Planning for Failures

Using a Toothbrush to Repair a Space Station

Flight Operations Directorate

Flight Director Office

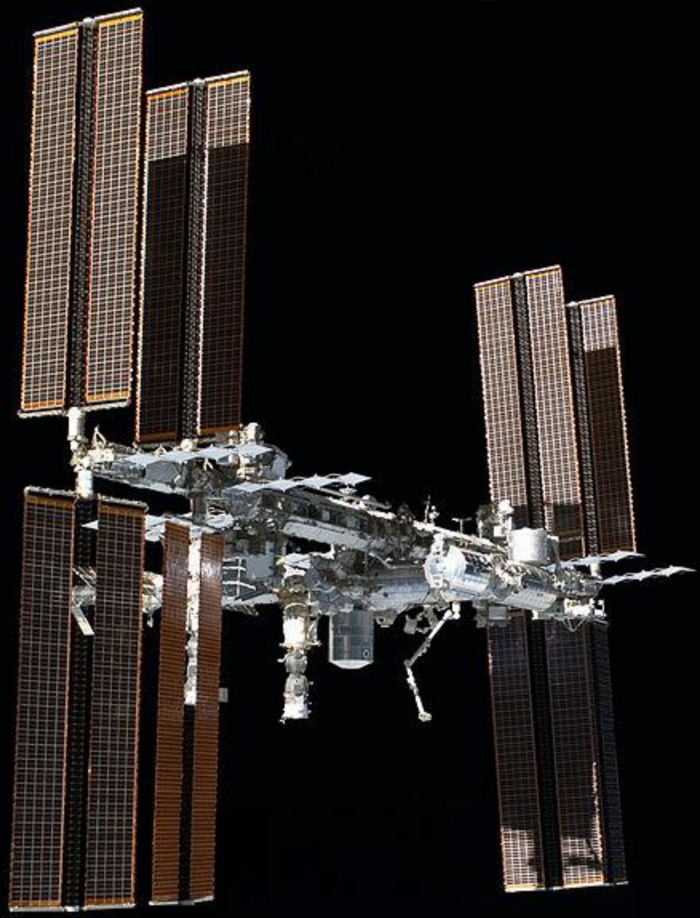
Ed Van Cise

@Carbon_Flight

@Space_Station

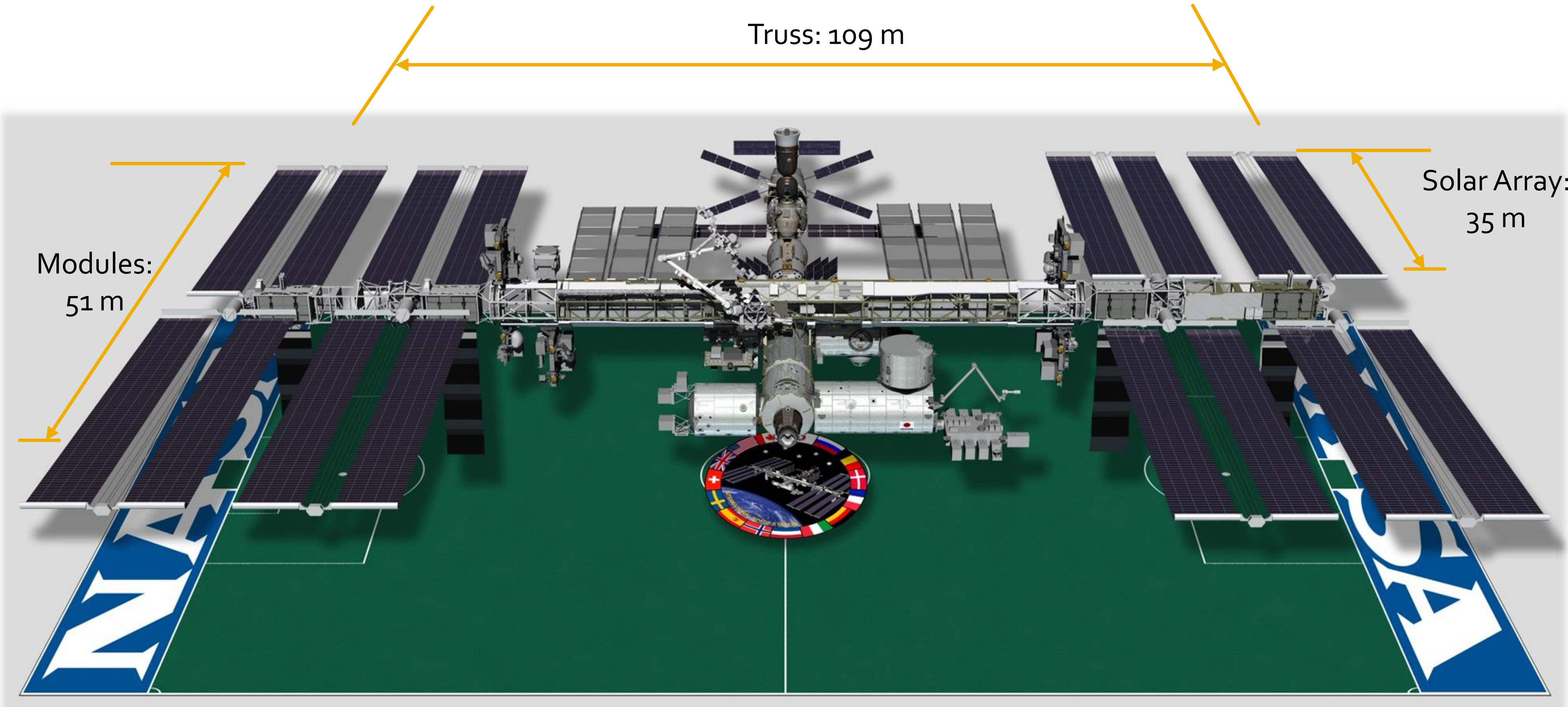
http://www.nasa.gov/station

International Space Station



- Microgravity research laboratory assembled in orbit between 1998-2011, manned continuously since 2000
- Components built by companies across 16 nations. 100+ launches from Florida, Virginia, Russia, Japan, and French Guiana
- Research crew of 6 astronauts and cosmonauts serve 6 month stay

Earth's Only Microgravity Research Laboratory



LARGE, CAPABLE LABORATORY:

Mass: 420,000 kg

Habitable Volume: 388 m^3

Solar Power Generation Capability: 84 kW

Numerous external and internal research platforms

REMOTE OUTPOST:

Altitude: 415 km

Orbital Speed: 28,000 kph (7.8 km/sec)

Orbital Period: 90 minutes (16 sunrises/sunsets per day)

Assembly

- 163 launches to ISS between Nov 1998 and Nov 2015
  - 37 U.S. space shuttle assembly missions to ferry components, logistics, consumables, research, and crew between Earth and ISS
- Space Shuttle was primary vehicle used to assemble ISS
  - Tremendous mass-to-orbit and orbit-to-Earth capability
  - Carried up to 7 crewmembers
  - Capability for up to ~10 docked days
  - Had its own airlock and robotic arm
  - Crew training occurred up until very close to launch
    - Late changes could be absorbed by the crews

Supportability & Logistics

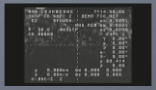
- Original plan
  - US Orbital Segment designed to be launched and serviced by the space shuttle
  - Maintenance concept centers on the "Orbital Replacement Unit" (ORU)
- Plans change – shuttle retires
  - Launch as many repair parts, especially parts only shuttle could launch, before the program ended
  - Develop new means and methods for diagnostics and troubleshooting as well as in-situ repair
  - Next generation spare parts being designed to use same footprint but have separate, stand-alone components that are able to be launched on today's rockets

- Lesson: Anticipate paradigm shift if you can
  - ISS was designed in the 1980s and 1990s when the expectation was that space shuttle would fly forever
  - Adapting now is much harder and likely much more expensive

Logistics Planning – Skip Cycles

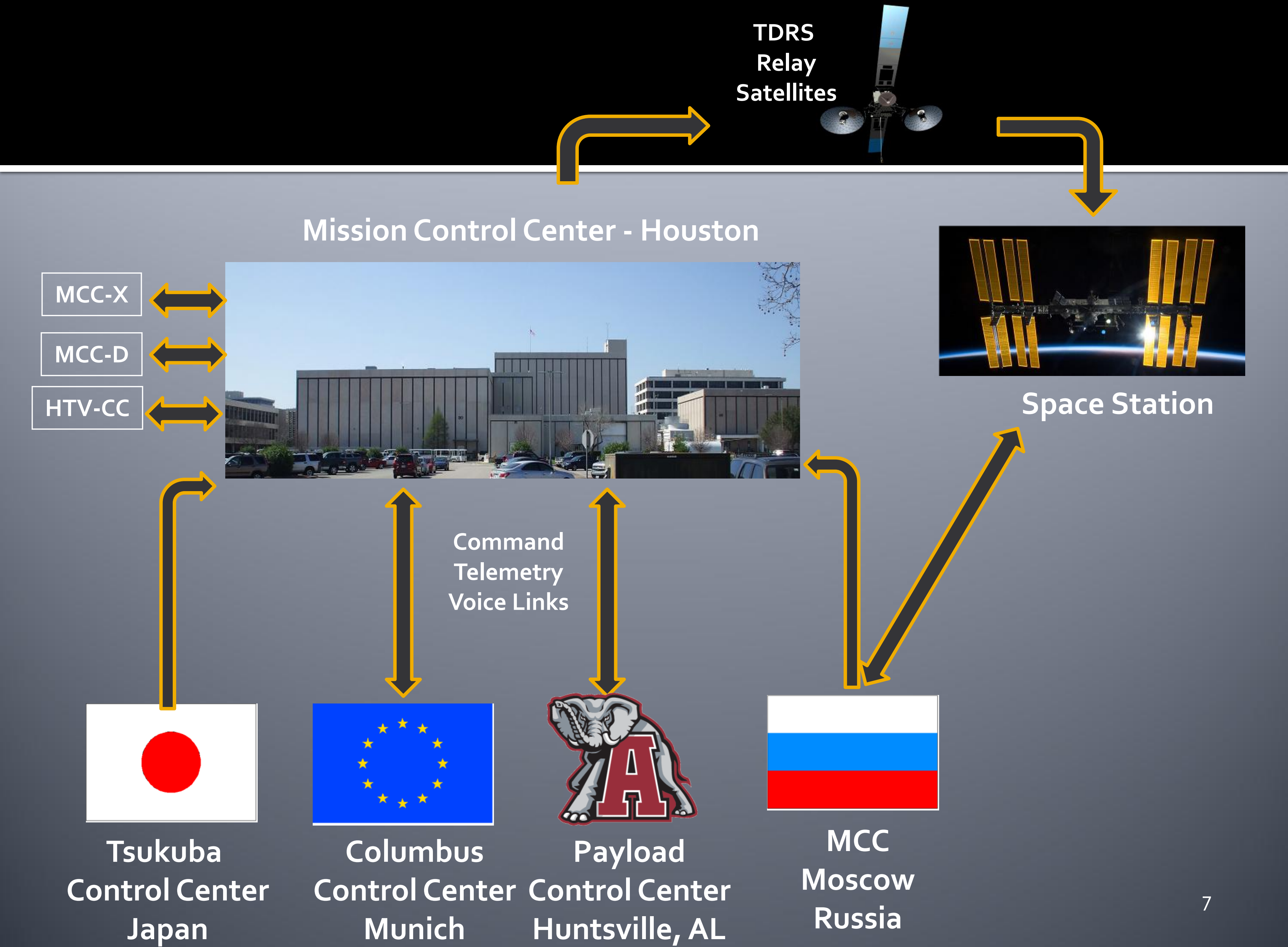
- ISS resupply requires Earth-launched cargo missions
- Spaceflight is complex and HARD
  - Launch schedules change frequently
  - Mission/cargo needs change
  - Weather happens
  - Rapid Unplanned Disassembly (RUD) happens
    - Orbital Sciences “Orb-3” loss after liftoff 28 Oct 2014
      - 2,200 kg lost

    - Russian Progress 59P loss at 3rd stage separation 28 Apr 2015
      - 2,400 kg lost



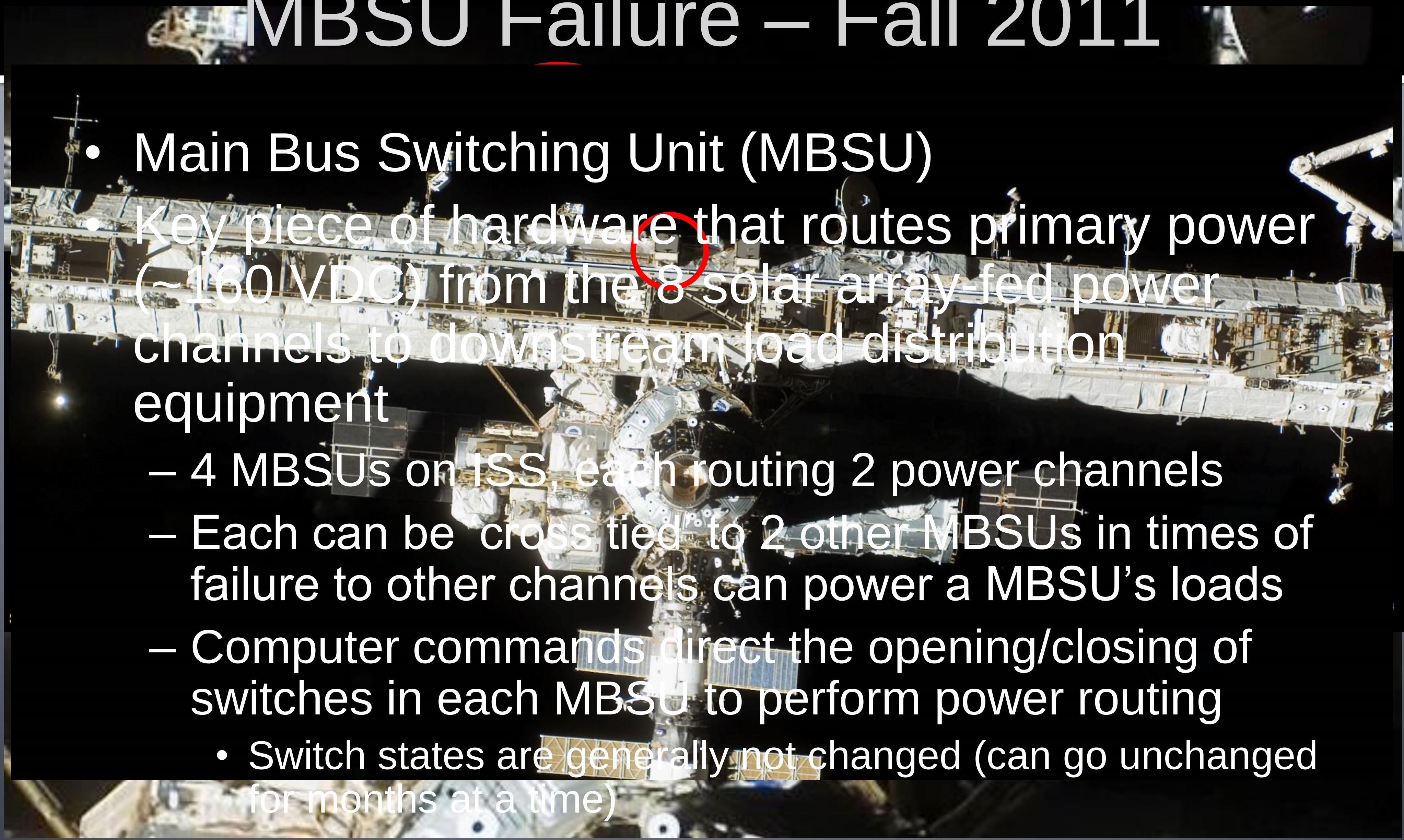
    - SpaceX CRS-7 loss during 1st stage 28 June 2015
      - 1,900 kg + International Docking Adapter lost

- Plan a skip cycle so you can tolerate schedule changes or logistics losses
  - ISS currently uses ~4-6 month skip cycles for critical consumables


TDRS
Relay
Satellites
Mission Control Center - Houston
Space Station
MCC-X
MCC-D
HTV-CC
Command
Telemetry
Voice Links
Tsukuba
Control Center
Japan
Columbus
Control Center
Munich
Payload
Control Center
Huntsville, AL
MCC
Moscow
Russia

Mission Control Center – Houston
FCR-1, est. 1965

MBSU Failure – Fall 2011

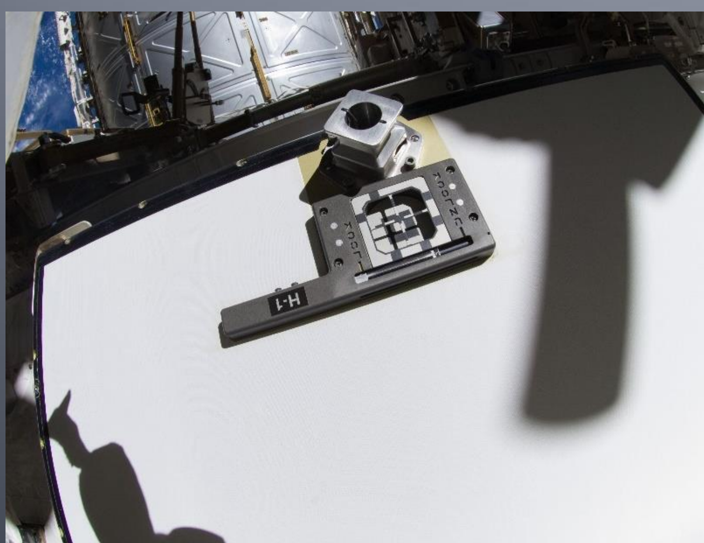


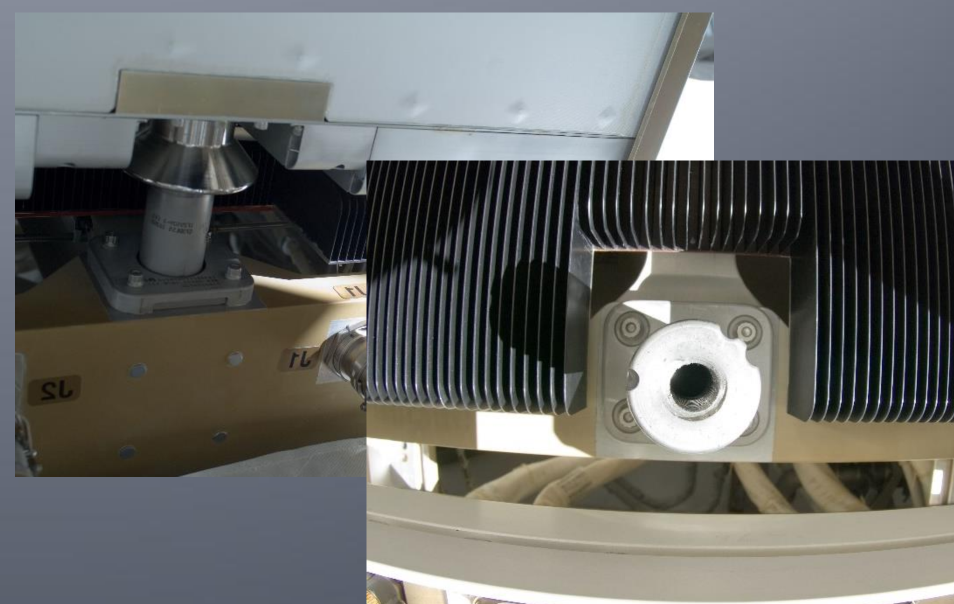
- Main Bus Switching Unit (MBSU)
- Key piece of hardware that routes primary power (~160 VDC) from the 8 solar array-fed power channels to downstream load distribution equipment
  - 4 MBSUs on ISS, each routing 2 power channels
  - Each can be 'cross tied' to 2 other MBSUs in times of failure to other channels can power a MBSU's loads
  - Computer commands direct the opening/closing of switches in each MBSU to perform power routing
    - Switch states are generally not changed (can go unchanged for months at a time)

MBSU Failure – Fall 2011

- MBSU 1 had a circuit card failure in Fall 2011 where it stopped communicating with its controlling computer
  - Switches remained open/closed, power was still being passed, but switch position could not be changed
- Decided the current condition was acceptable in the short term but the MBSU needed to be replaced “soon”
  - Replacement spacewalk targeted for Fall 2012

Two Bolts – How Hard Can It Be?



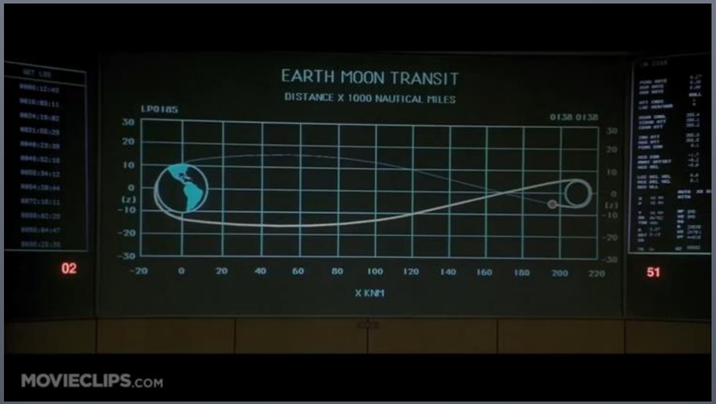


Six Days to Fix the Problem

- Found and utilized technicians that originally installed MBSU 1
- Sought input and expertise from hardware experts as well as crewmembers who had installed similar (H-Bolt) ORUs on ISS previously
- Determined there were two problems
  – Foreign Object Debris had likely damaged the truss's bolt receptacle; possibly when originally installed but also during previous spacewalk
  – Managing side loads on the jacking bolt was critically important
    - Once we cleaned the bolt receptacle, dithering was required!

Thread Cleaning
No Hardware Store Trips Allowed

- How do you clean nut threads without a tap and die set?
  - In space?
  - In a spacesuit?
  - With only the tools and parts you have on hand?
- Simple – challenge your teams to do it and get out of their way



MBSU Replacement Attempt #2

- Step 1: Clean the threads
  - A: Take some 0 Gauge (large) wire, spread the individual conductors out, and create a ‘wire brush.’ Use Pistol Grip Tool (PGT, big cordless drill) to run wire brush in and out of receptacle

Chimney Sweep

Ground version

On-orbit version

MBSU Replacement Attempt #2

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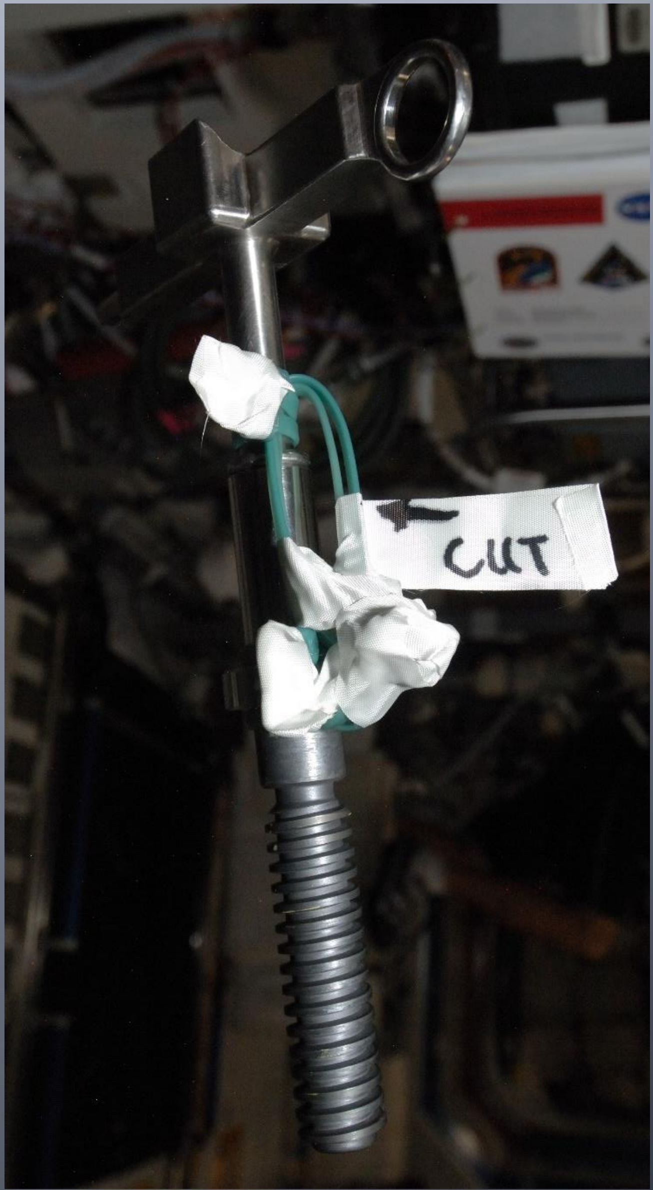
  - B: Disassemble spare computer in the ISS to retrieve its jacking bolt (same size bolt). Use it, attached to PGT, to chase the threads.

ACME Bolt



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  - B: Disassemble spare computer in the ISS to retrieve its jacking bolt (same size bolt). Use it, attached to PGT, to chase the threads.
  - C: Use compressed air tool to blow debris out of threads
  - D: Use modified toothbrush covered in grease for lubricating solar array joint, attached to PGT, to lubricate threads
    - Dry film lubricant was expected to have been removed on first spacewalk or by wire brush

Toothbrush

MBSU Replacement Attempt #2

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- Step 2: Install by dithering all the way

Dithering

Dithering Training Video

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  - D: Use modified toothbrush covered in grease for lubricating solar array joint, attached to PGT, to lubricate threads
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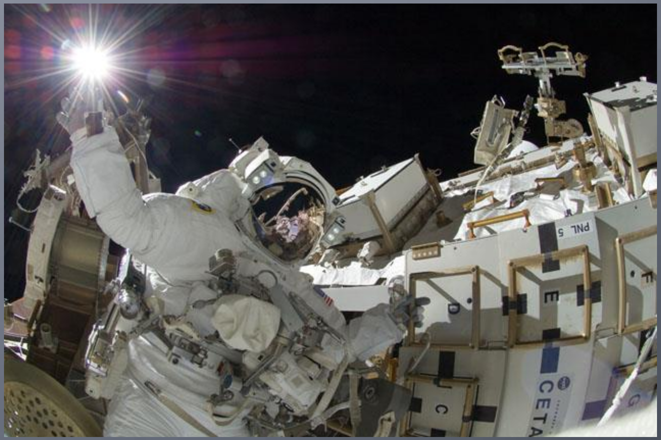
- Step 2: Install by dithering all the way
- Step 3: Complete any tasks possible that were supposed to be performed on previous spacewalk

Ingenuity, Teamwork, Leadership At All Levels



Success!

- Successful due to having pre-established a culture of high performance and independent leadership
  - Could not have turned this around in 6 days if stovepipes, micromanagement, and all approvals only at top level had prevailed

Success Enablers

- Leadership development
  - Infuse in culture of management, engineering, operations, crews
  - Purposeful development from the very beginning
  - Empower leadership at the lowest possible levels
- Collaboration across organization
  - Not just within operations organizations but across management, engineering, customers, operations, crew
  - Collaboration is a success multiplier – as long as the team at the end of the spear (operations) can translate it into execution
    - Otherwise it's just churn
- Paradigm shifts
  - Look for them, be open to them, welcome them
    - Even when it's painful
    - Think about possibilities even if you think they're never going to happen
      - You may not invest much in it, but thoughtfully decide, don't just dismiss
    - Benchmark; don't assume you're the best
- Designing for operability, reliability, and maintainability increases mission adaptability and flexibility

Questions?

Backup Charts

Foundations of Flight Operations

1. **To instill within ourselves these qualities essential to professional ex**
   - ***Discipline***…Being able to follow as well as to lead, knowing that we must master ourselves before we can master our task.
   - ***Competence***…There being no substitute for total preparation and complete dedication, for flight will not tolerate the careless or indifferent.
   - ***Confidence***…Believing in ourselves as well as others, knowing that we must master fear and hesitation before we can succeed.
   - ***Responsibility***…Realizing that it cannot be shifted to others, for it belongs to each of us; we must answer for what we do or fail to do.
   - ***Toughness***…Taking a stand when we must; and to try again and again, even if it means following a more difficult path.
   - ***Teamwork***…Respecting and using the abilities of others, realizing that we work toward a common goal, for success depends upon the efforts of all.
   - ***Vigilance***...Being always attentive to the dangers of flight; never accepting success as a substitute for rigor in everything we do.

2. **To always be aware that, suddenly and unexpectedly, we may find ourselves in a role where our performance has ultimate consequences.**

3. **To recognize that the greatest error is not to have tried and failed, but that, in the trying, we do not give it our best effort.**

Stone Tablets of Flight Control

I. Come prepared for your shift. Understand how your discipline fits into the day's activities. Be familiar with unique Flight Data File for the activities.

II. Listen closely when the crew talks. If you determine that the information doesn't affect your discipline then you may resume your discussions, unless they were on the flight loop.

III. Condition yourself to react to A/G discussions without having to be prompted by the Flight Director.

IV. When the crew's comments affect your discipline immediately follow their call with a tailored acknowledgment on the flight loop. For example:

    "WE COPY FLIGHT, STANDBY WHILE WE LOOK AT IT."
    "COPY FLIGHT, IT'S A TRANSDUCER FAILURE, NO ACTION."
    "WE COPY AND CONCUR FLIGHT."
    "COPY FLIGHT, HAVE THEN WORK MAL...."

I. Listen closely to your instructions that get read to the crew. If it has been a while since you made the request for the uplink, report on the flight loop that you copied the uplink. This lets the flight director know the instructions were read as you intended and you are ready to observe the result. When the crew repeats uplinked instructions, particularly those with more than a couple of steps, acknowledges on the flight loop with "GOOD READ BACK FLIGHT".

II. Minimize you discussions on the flight loop when the crew is talking. Criticality of your need will dictate this. A good rule of thumb would be to wait so CAPCOM can listen, if waiting is possible.

III. An ideal exchange between the crew and the MCC is one in which the Flight Director talks the least. In this case the Flight Director can use quick vocal approvals on the flight loop to enhance the efficiency of the communication.

IV. Minimize discussion over the airways. Use loops unless impractical to do so.

V. Be ahead of the crew in finding changes to procedures based on flight plan changes or previous failures. Look ahead.

VI. Switch/circuit breaker actions should be called out with panel, row, and device nomenclature.

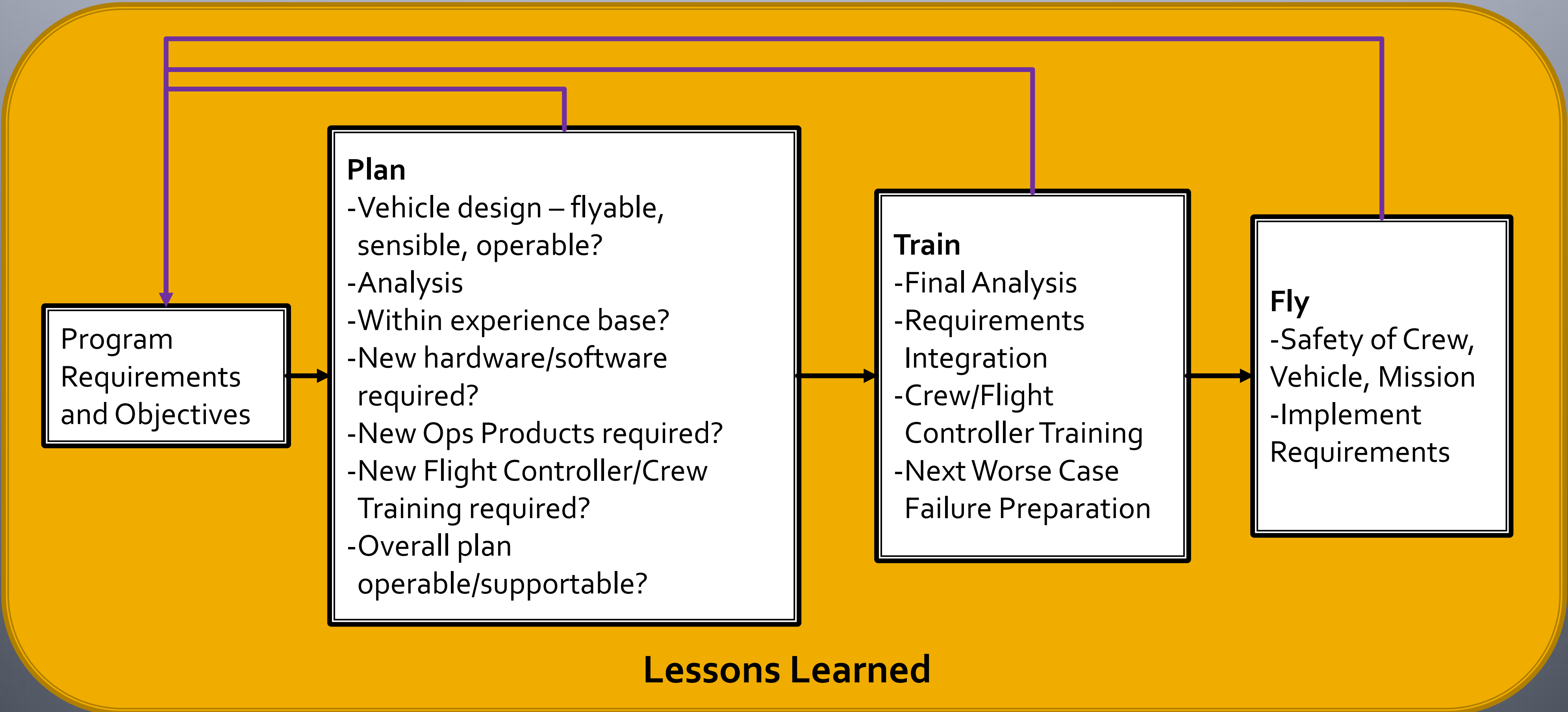
VII. If you have time to write a flight note, write a flight note.

VIII. Flight note and/or vocal actions should include what you want done, by when, and why. When vocalizing this the preferred order is to report what has happened followed by the action required within some time frame. For example:

    "FLIGHT, THE "A" HEATER ON XYZ JUST FAILED SO I WOULD LIKE THE CREW TO SWITCH TO THE "B" SIDE WITHIN 10 MINUTES. THE SWITCH IS ON PANEL......"

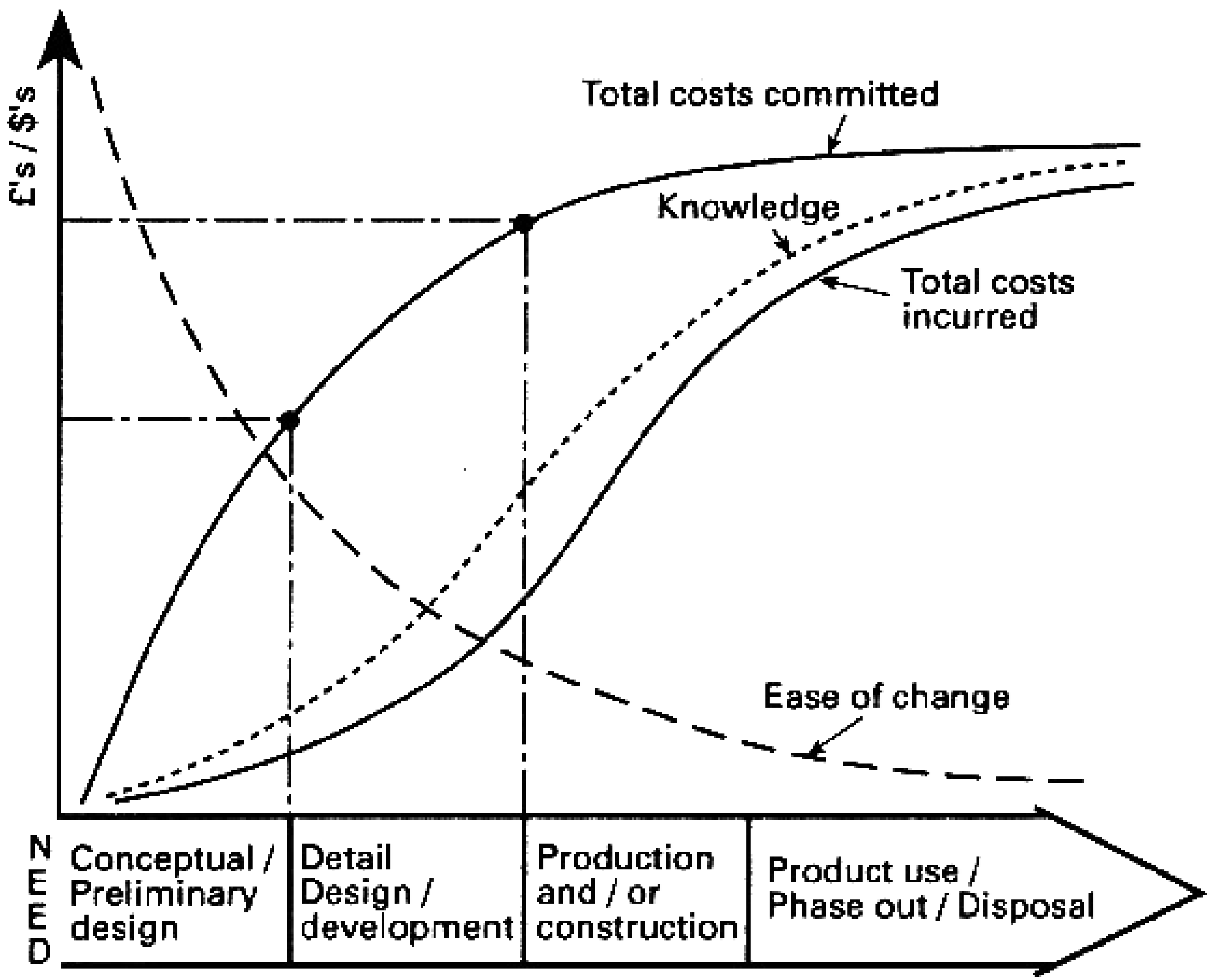
Last Updated: 7/4/96

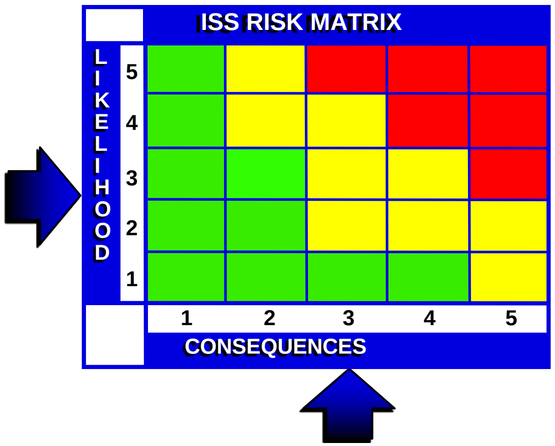
Flight Operations - Plan/Train/Fly



- All aspects of P/T/F embedded in Lessons Learned culture
  - Encode, Duplicate successes
  - Learn from, Avoid mistakes
- All aspects of P/T/F provide feedback to the Program on the risks/concerns/recommendations of Program Requirements and Objectives

Operations Integration and Risk Management

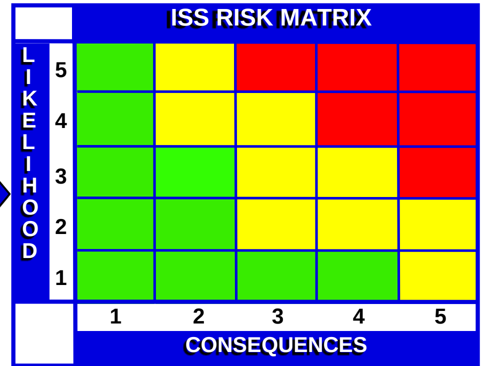




ISS PROGRAM RISK SCORECARD

Likelihood Rating

5	Very Likely	Expected to happen in the life of the program Controls are missing or insufficient
4	Likely	Likely to happen in the life of the program Controls have significant limitations or uncertainty
3	Possible	Could happen in the life of the program Controls exist, with some limitations or uncertainty
2	Unlikely	Unlikely to happen in the life of the program Controls have minor limitations or uncertainty
1	Highly Unlikely	Extremely remote possibility that it will happen in the life of the program Strong controls in place



Mitigation

- High – Implement new process(es) or change baseline plan(s)
- Medium – Aggressively manage; consider alternative process
- Low – Manage within normal processes; monitor

Consequence Rating	1	2	3	4	5
Mission Success / Operational Performance (Technical)	Minor or no impact to mission objectives Nominal Execution of Mission Minor reduction in performance Minor or no impact to design or operating margins	Failure to meet any single mission objective Operating in a degraded state Moderate reduction in performance Can handle within design or operating margins Damage to non-critical system, element, ground facility, function, or emergency system	Significant impact to mission objectives Operational Workarounds available Significant reduction in performance Significant loss of design or operating margin Loss of any non-critical system, element, ground facility, or function Loss of emergency system	Loss of multiple mission objectives Major increase in flight operations timelines or complexity Major degradation in performance Loss of all design or operating margin Damage to critical system, element, ground facility, or function Planned De-Crewing	Loss of entire mission No alternatives exist Loss of ISS or any critical system, element, major ground facility or function ISS in a condition which prevents rendezvous/docking operations Emergency Evacuation
Safety	No injury	Minor injury, minor illness	Significant or long-term injury, illness, incapacitation or impairment Non-disabling injury	Permanent injury, impairment or incapacitation	Loss of Life Disabling injury
Cost - Score by cost of mitigating risk	Minimal impact (<$100K) or 0 to 2.5% increase	Moderate impact ($100K up to $1M) or 2.5% to 5% increase	Significant impact ($1M up to $10M) or 5% to 7.5% increase	Major impact ($10M up to $50M) Or 7.5% to 10% increase	Major impact (> $50M) Or >10% increase
Schedule	Minor or no impact	Can handle with schedule reserve, no impact to key project milestone or critical path	Project milestone slip No impact to Program critical path	Impact to Program milestone and/or Program critical path	Cannot meet program critical path milestone(s)

Note: Risk management is a communication system where a *qualitative* score can help in understanding of a risk. This card is only a rough guide for determining a likelihood and consequence for a risk. Significant resources should not be spent scoring a risk. Score is relative to the risk's highest elevation; i.e. sub-org, Org, or Top Program Risk.

NASA/ISS Program Oversight

Mission Management

Increment Lead Flight Director

Real Time
Decision Making
Risk Management

Flight Director

Nominal and Off-Nominal
System management

Flight Controllers

Crew

- *Office Support*
- *Offline Analysis*
- *Engineering Support*
- *Development*

Offline/Non Real Time Support

A High Performing, High Reliability Organization is Mandatory

Characteristics of High Performing Organizations

- **Leadership** – ***Leadership is aligned and effective deep within the organization***
- **Leadership in Mission Control**
  - **Unambiguous chain of command within MCC-H and between Control Centers**
  - **Leadership within a discipline is expected on and off console; "Lead Your Leader" reflects our goal for leadership development at all levels**

- **Design** – ***The structure is lean and reflects the organization's strategic focus***
- **Design in Mission Control**
  - **Documented processes, training flows, and certification guides establish both the ends and the means; regularly reviewed to ensure the methods align with changing strategic goals**

- **People** – ***The organization effectively translates business strategy into a powerful people strategy, attracting and retaining the most capable individuals***
- **People in Mission Control**
  - **Selective recruiting, Flight Controller Boot Camp, progressively complex training and simulations, regular skills assessments and pass/fail evaluations with documented pass/fail criterion**

Source: Bhalla, Vikram; Caye, Jean-Michel; Dyer, Andrew; Dymond, Lisa; Morieux, Yves; Orlander, Paul (2011). "High-Performance Organizations, The Secrets of Their Success," Used with permission

Characteristics of High Performing Organizations

- **Change Management** – ***The organization can drive and sustain large-scale change and anticipate and adapt***
- **Change Management in Mission Control**
  - **Mission Control is a balance between being nimble enough to adapt to unexpected change yet knowledgeable enough to ascertain whether the change is within accepted limits; Next Worse Failure planning**

- **Culture and Engagement** – ***The culture is shaped to achieve strategic goals. Employees pursue corporate objectives.***
- **Culture and Engagement in Mission Control**
  - **Flight Controller Manifesto, Stone Tablets of Flight Control, Foundations of Flight Operations, Plan/Train/Fly, Next Worse Failure, Lessons Learned JOPs**
    - » **Part of Flight Operations training from Day 1**

Source: Bhalla, Vikram; Caye, Jean-Michel; Dyer, Andrew; Dymond, Lisa; Morieux, Yves; Orlander, Paul (2011). "High-Performance Organizations, The Secrets of Their Success," Used with permission

High Reliability Organizations

- Characteristics of successful organizations in high-risk industries
  - Preoccupation with Failure
  - Reluctance to Simplify Interpretations
  - Sensitivity to Operations
  - Commitment to Resilience
  - Deference to Expertise

Anticipation (Prevention)

Containment (Reacting)

Source: Weick, Karl E.; Kathleen M. Sutcliffe (2001). Managing the Unexpected - Assuring High Performance in an Age of Complexity. San Francisco, CA, USA: Jossey-Bass. pp. 10–17. ISBN 0-7879-5627-9