Risks from Decreasing Ground Support for Human Spaceflight Missions Beyond Low Earth Orbit

Spacecraft Anomalies and Failures 2023 Workshop

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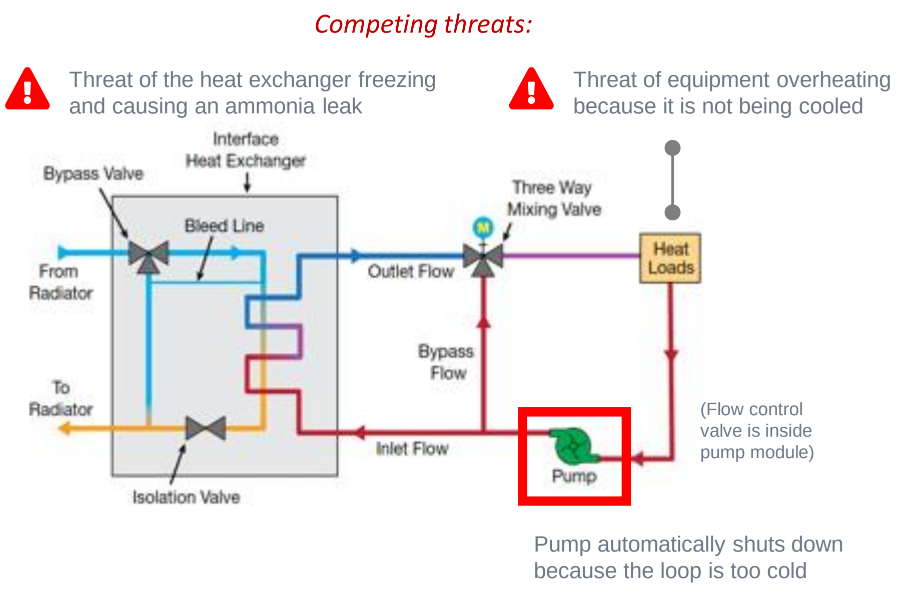
Mars Exploration Rover 2003 Mission
Sol 18 Anomaly

Flash memory overload causing repeating system resets

Cooling ISS 2013 Loop A Anomaly

Summary of Anomaly Response and Resolution:

- External Cooling Loop A (one of two loops) automatically shut down when an under-temperature fault was detected
  - If too cold, water in internal heat exchangers can freeze and breach the ammonia barrier, harming the crew
- Crew told to continue with nominal schedule while ground responded to alarms and triaged systems to determine which could be moved to Loop B or powered down
  - A single cooling loop can not cool all ISS systems
  - Cooling must be maintained to the electrical power system switches and converters or power is lost
- MCC SPARTAN performed pump recovery procedure putting the Flow Control Valve (FCV) in full bypass mode, but Loop A temperature remained too cold
- MCC + MER performed manual tests to characterize FCV response and attempted workarounds (e.g., utilizing line heaters, other valves, etc.) to get loop to safe temp
- No methods to raise loop temperature were successful—after 7 days, troubleshooting was stopped with decision to replace pump module via EVA



Active Thermal Control System: Schematic

Anomaly characteristics:

Mapping the 2013 Cooling Loop A Anomaly to More Earth-independent Ops

Causal relationships are not immediately understood

- 30+ alarms in first 30 min, including temperature levels, loss of comm with PCVP*, command sequence failures— challenge to isolate initiating event
- Expertise required for specific Active Thermal Control System (ATCS) operation as well as for system-level effects of lack of cooling
- Complexity of system – TCS elements, functions, locations, effects on cooling behavior, and failure modes; and of anomaly – sudden change in FCV behavior with no apparent cause
- Challenge of safely perturbing the system to gain understanding of cause and effect—e.g., power cycling pump module, exercising FCV through range of settings, etc.

No perfect information during initial stages

- Procedure sets FCV to full bypass, but valve position actually offset by 30 deg and cannot reach full bypass position
- Actual FCV position not measured but calculated from flow rate
- FOD (blockage) or other mechanical issue with valve cannot be observed
- Temperature sensors not located in critical locations (e.g., heat exchanger)
- Uncertain prediction of temperature variation of electrical switches/converters without cooling

Intervention options

- Creativity required to generate workaround options, e.g., use of line heaters, other valving, etc. to raise temps
- Systems thinking to perform risk assessments, e.g., risks associated with potential for common cause failure in Cooling Loop B, EVA R&R, etc.
- Rapid synthesis and decision-making -- FCV troubleshooting started within 90 minutes of first alarms
- Resource limited environment inc. redundancy, sparing, crew time – actual anomaly required 24/7, 14 days, 4 shifts/day to resolve
- Procedures may have unexpected outcomes— initial restart of pump drove temps lower rather than recovering them

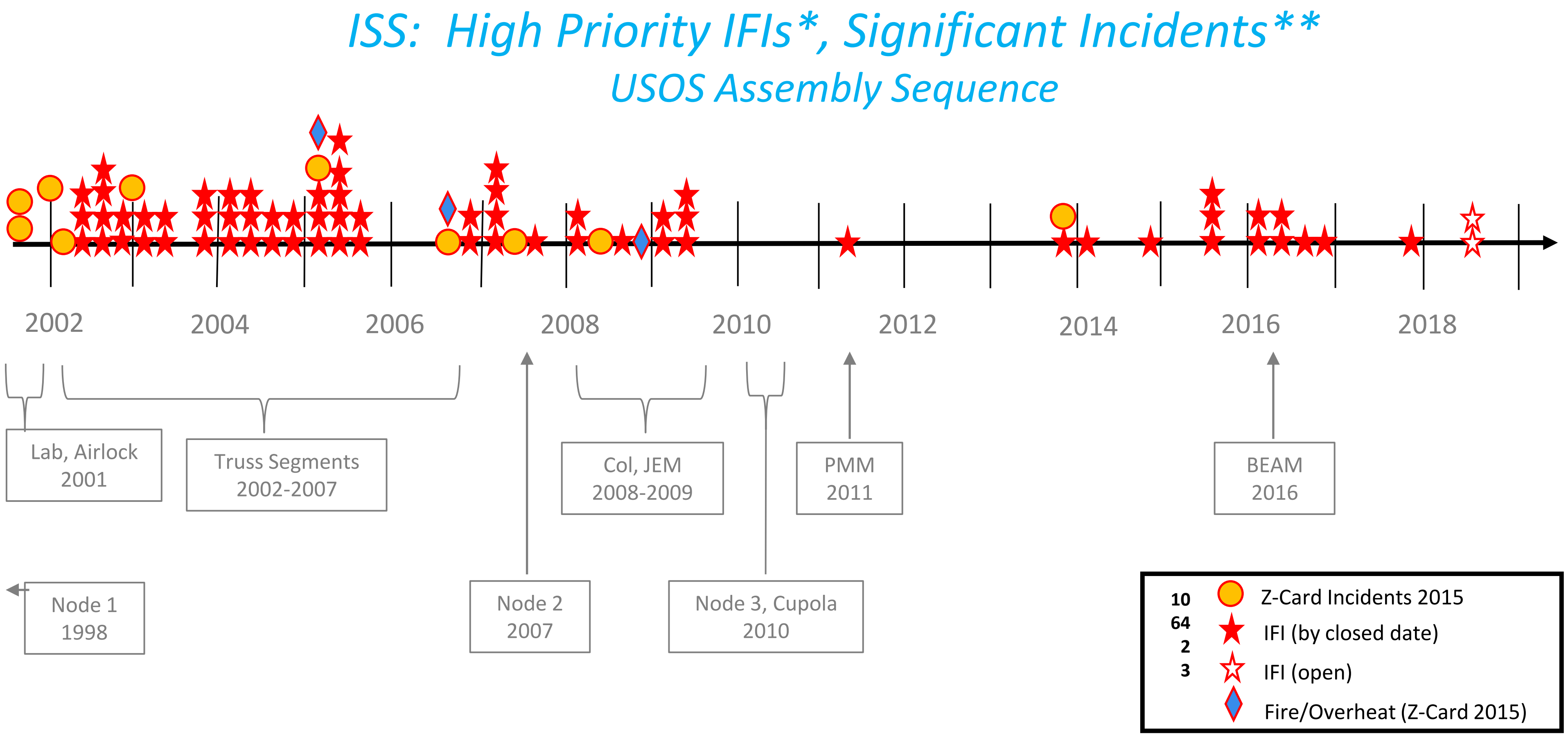
Time pressure

- Short time-to-effect for equipment overheating and risk associated with reduced redundancy
- Complex pump recovery procedure must be started immediately
- Competing priorities: must restart pump, begin diagnosis, and triage equipment simultaneously
- Simultaneous efforts required (safing, investigating, downstream impact)

*PCVP = Pump and Control Valve Package (inc. firmware)

High Priority IFIs

Analysis of Items for Investigation (IFI's) and Anomaly Reports



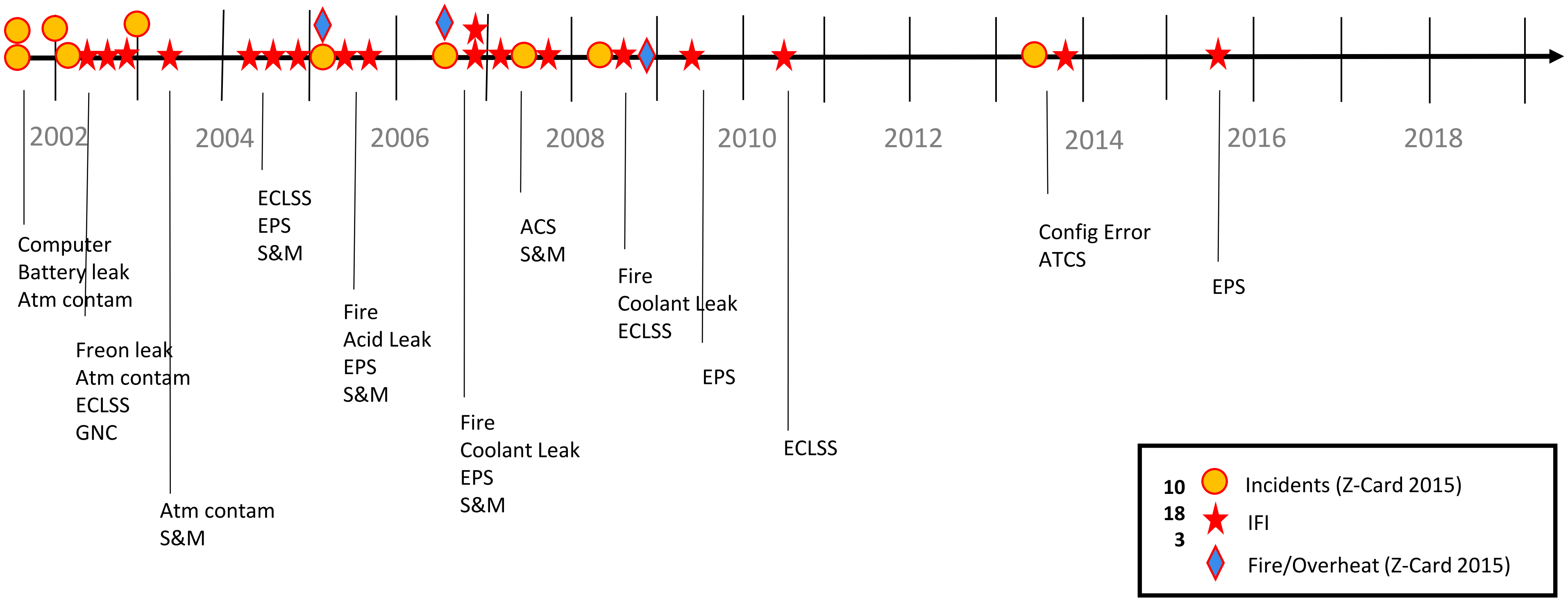
* High priority = LOC/LOM potential, Crit1 failure, etc.

** Significant Incidents = JSC SMA ID of major losses, close calls

High Priority IFIs

Analysis of Items for Investigation (IFI's) and Anomaly Reports

*ISS: High Priority IFIs, Significant Incidents in Vehicle Systems Requiring Urgent Diagnosis**



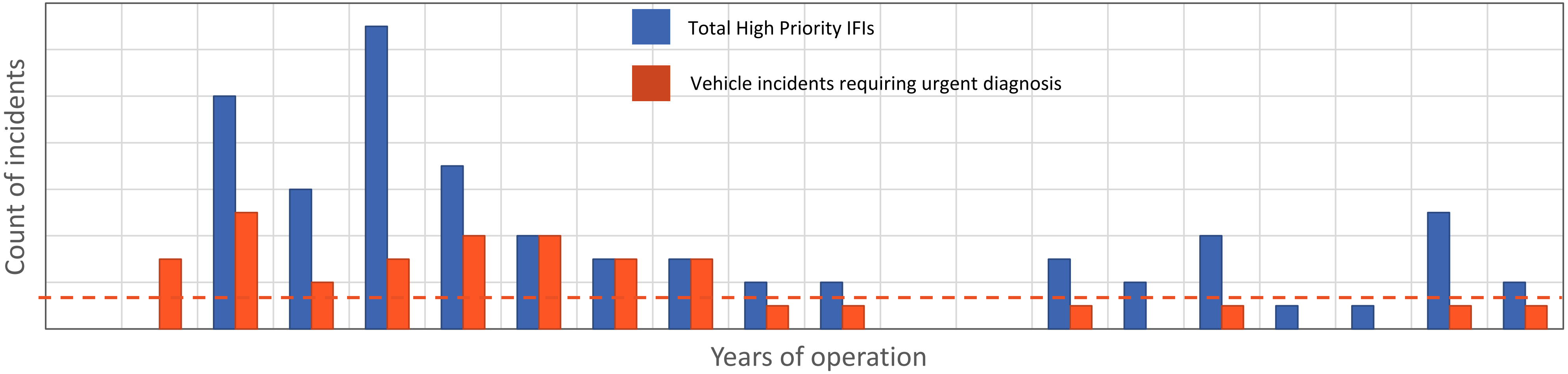
**excludes EVA, VIPER, CHECS, Prop (ops), EVR*

Anomaly Rates for Human Spaceflight

Analysis of Items for Investigation (IFI's) and Anomaly Reports

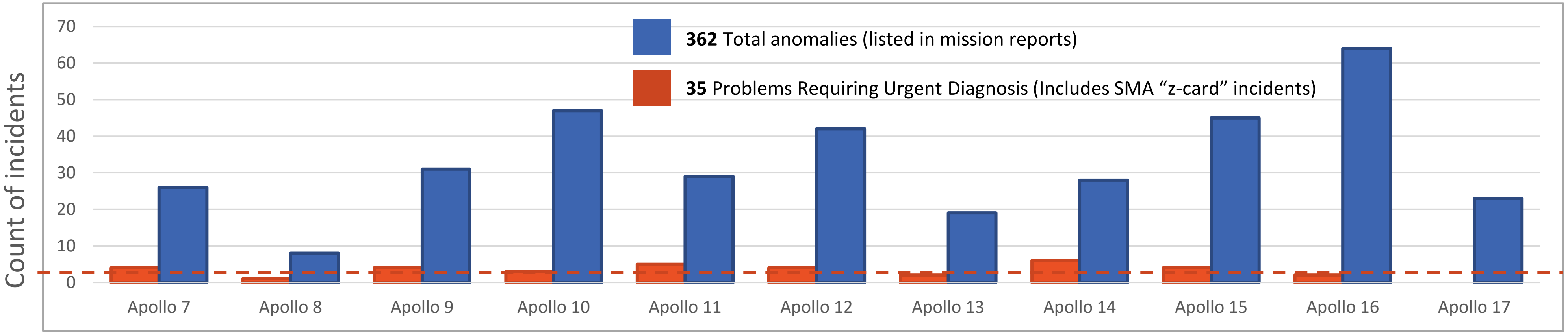
ISS

Avg: 1.7/year
Vehicle incidents requiring urgent diagnosis



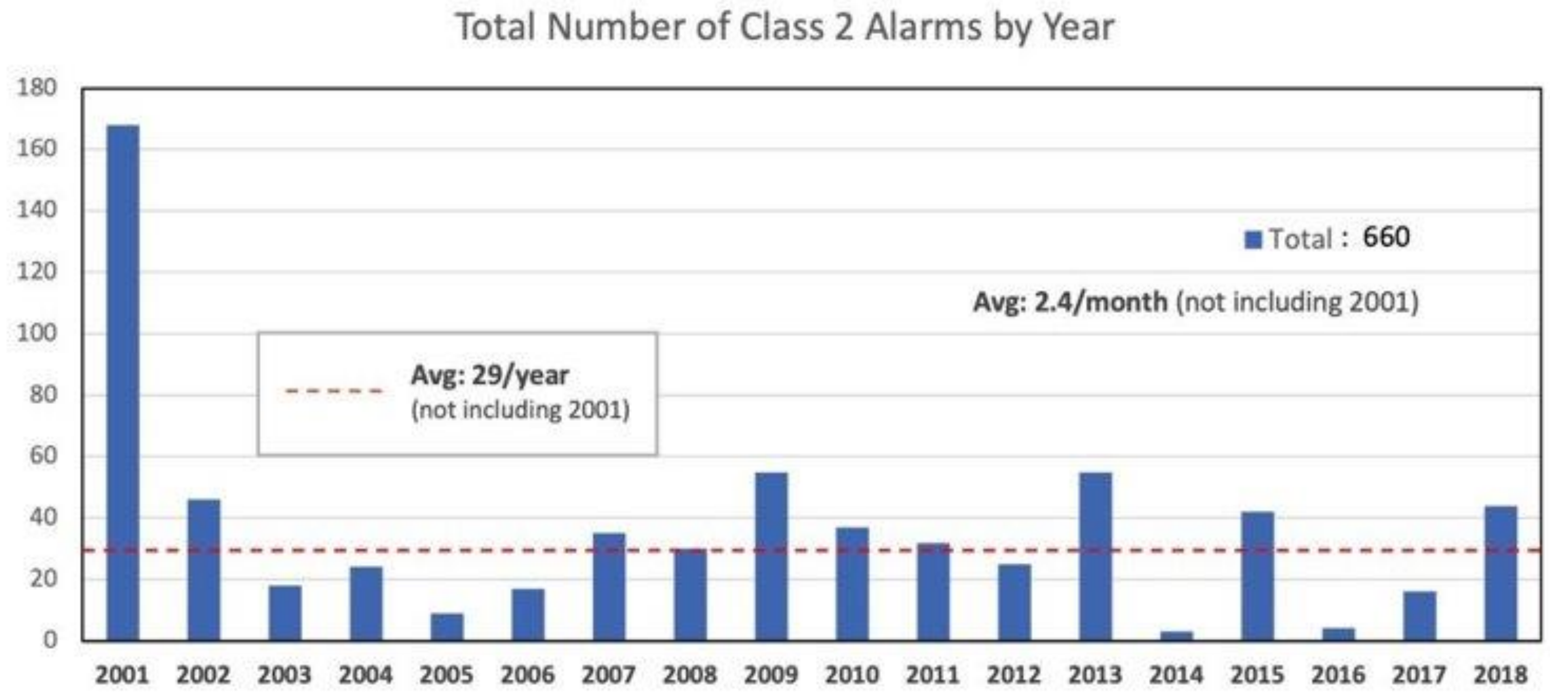
Apollo

Avg: 3/mission
Vehicle incidents requiring urgent diagnosis

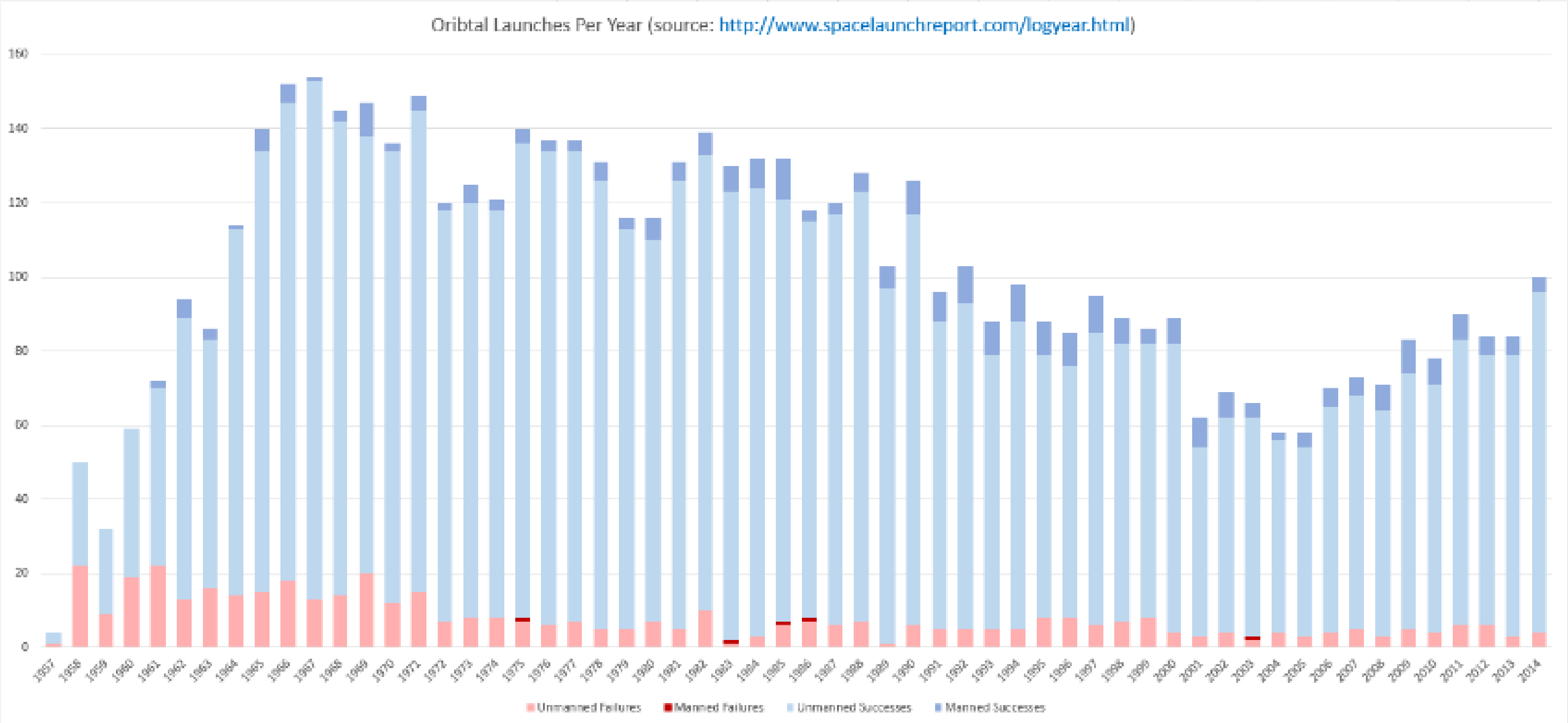


Caution & Warning System Data

"Class 2 alarms (warnings) indicate that the crew or ground needs to take immediate action to avoid injury or death of the crew or damage to the ISS."



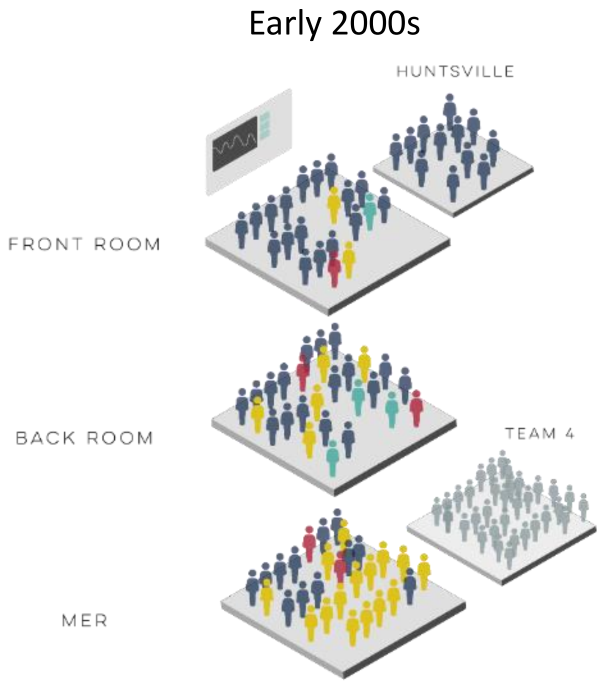
Outcomes in US Launch Systems

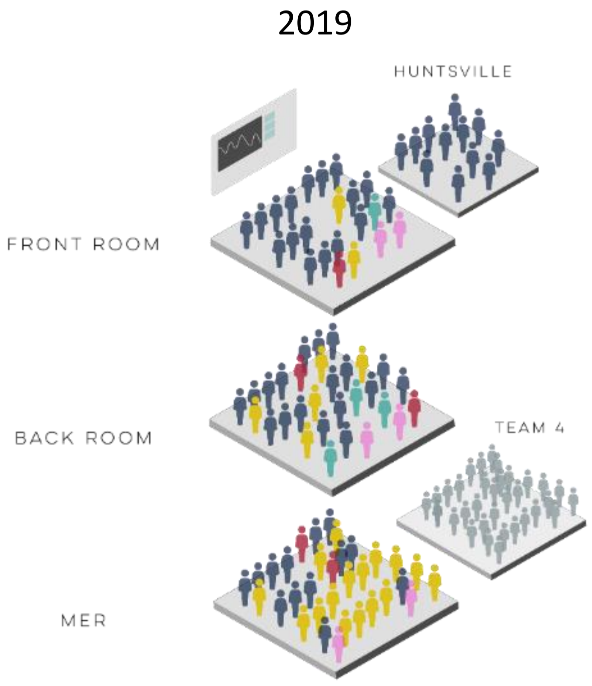


Mission Control

60 (FRONT+BACK+MER) + 5 (ROBO) + 23 (EVA) + 4 (VVO) + 10 ~ 50 (TEAM 4) + 6 (JSL/OPS) = **108 ~ 148** (All-hands-on-deck)

MCC Staffing (Orbit 2, except Team 4)





NOMINAL OPERATIONS
ROBOTICS OPERATIONS
EVA OPERATIONS
VISITING VEHICLE OPERATIONS AND STATION ASSEMBLY
JSL / OPS LAN SOFTWARE UPGRADE

Aviation Accidents: 80-90% Human Error (Not)

3.2.3 Managing Malfunctions

Finding 3 - Managing Malfunctions.
Pilots successfully manage equipment malfunctions as threats that occur in normal operations. However, insufficient system knowledge, flightcrew procedure, or understanding of aircraft state may decrease pilots' ability to respond to failure situations. This is a particular concern for failure situations which do not have procedures or checklists, or where the procedures or checklists do not completely apply.

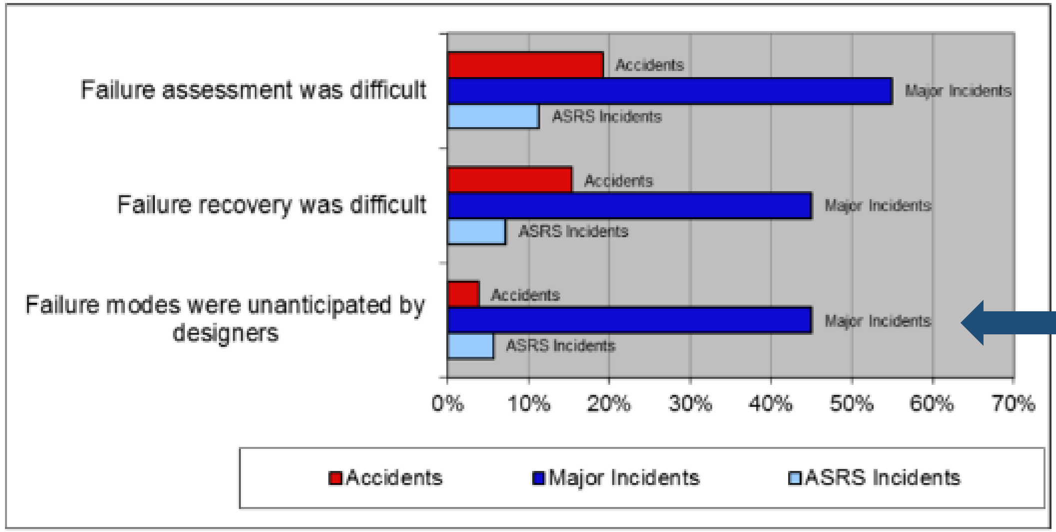
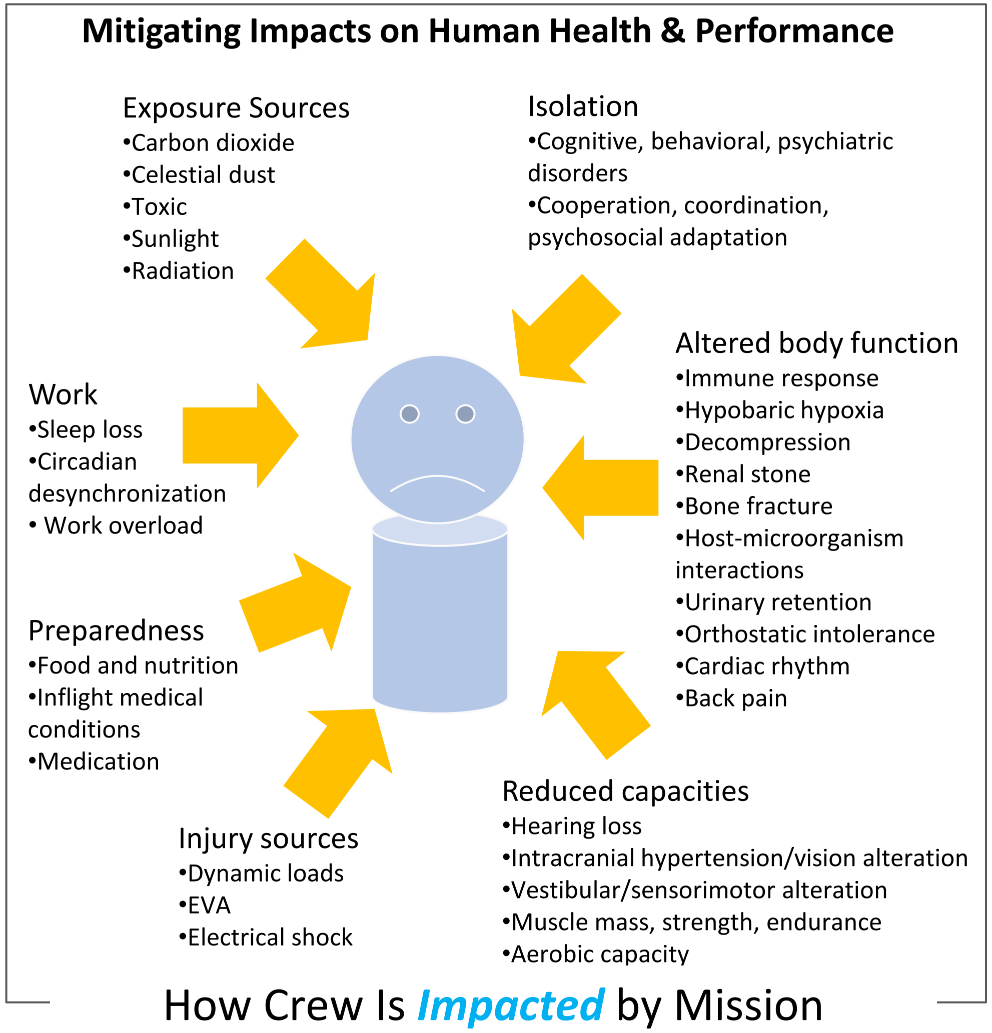


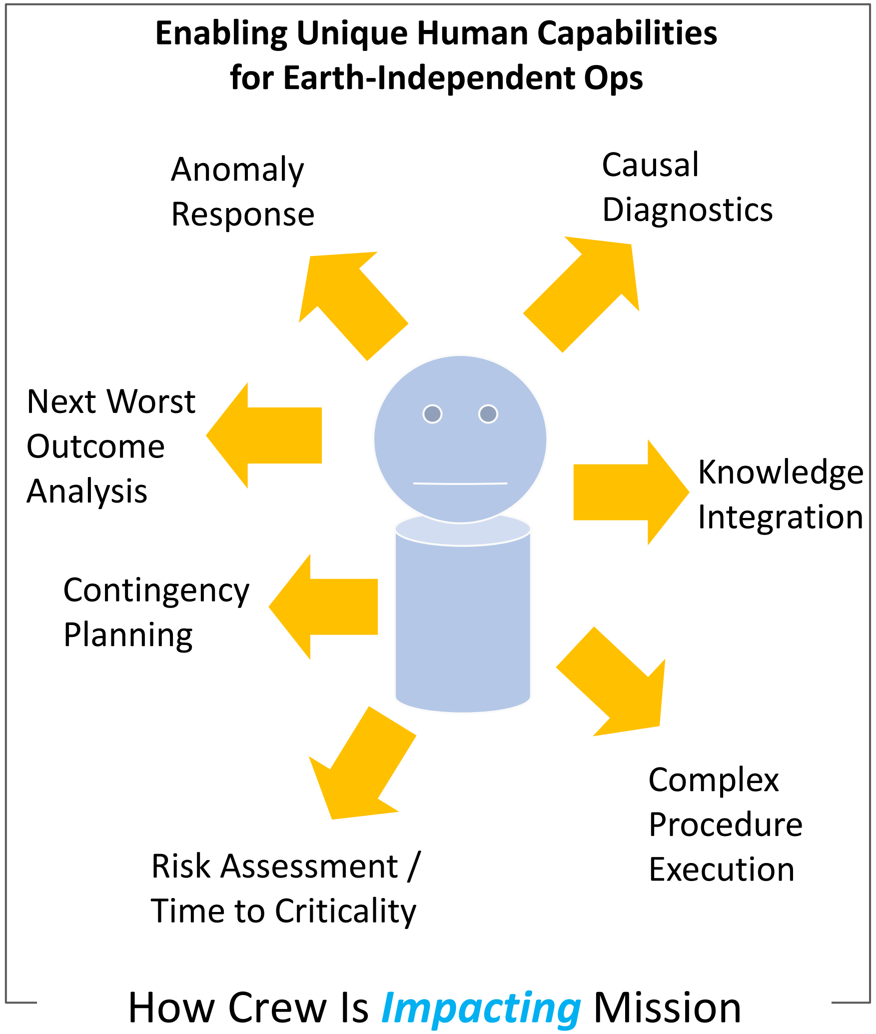
Figure 9. Failure Issues.

Over 40% of failure modes were unanticipated by designers, cases where pilots have to rely on their knowledge, skill and other aspects of airmanship to mitigate the risk because there was no procedure to follow

Source: National Transportation Safety Board. (2013). Final report of the performance-based operations aviation rulemaking committee / commercial aviation safety team flight deck automation working group (Docket No. SA-537, Exhibit No. 14-E).

Humans in Extreme Environments





Humans Cause Safety

3.2.1 Pilots Mitigate Risk

Finding 1 - Pilot Mitigation of Safety and Operational Risks.
Pilots mitigate safety and operational risks on a frequent basis, and the aviation system is designed to rely on that mitigation.

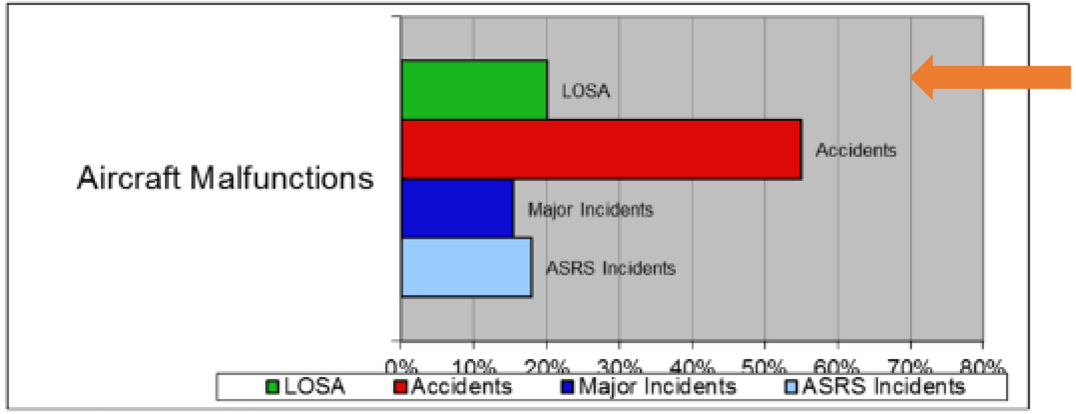


Figure 8. Aircraft Malfunctions.

Aircraft malfunctions were noted to be a threat in 20% of normal flights
(based on Line Operations Safety Audit [LOSA] data)

Source: National Transportation Safety Board. (2013). Final report of the performance-based operations aviation rulemaking committee / commercial aviation safety team flight deck automation working group (Docket No. SA-537, Exhibit No. 14-E).

	Mercury/ Gemini	Apollo	SkyLab	Mir	Shuttle	ISS	Gateway	Artemis III	Lunar Basecamp	Mars
Longest flight time	~4 days	12 days (Apollo 17)	170 days	15 years	17 days (Columbia 1996)	23 years	~15 years	~30 days ?	~40 days ?	~2-4 years
Longest surface time	N/A	3 days	N/A	N/A	N/A	N/A	N/A	~6.5 days	~30 days	Weeks to years depending on DRM
Longest crewed mission	~4 days	12 days (Apollo 17)	84 days	437 days (1995)	17 days (Columbia 1996)	355 days (2022)	~30 days	N/A	N/A	N/A
Longest Period w/out Resupply	None	None	84 days	20 days	None	~115 days	N/A	N/A	N/A	N/A
Comm Delay (round-trip)	~ 1.5 second delay	~ 3 second delay	~ 1.5 second delay	~ 1.5 second delay	~ 1.5 second delay	~ 1.5 second delay	~ 6-12 second Delay?	~ 6-12 second Delay?	~ 6-12 second Delay?	Up to ~ 40 min
Evacuation	Hours	Hours	Hours	Hours	Hours	Hours	Days	Days	Days	Months/ years if possible
Spares/ Tools	Minimal	Minimal	Some	Some	Some	A lot	Minimal	Minimal	A lot?	A lot?
Systems Reuse	No	No	Yes	Yes	Yes, after ground maint.	Yes	Yes	Yes	Yes	Yes

Short-duration and one-time use

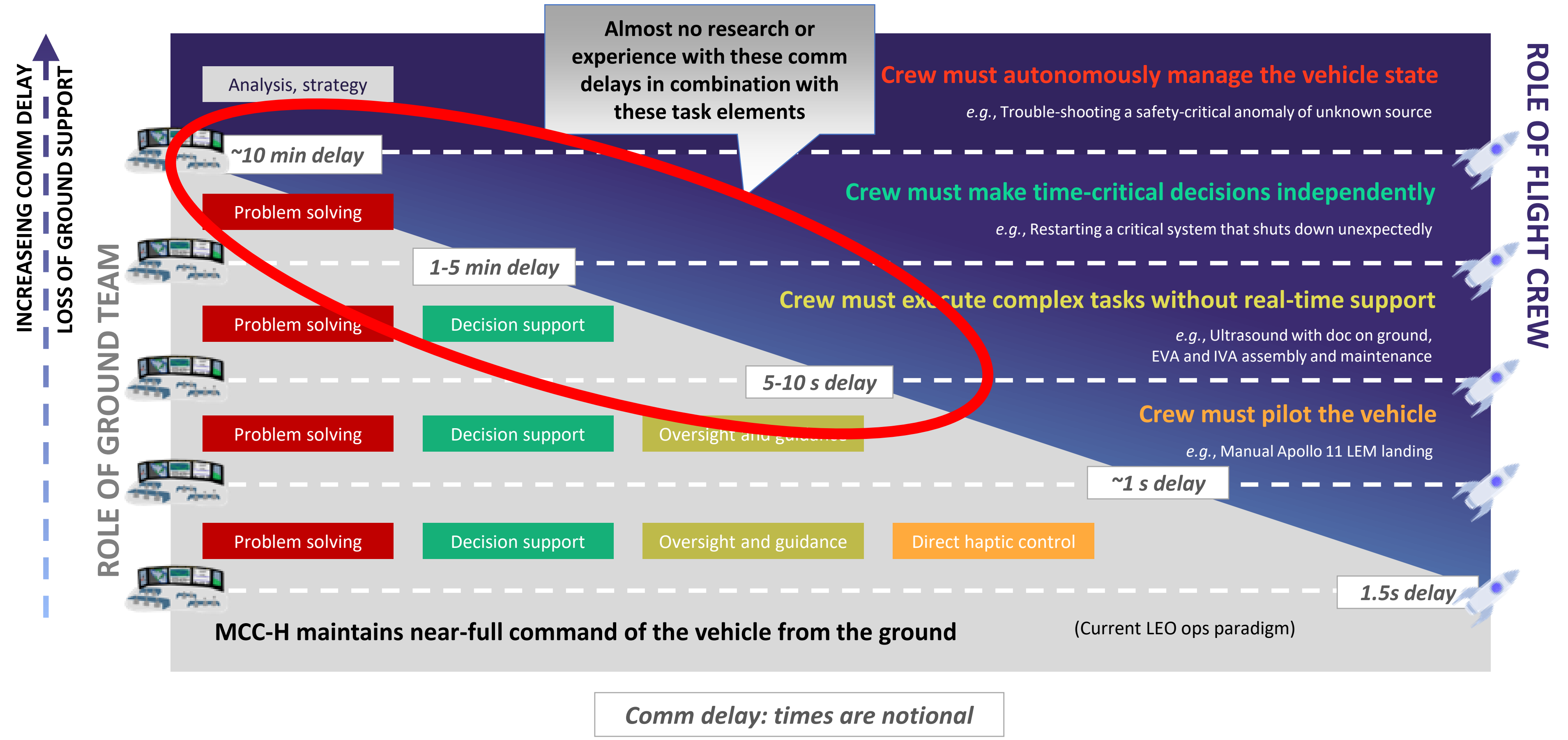
OR

Short-duration and maintained on the ground

OR

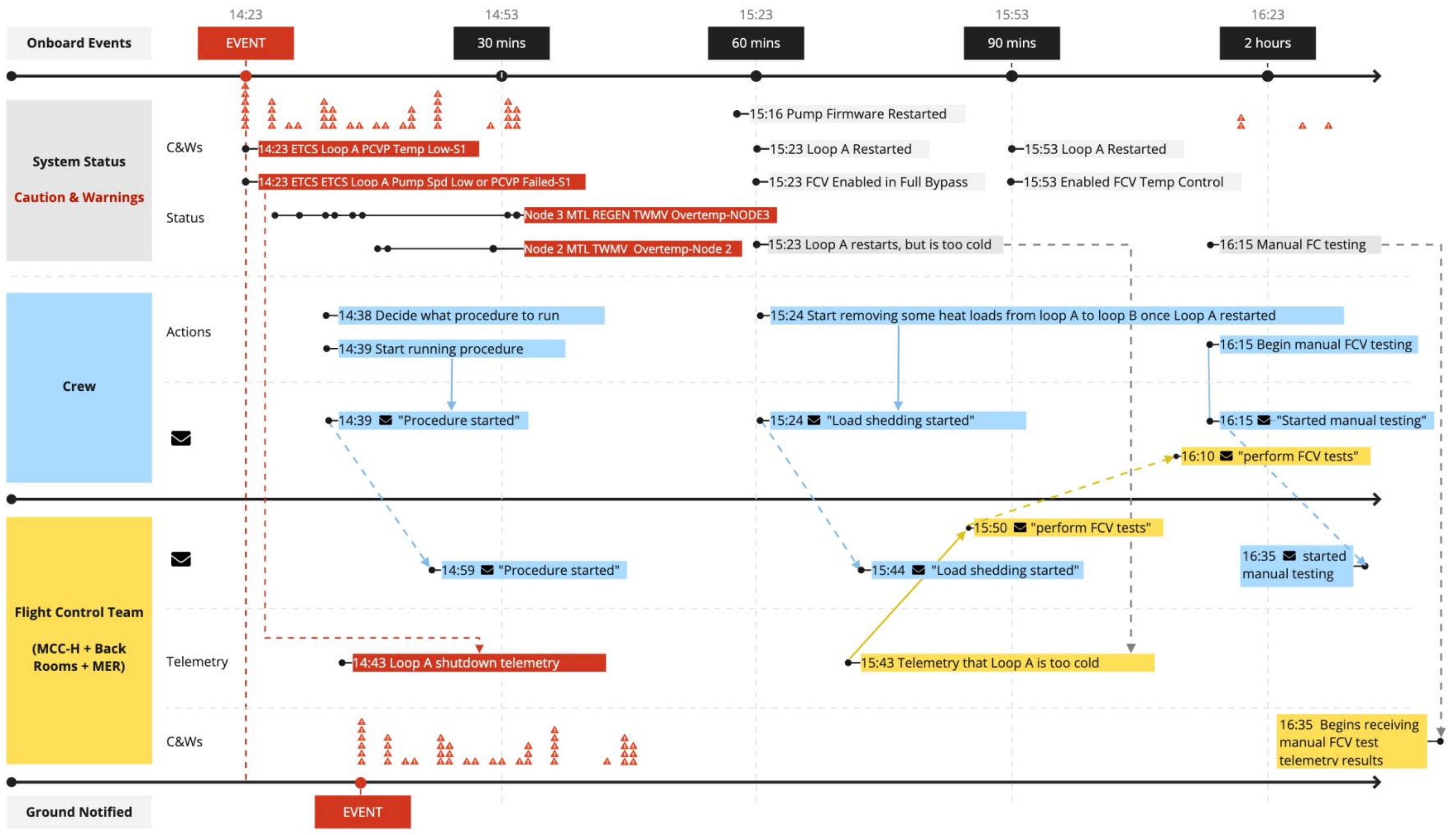
Long-duration and easy access from Earth

Notional Ground-to-Onboard Shift of Safety-Critical Operations with Increasing Comm Delay

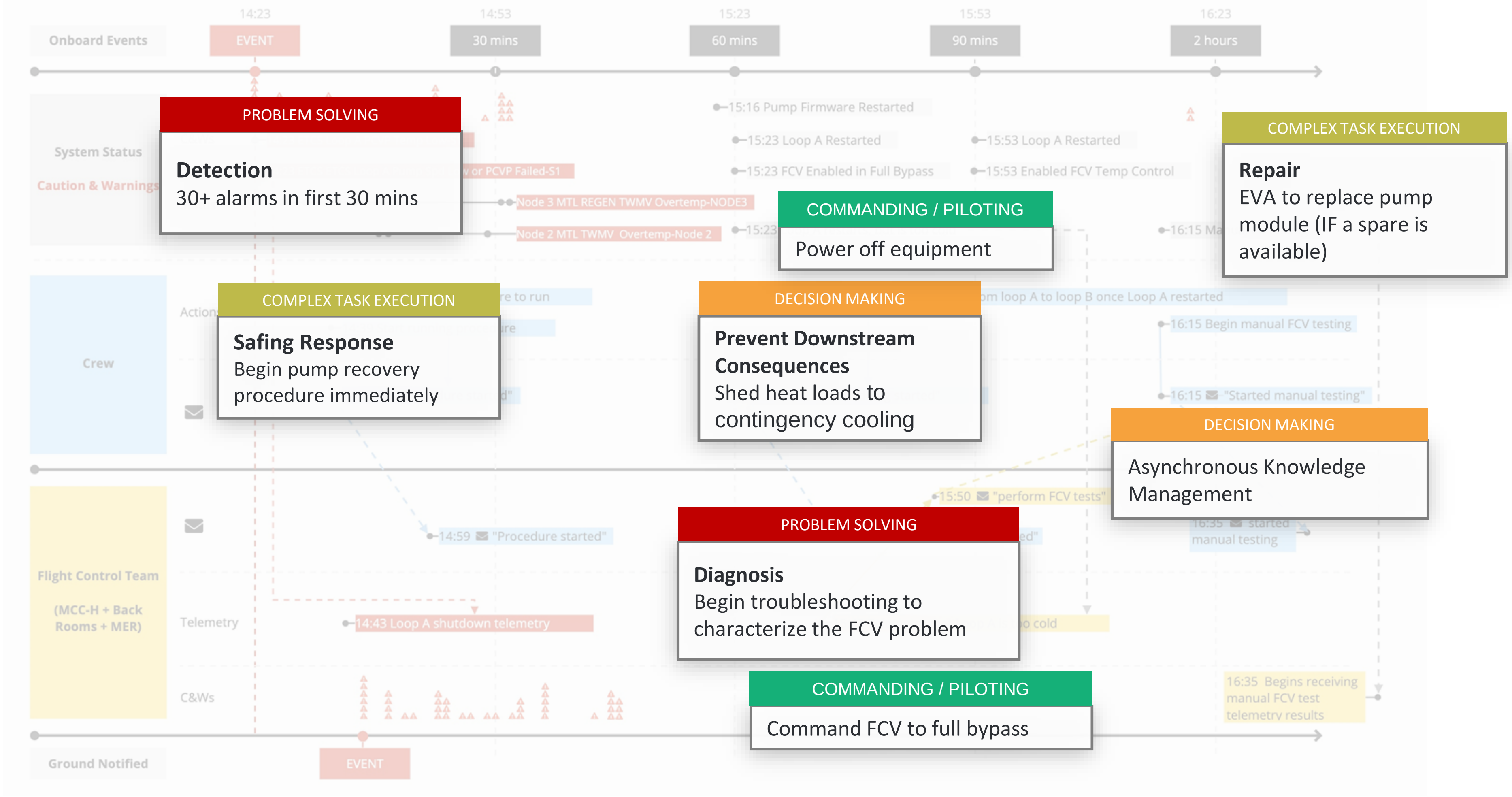


Note: Ground will always have more expertise and personnel; anything that can be worked at a pace that allows interaction with the ground will utilize those resources

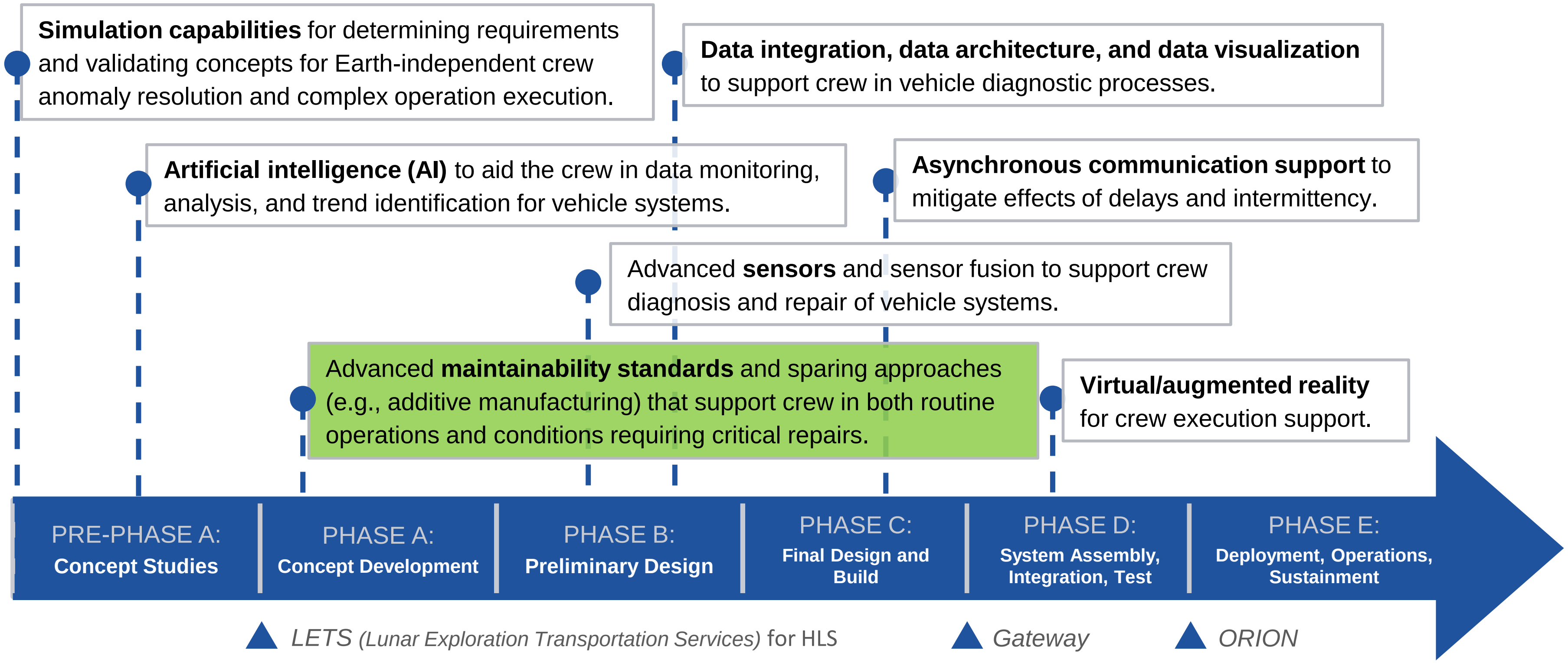
Mars Transit Projection of the ISS Cooling Loop A Anomaly



Mars Transit Projection of crew anomaly response



Engineering & Technology Gaps



Timeline points indicate when the capability should be available