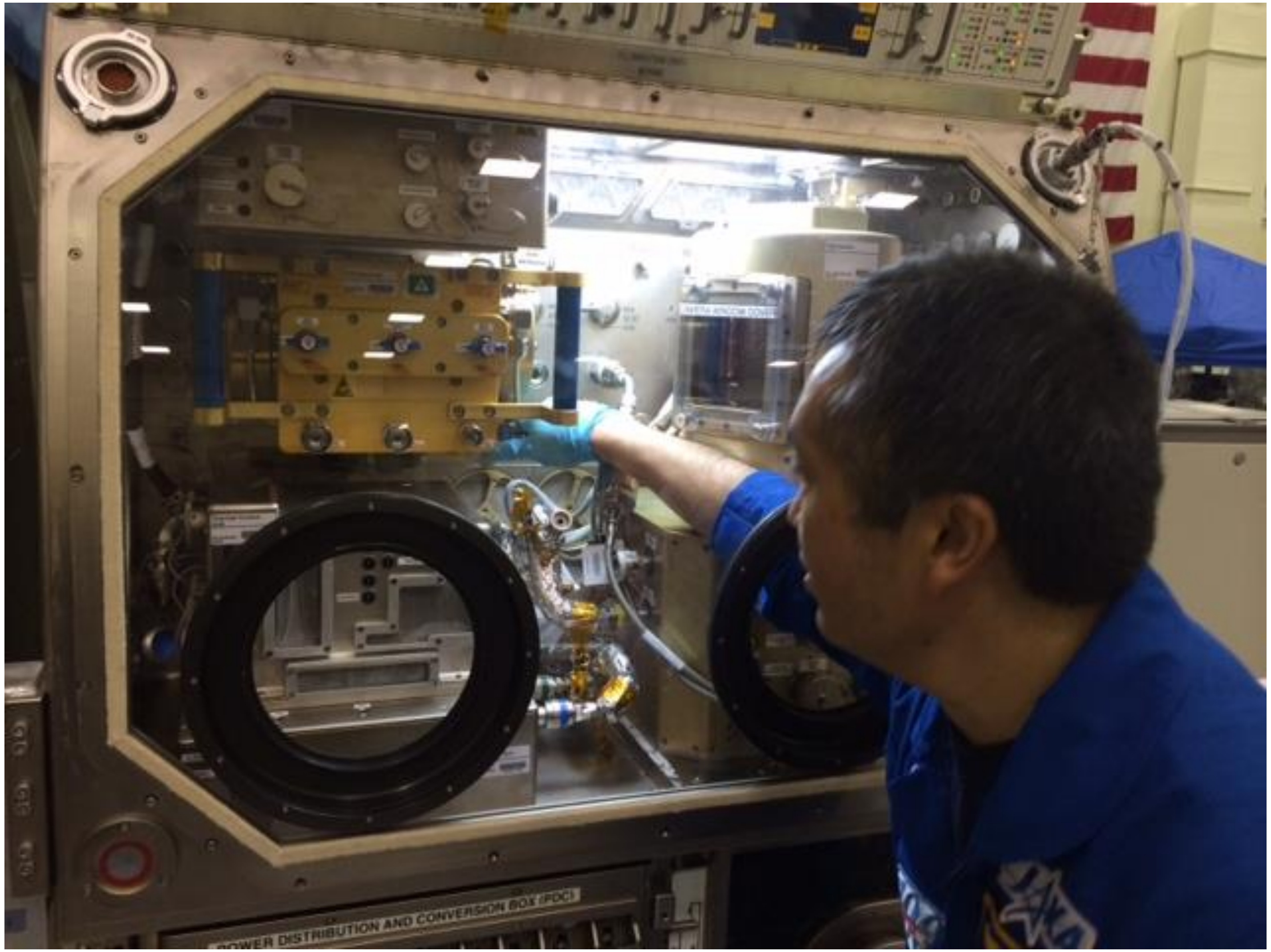
ISS Human Factors Implementation Team (HFIT)



- **HFIT and Human Dependability**
  - HFIT doesn’t study the fallibility of the human’s cognitive abilities itself.
  - HFIT’s design guidance recommendations help reduce **design-induced** errors for crew interfaces because designs are consistent with human expectations for how hardware should operate (intuitive).

ISS Human Factors Implementation Team (HFIT)

- In many cases, experiment real estate is limited and the PD must space hardware tightly.
- Having Human Factors involved helps the PD optimize spacing to allow for crew access.
- HFIT feedback helps choreograph the sequencing of mating tasks during installation operations.
- Although the guidelines state you're not supposed to require removing one ORU or connector to gain access to another object, that cannot always be avoided, since the PD is trying to maximize their experiment's capabilities in a limited volume.



ISS Human Factors Implementation Team (HFIT)

- Common challenges of designing flight hardware:
  - Crew Accessibility
    - Tight spaces: As noted on the previous slide, maximizing science capability in a limited space can lead to crew accessibility issues.
      - Consider enlisting the help of someone *unfamiliar with the design* with large hands and arms, with the idea that their access would represent a worst case.
    - Reach issues: Sometimes the ability of the crew to reach an object is the biggest design driver. In that case, enlist the help of someone *unfamiliar with the design* with short arms to see if they can reach the object.
  - Strength
    - If strength, such as to torque a connector or crew actuated fastener, is an issue, enlist the help of someone with small hands, who may be weaker than then average person, to see if they can complete the task.
      - The goal is to design connectors and fasteners to be able to be tightened by hand, but if it’s not possible or there is any doubt about the crew being able to perform the task, then plan for a tool to be available. Standard ISS tools should be considered before designing unique tools.

Examples of HFIT's positive impact on design

Before HFIT

After HFIT

- **Connector Spacing example**
  - On the image to the left, note the tight spacing of these electrical connectors.
  - The PD recessed the connectors hoping to meet the protrusion requirements in SSP 57000.
  - However, the recessing in combination with the tight spacing made the mating of the connectors by hand impossible.
  - HFIT recommended the PD spread out the connectors as much as is feasible in the available real-estate. The CAD image to the right shows the PD's updated drawing.
- **Labeling**: Note that due to the connectors and associated controls arrangement, HFIT recommended labels be rotated 90 degrees to allow for the best group labeling and to avoid the risk of crew mis-associating one object's label as being the label for a different object.

Examples of HFIT's positive impact on design

- **No Handles for removal example**
  - A double-locker payload's PD was not planning to design handles for the crew to use for installation or removal.
    - The plan was for crew to push against flat area of the subrack to push it into the rack.
    - Pushing the subrack works for installation, but when the crew needs to remove the subrack, they would have had to pull on connectors or other objects not designed for such forces, and not placed in a symmetric layout that would provide even forces to pull the subrack out. Also, those connectors/other objects could be damaged in the process.
    - HFIT recommended the PD add handles on the front of the locker to provide even forces to aid the crew in removing the locker.
  - PD is now plans to implement low profile (flat) fabric handles that can be used to pull the subrack out easily.

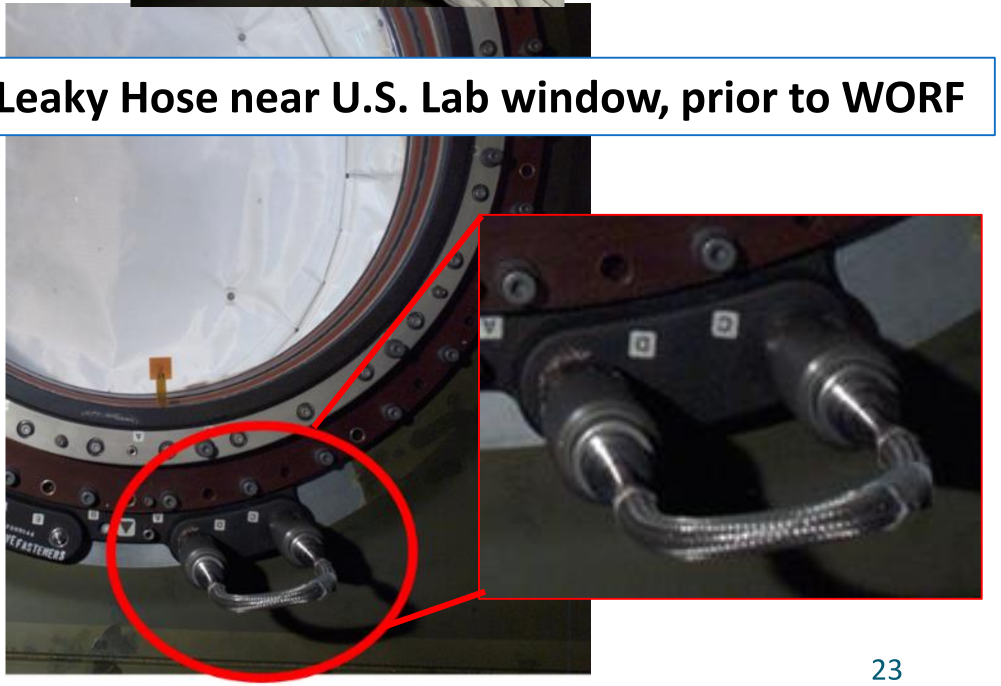
Examples of HFIT’s positive impact on design

- **Lesson learned regarding why having handles is good design**

  Consider the potential negative consequences of the crew using objects, such as cable and hoses as translation or stabilization aids.

  - Early in ISS, near the U.S. Lab window before the Window Observational Research Facility (WORF) rack was installed; multiple crew used a nearby U-shaped hose as a handhold because it was the most convenient object to grab as a restraint, and it looked like a handle! It lacked a Caution/Warning label telling crew not to grab it.
  - Over time, the hose (circled in red) was discovered to be the cause of a slow but steady leak of air from the ISS. The hose was replaced. The risk could have been much worse than a slow leak. It could have caused a rapid depress of ISS. At a minimum, it wasted ISS resources.

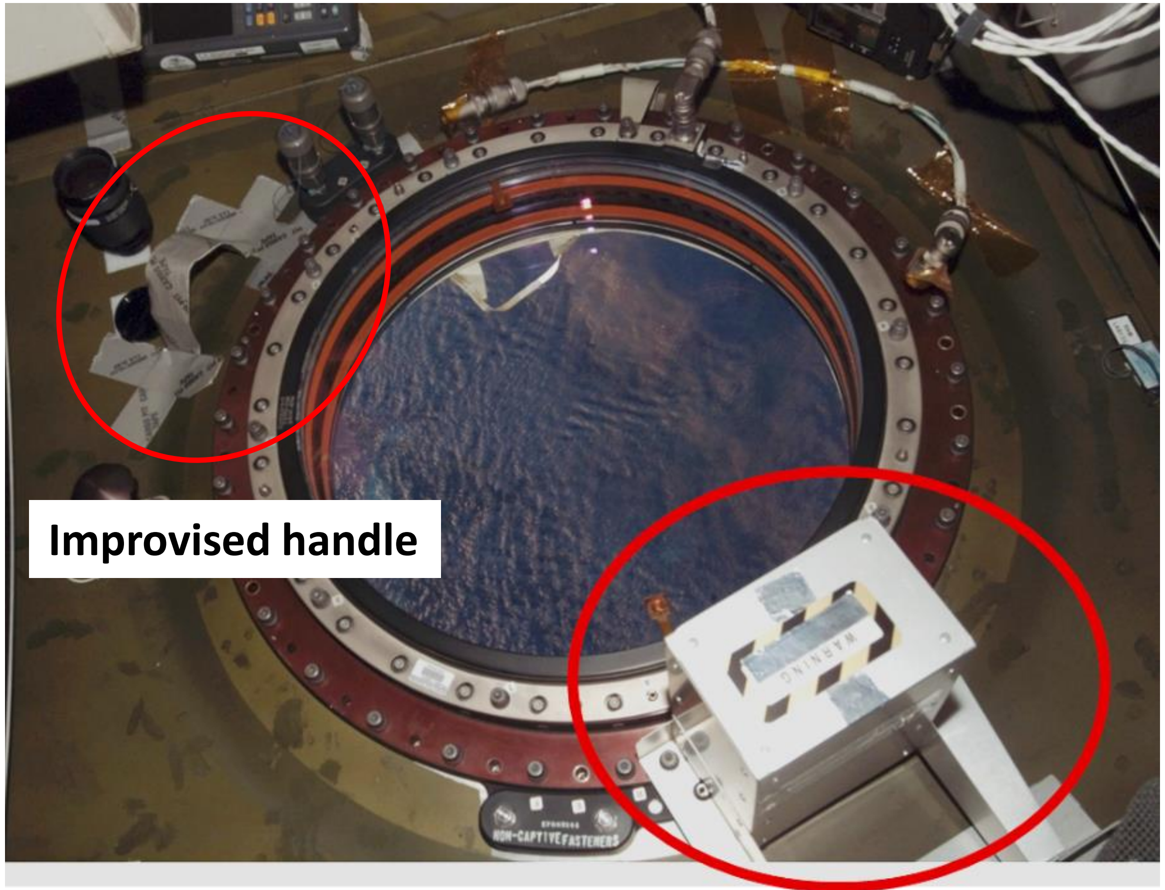
This isn’t the leaky hose, but a nearby cable that also happened to be a convenient handle



Leaky Hose near U.S. Lab window, prior to WORF

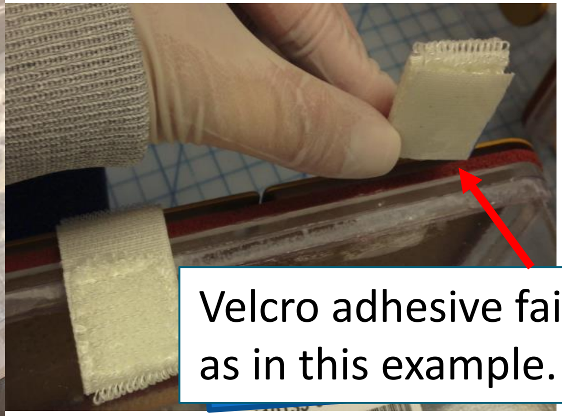
Examples of HFIT's positive impact on design

Solution to Leaky Hose near U.S. Lab window

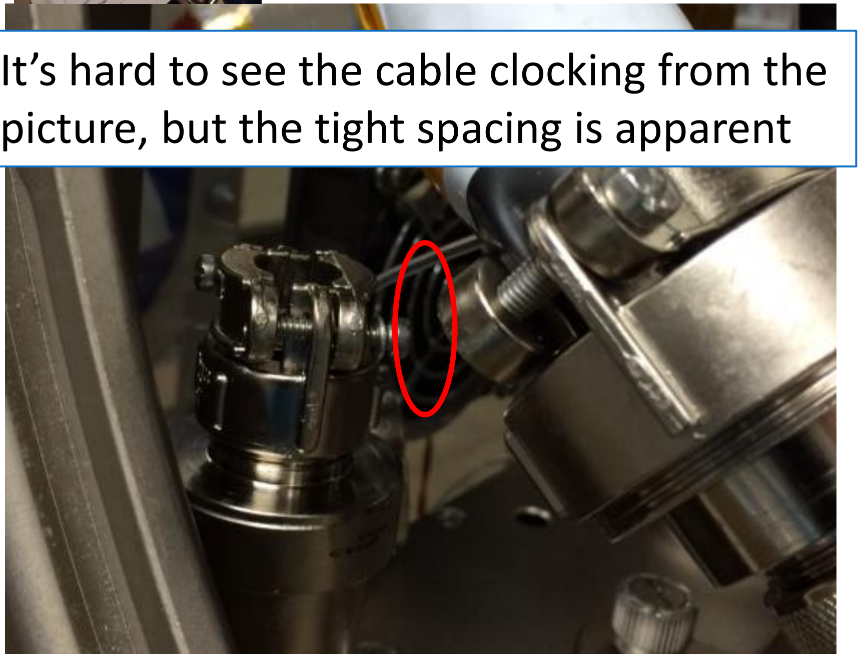


- **Lesson learned regarding why having handles is good design (continued)**
  - A box was added to cover the hose.
  - Note the improvised handle made out of tape – not an ideal solution.
  - Two lessons:
    - Consider adding a handle to your hardware to prevent the crew from grabbing an object not designed to be used as a stabilization or translation aid. The crew will use a handle when one is available.
    - If that is not possible, add a Caution label "CAUTION", "Do not use object as a handhold. Damage may result".
  - NBC Story on the leaky hose can be found at: http://www.nbcnews.com/id/4253674/ns/technology_and_science-space/t/space-station-crew-prepares-fix-window/#.WcQfVmxe6Ul

Examples of HFIT's positive impact on design



- **Kit falling apart example**
  - During a final HFIT evaluation, a kit was found to be falling apart because the Velcro adhesive was not strong enough to keep the Velcro on the kit.
  - This could have led to contents floating away and getting lost, and increase crew time to find it or clean up any spillage.
  - The PD repaired the kit with better Velcro and reinforced with strong adhesive. On-orbit problems were avoided.



Connector Clocking/interference example

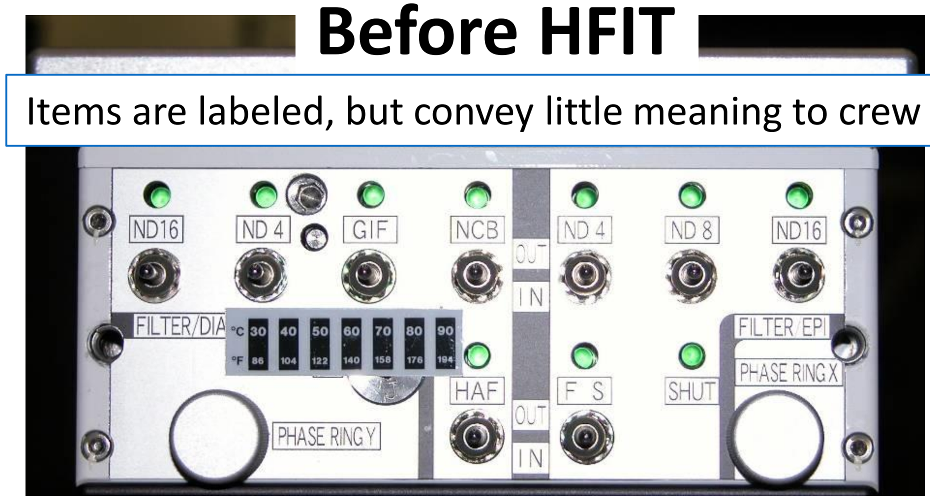
- A connector on the Control Unit of a payload was clocked in a way that interfered with a neighboring Ethernet cable because the spacing was tight. It was impossible to mate the needed connection at the HFIT evaluation, and this would have meant mission failure had it not been discovered. The clocking was modified, allowing the crew to mate the connection.
- For this same payload, a few label mistakes were also found by HFIT. For example, some cable end labels with mating information didn't match connector port labeling on the hardware. This could have led to the crew making mistakes, or wasted crew time to troubleshoot the discrepancy. The PD corrected the labeling.

Examples of HFIT's positive impact on design

- **Labeling example**
  - Labeling can have a big impact on the success of on-orbit operations. It is the crew's first cue as to how to interact with hardware.
  - It defines what objects are through their Operational Nomenclature (OpNom), and identifies all the items they will interface with.
  - When considering label designs, try to convey the meaning or function of objects in the most concise way to help the crew understand what they need to do.
  - Good procedures are a necessity, but clear labeling can prevent the crew having to call down to Mission Control to ask how to perform a task if the labeling stands is clear.
  - Astronauts like to understand the meaning behind the science of payloads, because it helps them describe such research during public affairs interviews, but labeling should not be so complex as to be confusing.

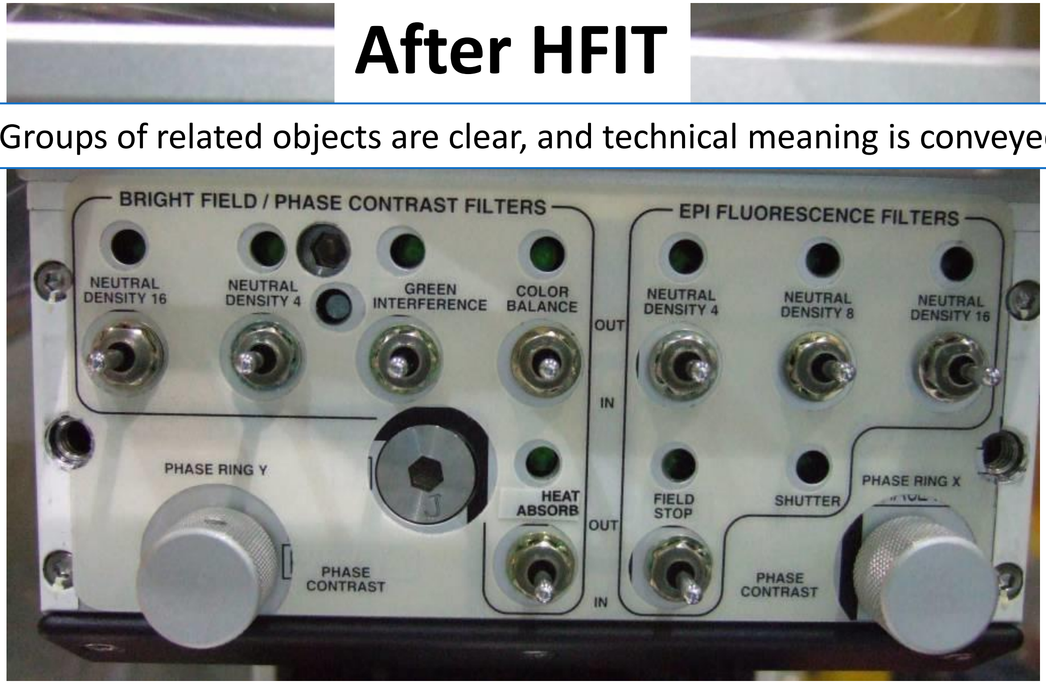
Before HFIT

Items are labeled, but convey little meaning to crew



After HFIT

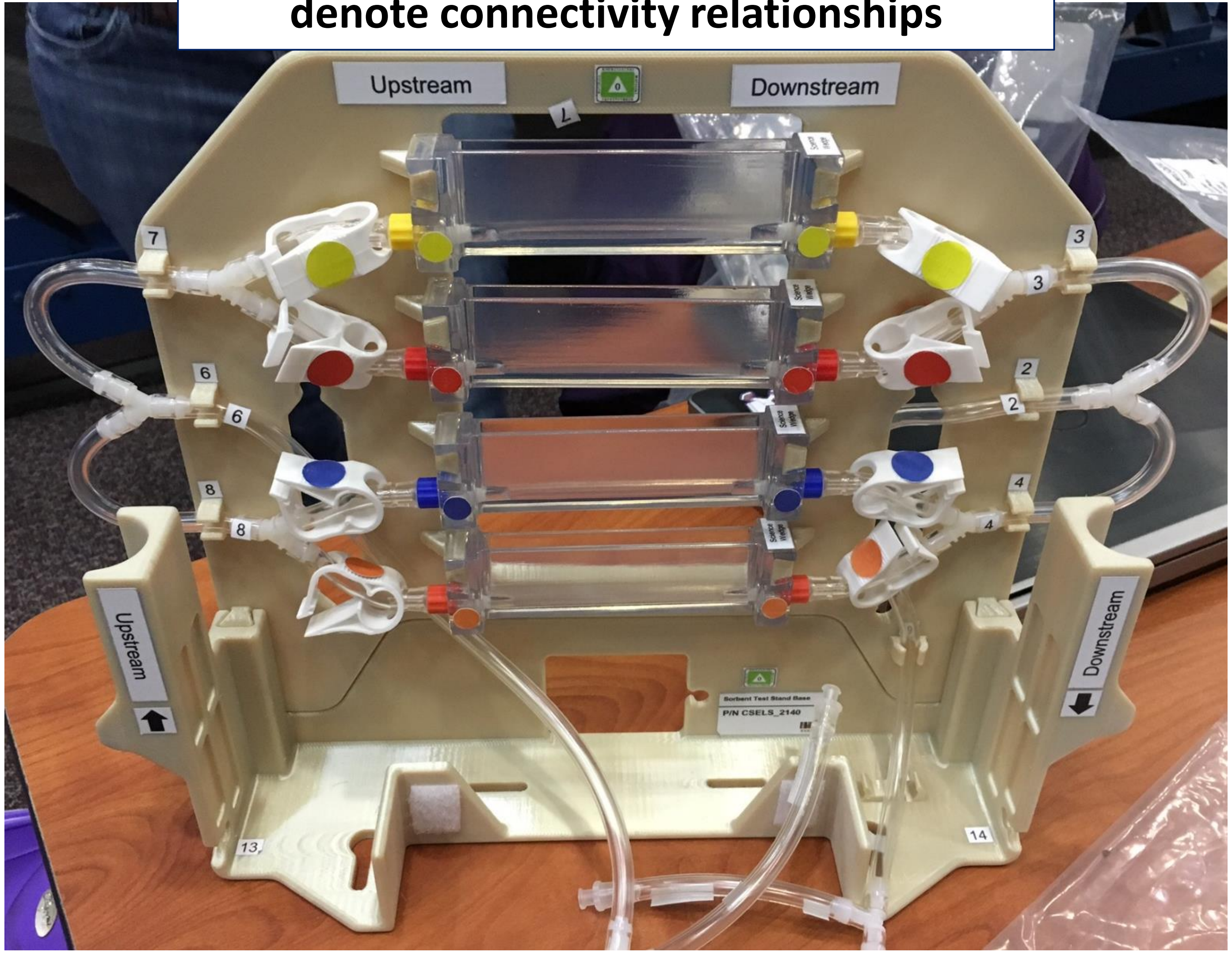
Groups of related objects are clear, and technical meaning is conveyed



Examples of HFIT's positive impact on design

- **Labeling example, continued**
  - In the example to the right, there were many similar, intricate capillary hose and test stand connections for crew to mate.
  - HFIT recommended using simple color coding and numbering that will stand out to help crew make the right connections.
  - Note: Normally red and yellow are reserved for Caution and Warning purposes, but from the context here it is obvious the colors only denote connectivity relationships.

Use of simple color coding and numbers to denote connectivity relationships

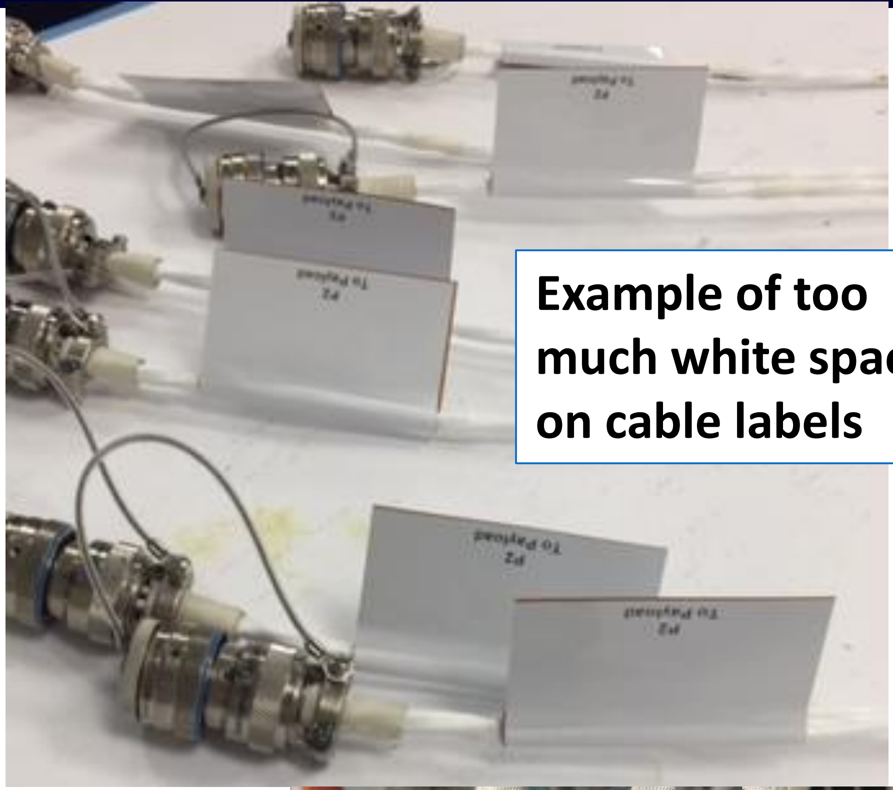


Examples of unfortunate design choices

- **LED color selection example**
  - There is a payload that used a red LED to indicate that it is operating properly. The ISS crew thought enough about this example to call it out specifically in an ISS crew debrief as being a problem for them on-orbit.
  - For ISS Systems and payloads, Green is meant to convey hardware/software operating properly (nominally) with no faults.
  - Red and yellow are reserved for ISS System-level Cautions and Warnings.
  - Since payloads are not supposed to negatively impact ISS Systems, orange is reserved for "payload alerts", when a payload is not functioning properly.

Examples of unfortunate design choices

- **Excessive white space on labels example**
  - Payload cable labels were huge and contained more white space than needed to hold the text, maximizing the footprint of the labels.
  - This was considered a big deal by upper ISS management who saw the cables. Management made the PD fix the labels, although it technically didn't meet the RISE criteria of preventing crew injury or neighboring hardware damage.
  - Overly large labels can make cables more unwieldy to interact with and exacerbate visual clutter.
  - The goal is to have large enough text for labels to be readable, but minimize the footprint of the label itself. See good examples to the right.



Example of too much white space on cable labels

Example of readable cable labels with minimum white space

HFIT's role in Cost Avoidance

- **In 2002 and before, there were a large number of Human Factors requirements violations**
  - A large majority (2/3rds) of the Exceptions (waiver requests) for SSP 57000 requirements were due to Human Factors requirements non-compliances.
  - ISS determined that each Exception cost the program an average of $15,000 to process, including the time it takes for various stakeholders and program personnel to review the Exception and support meetings.
- **For the first 4 years of HFIT (2003-2007):**
  - 160 Exceptions were avoided, because either: HFIT and the PD were able to avoid non-compliances altogether, or HFIT accepted the non-compliances because they were minor, and not safety-related.
  - Based on the average cost of processing an Exception, an estimated $2.4 million was saved by avoiding Exception reviews and meetings.

HFIT's role in Cost Avoidance

- ISS Program processes have changed since the early HFIT years, but it reasonable to assume the $2.4 million savings has at least tripled.
  - Perhaps not quadrupled, because there are generally fewer requirement non-compliances compared to the early HFIT years, because PDs have learned how to comply with the requirements.
- Cost savings to the program in terms on reduced crew time to operate or troubleshoot payloads is hard to quantify, because problems were avoided.
- The key to saving money for the life-cycle of flight hardware is to have Human Factors involved early and often.

Human Factors Requirements News

- Human Factors requirements in SSP 57000, section 3.12
  - Before RISE: There were 103 "shall" requirements (formally verified), 4 "should" guidelines (SSP 57000 Rev P)
  - After RISE: There are 26 "shall" requirements, 46 "should" guidelines (SSP 57000 Rev R)
    - To remain a "shall", the requirement must prevent crew injury or prevent damage to neighboring hardware. If violating the requirement only hurts the payload in question, or relates to the mission success of the payload, it was reduced to a guideline.
    - Crew Interface Label Requirement and the Appendix of instructions it points to were kept largely intact, with few updates.

Human Factors Labeling Requirements News

- **ISS Label Requirement and Process Improvement Team, formed in late 2016 to**
  - Improve Payload label requirements in SSP 57000 to better meet RISE criteria (prevent injury or neighboring hardware damage), and reduce duplication
  - Improve the eLabel process
    - Issues with the tool (e.g. software bugs, non-intuitive features) have frustrated ISS payload developers wanting to receive label approval.
  - **Major Payload Label Requirements Update**
    - Appendix O deleted, requirements and guidelines moved to section 3.12
    - Reduced label requirements to 10 high level "shall" requirements with associated tables of detailed how-to requirements. Guidelines similarly have tables of instructions.
    - 40% reduction in requirements
    - No duplication
    - Requirements are clearer, organized better

TABLE 3.12.7.2.1-1 BASIC LABELING REQUIREMENTS

a.	All items labeled	All items on hardware that have a crew interface are to be identified, including, but not limited to: controls, switches, connectors, LEDs, containers, vents, valves, etc. *Rationale: Identifying every crew interface item is important for safe operation.*
b.	Label per operational purpose	Labels for crew interfaces are to contain information regarding the operational purpose, or function. For example, controls need to be labeled in terms of their function (e.g. power, data). *Rationale: Labeling hardware items per their operational purpose ensures the crew safely operates the hardware as the PD intended and avoids hardware damage that human error could cause.*
c.	OpNom	All flight hardware with crew interfaces are to be identified with the ODFCB approved OpNom, SSP 50254 and applicable partner annexes. This includes the list of contents on stowage container labels, and acronyms and abbreviations. *Rationale: This is critical to rapidly and accurately identifying hardware items.*
d.	Part and Serial Numbers	Flight hardware is to be labeled with its part number (required) and serial number (if exists). *Rationale: This is critical to rapidly and accurately identifying hardware items.*

HFIT Points of Contact

Flight Crew Integration (FCI)

- Laura Duvall: 1.281.483.0244 (NASA FCI System Manager)
- Rich Ellenberger: 1.281.483.5238 (NASA FCI System Manager Deputy)

Payload HFIT Representatives

- Juan Davaloz: HFIT Contractor Lead
- Jenae Aber: HFIT team member
- Antonius Widjokongko: HFIT team member
- Nicole Schoenstein: HFIT team member
- Sean Schimelpfenig: HFIT team member
- Pam Fournier-Gonzalez HFIT team member