NASA Engineering and Safety Center 2021 Study:
Safe Human Expeditions Beyond Low-Earth Orbit

Risks From Decreasing Ground Support

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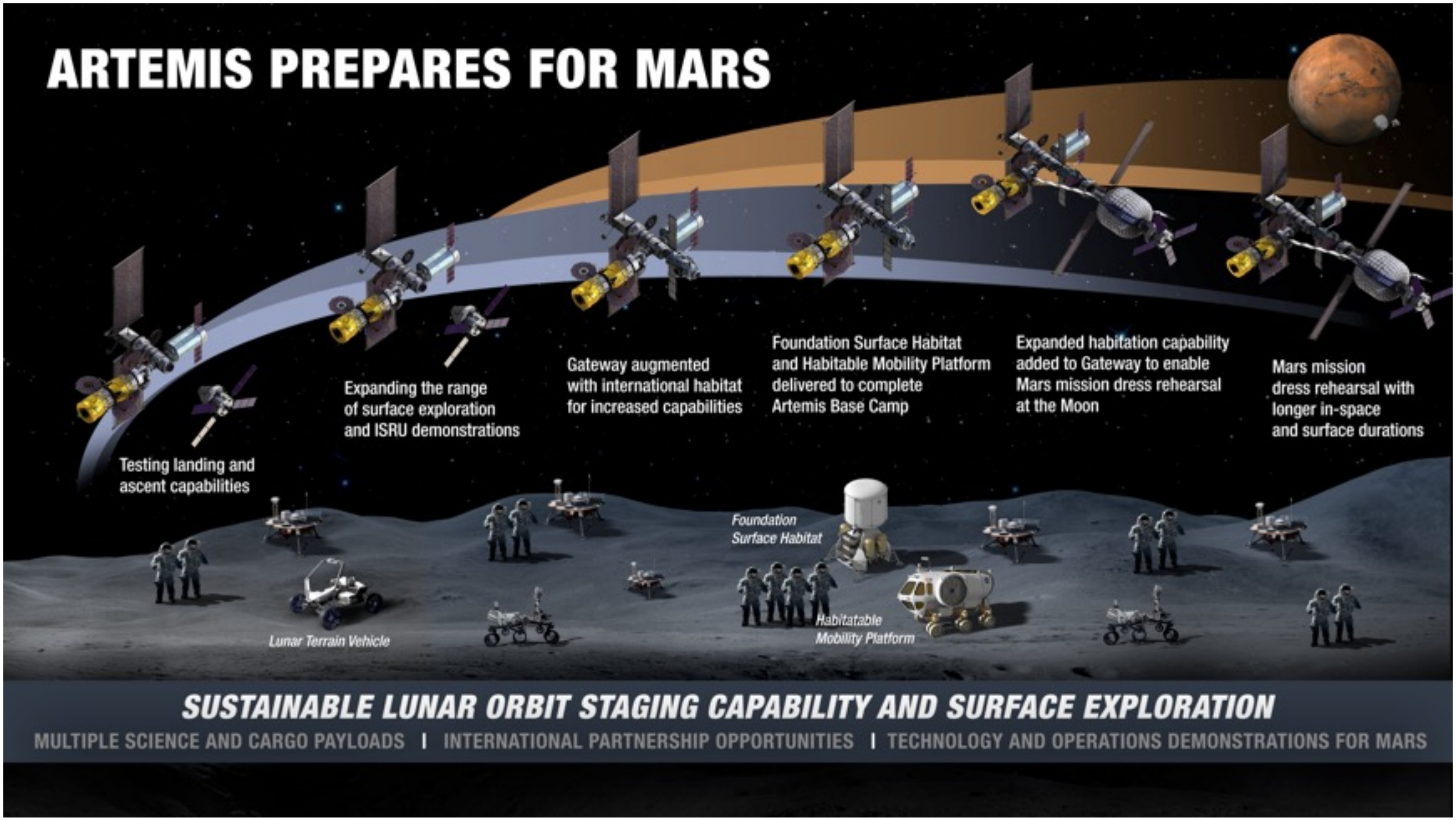
Ames Research Center


ARTEMIS PREPARES FOR MARS
Testing landing and ascent capabilities
Expanding the range of surface exploration and ISRU demonstrations
Gateway augmented with international habitat for increased capabilities
Foundation Surface Habitat and Habitable Mobility Platform delivered to complete Artemis Base Camp
Expanded habitation capability added to Gateway to enable Mars mission dress rehearsal at the Moon
Mars mission dress rehearsal with longer in-space and surface durations
Foundation Surface Habitat
Lunar Terrain Vehicle
Habitatable Mobility Platform
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION
MULTIPLE SCIENCE AND CARGO PAYLOADS | INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

	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

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Short-duration and one-time use

OR

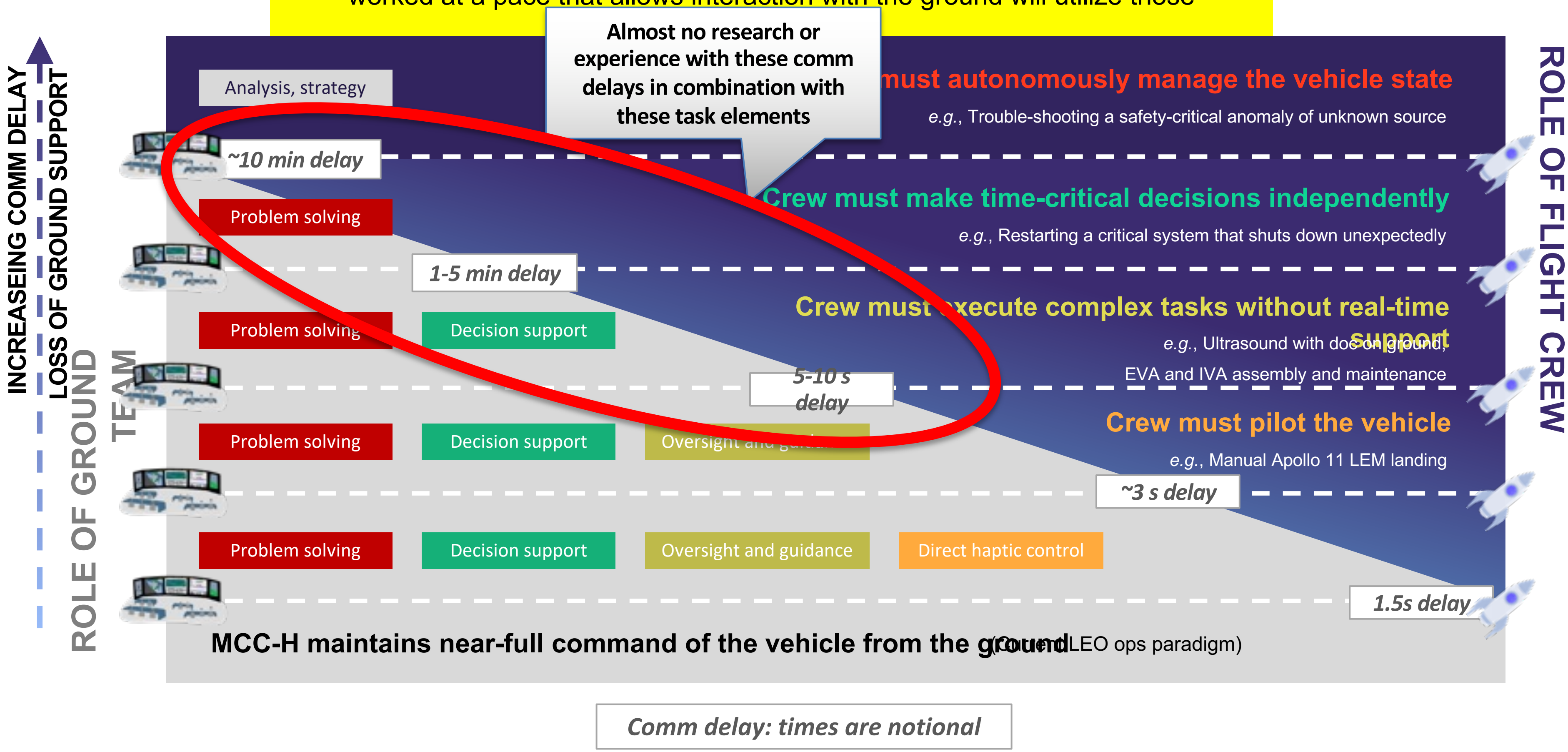
Short-duration and maintained on the ground

OR

Long-duration and easy access from Earth

Ground-to-onboard shift of safety-critical operations with increasing comm delay

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



Communication Delay Studies

Analog	AMO†	DRATS†	DSH†	ISTAR† (planned)	NEEMO† (7,9,13,14,16)	ISS*	ECLSS Computer Sim**
Year	2012	2010, 2011, 2012	2012	Incr35/36	2004, 2006, 2007, 2010, 2012	2016	2014
Duration (days)	8	9-14	10	90-180	10-18	166	?
1-way Comm delay (sec)	1.2, 5, 50, 300	0, 50, 600, 1200	50	50(?)	0-2, 50, 200, 600, 1200	50	300
Crew	4	2-4	4	1	6	3	24x3
Normal Ops	✓	✓	✓	✓	✓	✓	✓
EVA		✓	✓		✓		
Medical/ Emergency	✓	✓(?)	✓		✓		
Maintenance	✓	✓	✓	✓		✓	✓
Contingency	✓	✓	✓		✓		✓
Troubleshooting	✓		✓				✓

†from Rader, et al., 2013 *from Kintz, 2016 **from Fischer and Mosier, 2014

Communication Delay Studies: Reported Challenges

- Even short comm delays can disrupt MCC-crew interactions
  - Apollo missions: comm delay as short as 1.25 seconds (one way) precluded ground control from effectively providing "overwatch" on rapidly unfolding issues
  - NEEMO: tele-surgery not possible > 1 sec delay
- As transmission delays increase, space-ground communications degrade significantly
  - "Transmission delays disrupted the structure of space-ground communications as contributions by flight controllers and astronauts overlapped or were out of sequence." [Fischer, et. al., 2013]
  - "Situational awareness and actions/responses by crew and mission control when separated by a time delayed communications link can and will diverge rapidly in dynamic situations (*i.e.*, emergencies, quick changing circumstances…)" [Rader et. al., 2012]

Communication Delay Studies: Reported Challenges

- Degraded space-ground communications adversely affect team performance
  - "Teams took significantly longer to repair system failures under time delay than when they had no time delay." [Fischer and Mosier, 2014]
  - "At delays of 300 sec or longer, crew performance was similar to that when there was no communication between MC and the crew." [Rader et al, 2012]
- Countermeasures for asynchronous comm have not been proven
  - With delayed comm the communication medium (text vs voice) had no effect on performance of distributed teams [Fischer and Mosier, 2014]
  - NEEMO missions showed that all communications tools need significant enhancements to be operationally robust in a delayed environment [Rader et al, 2012]

Communication Delay Studies: Limitations

- Definitions of operational regimes (e.g., "contingency)
- Levels of situational or task complexity
- Controls
- Measures of simulation fidelity
- Measures of outcomes (*e.g.*, "degraded capabilities")
- Repeatability
- Small sample sizes

"The reported impacts of communication delays in low fidelity environments may be underestimated, particularly for tasks involving highly complex, dangerous, and/or off-nominal situations." [Kintz et al 2016]

Off-Nominal Scenario Criteria

Impact to a critical system with the following characteristics:

Causal relationships are not immediately understood

- Competing alarms across systems – challenge of isolating the initiation
- Specific expertise required; challenge of "from 80+ people to 4" working the problem
- Complexity of system and of anomaly
- Challenge of safely perturbing the system to gain understanding of cause and effect

No perfect information during initial stages

- Sensors data may be incorrect or incomplete
- Sensors are limited resource, do not cover all parts of the system
- Historical data may be limited or unavailable
- Challenge to parse out relevant data

Intervention options

- Creativity required to generate workaround options
- Systems thinking to perform risk assessments
- Rapid synthesis and decision-making
- Resource limited environment, limited redundancy, sparing, etc.
- Procedures may have unexpected outcomes

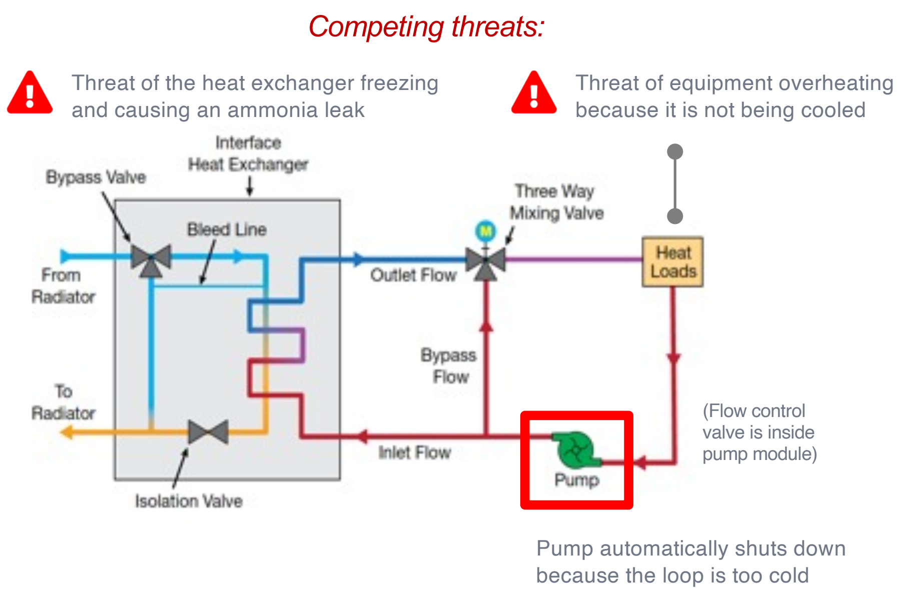
Time pressure

- Short time-to-effect (to prevent adverse outcomes)
- Time pressure on execution/completion of procedure
- Competing priorities (e.g., inattention to other critical operations)
- Simultaneous efforts required (safing, investigating, downstream impact)

Overview: **Cooling Loop A Anomaly of 2013**

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

Cooling Loop A Anomaly of 2013 Scenario

Summary of Anomaly Response and Resolution:

The anomaly began when the fault detection, isolation, and recovery (FDIR) software automatically shut down Cooling Loop A after the loop became too cold to operate safely. Six alarms sounded in the first minute of the failure (four of which were heard onboard), and over the course of the next 30 minutes, over 30 alarms would sound. When the first alarms sounded, the crew was immediately informed that the ground was aware and responding. The ground team (including people in MCC-H, MPSRs, and the MER) had to move quickly as this fault required urgent response.

ISS's two cooling loops (A&B) are not fully redundant and so many onboard systems were suddenly in danger of overheating, including critical electrical power system switches and converters. The ground team determined the systems that needed to be moved to Loop B and those that should be safely powered down, based on thermal system constraints documentation. Simultaneously, the ground team began procedures to restart the pump. Pump recovery procedures were time-constrained and had to be initiated almost immediately to restore required cooling and redundancy.

Although restarted in full bypass mode (no ammonia flowing), the temperature in the loop remained too low. During the next few hours, the ground team commanded various flow control value positions to characterize the loop response and understand the continuing fault. At the same time, the ground was analyzing and redistributing heat loads. The crew assisted in powering down certain equipment onboard the ISS at the end of their day, but otherwise maintained nominal operations.

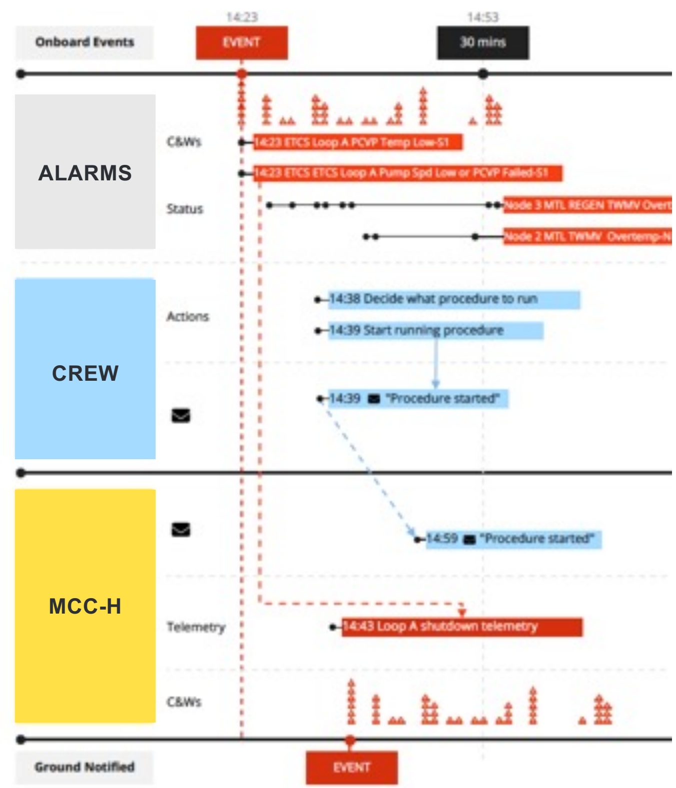
Over the next seven days, the MCC attempted numerous interventions, all commanded-from-the-ground, including utilizing line heaters, power cycling the pump, adjusting other valves, etc. Ultimately, the FCV operation could not be recovered – the pump module had to be replaced through an EVA. The ground and crew then began intensive EVA preparations.

The graphic on the right describes the same initial anomaly response as it would occur during Mars transit, with the crew assuming the lead and commanding of resolution activities due to comm delay.

Safe Human Exploration Beyond LEO Workshop Report:
https://www.nasa.gov/sites/default/files/atoms/files/nesc-rp-20-01589_nasa-tm-20220002905.pdf

The International Space Station: Operating an Outpost in the New Frontier:
https://www.nasa.gov/connect/ebooks/the-international-space-station-operating-an-outpost

Timeline: the first ~1 hour of anomaly response mapped to Mars transit



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

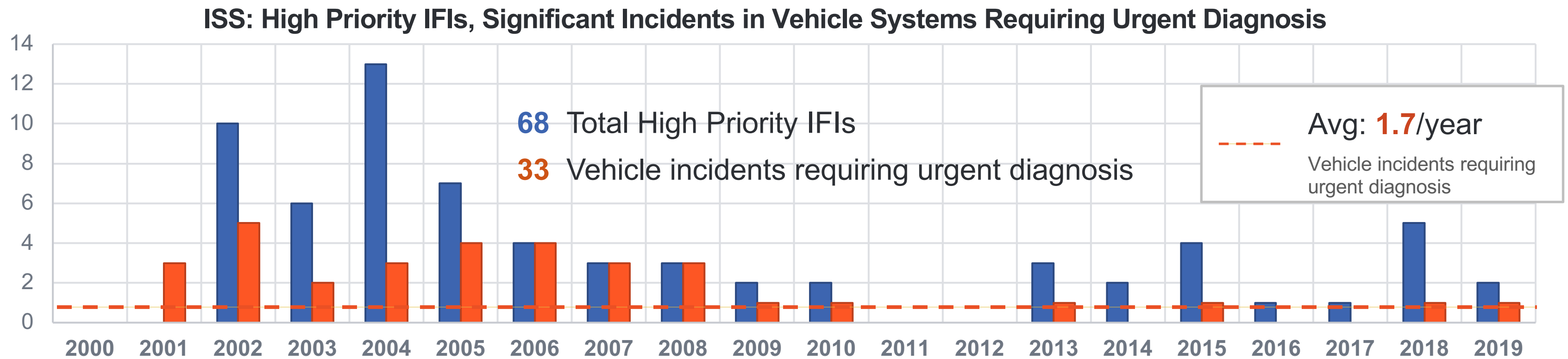
- Creativity required to generate workaround options, e.g., use of line heaters, other valving, etc. to raise temps
- Systems thinking to perform risk assessments, e.g., risks associated with potential for common cause failure in Cooling Loop B, EVA R&R, etc.
- Rapid synthesis and decision-making -- 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

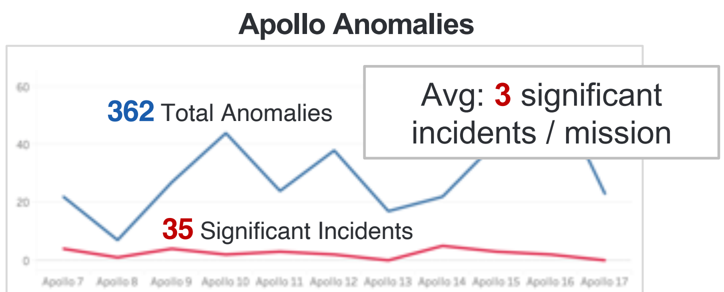
Time pressure

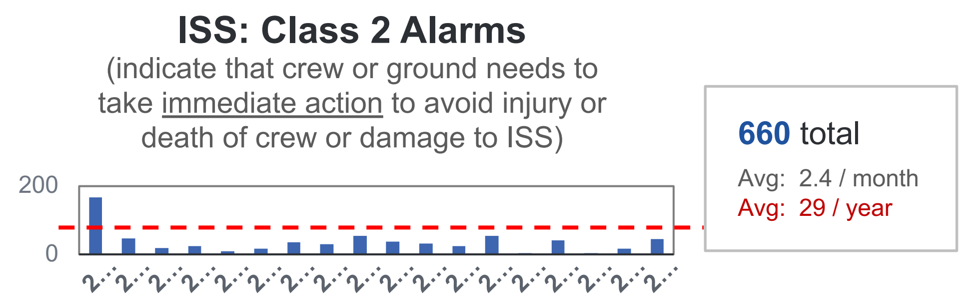
- Short time-to-effect for equipment overheating and risk associated with reduced redundancy
- Complex pump recovery procedure must be started immediately
- Competing priorities: must restart pump, begin diagnosis, and triage equipment simultaneously
- Simultaneous efforts required (safing, investigating,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

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

Anomaly Rates for Human Spaceflight







2. THE STATE OF THE PRACTICE

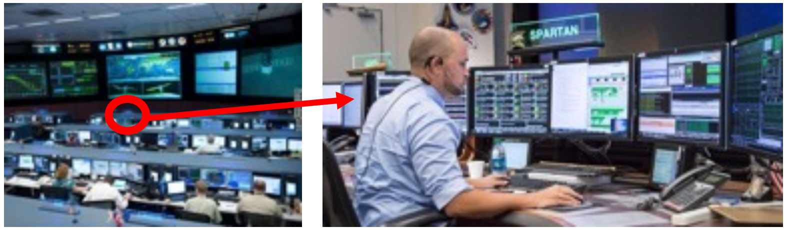
Current Mitigations

NASA’s mission operations paradigm is one of near-complete **real-time dependence** on experts on the ground to control and manage the combined state of the mission, vehicle, and crew.

The ISS relies on frequent resupply of spare parts and other resources from visiting vehicles to maintain the vehicle

An example Orbital Replacement Unit (ORU)

MCC-H constantly manages the state of the vehicle



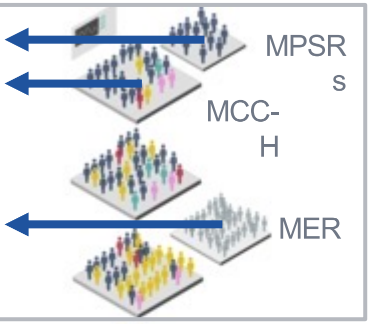
Amount of data evaluated by a single flight controller

Mission Control provides crew with real-time direction and oversight for complex task execution

Mission Control Expertise:

(Mission Control Center (MCC-H), Mission Evaluation Room (MER), and support rooms)

- **85+** specialists available
- **~660** years combined on-console experience
- **22** <u>unique</u> console disciplines

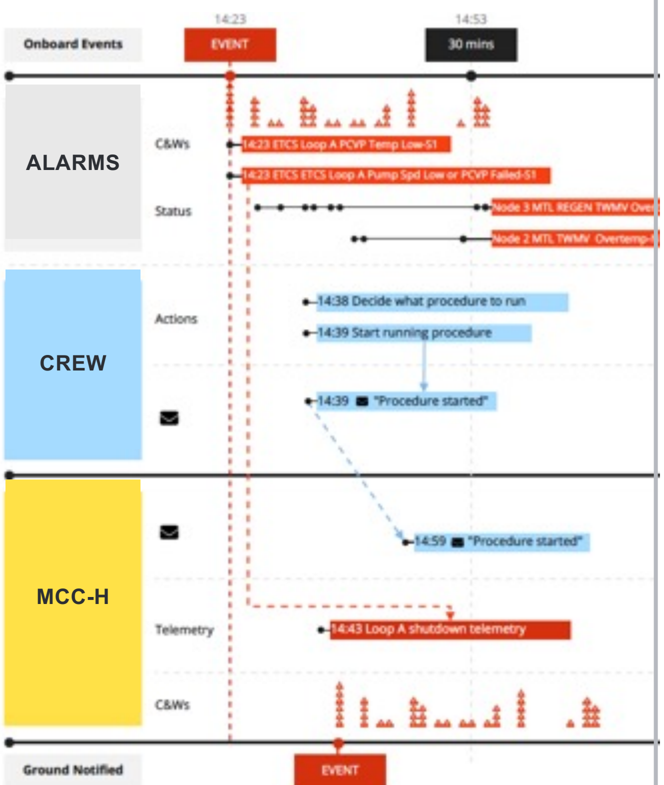


NASA’S HSIA has evolved but not fundamentally changed…

Apollo, 1961 - 1973

ISS, 2000 - present

Timeline: the first ~1 hour of anomaly response in Mars transit

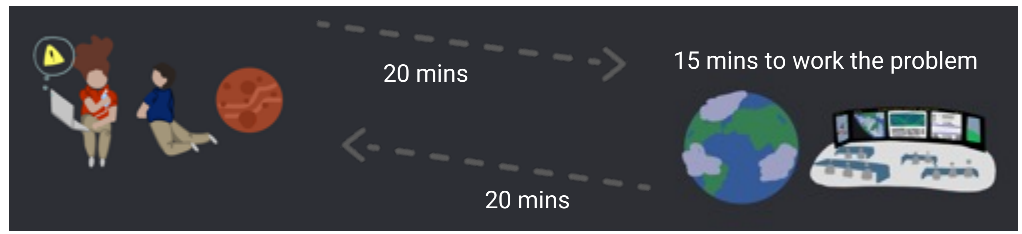


Based on the ISS Cooling Loop A incident of 2013

3. FUTURE MITIGATIONS

A Paradigm Shift is Needed

The risk has been assessed to be red, but the evidence base is insufficient to guide countermeasure development



Advice from MCC ~55 mins outdated

Lack of evidence-base results in singular countermeasure perspectives:

1. Aspiration to engineer more reliable / robust systems so that anomalies do not occur
2. Notion that Artificial Intelligence will address anomalies
3. Assumption that MCC can continue to address anomalies, even with delayed comm
4. Perspective that training can be amplified to prepare crew to address anomalies

Earth-independent operations are not viable without advances in all four of these areas and in other countermeasures

Engineering & Technology Gaps

Timeline points indicate when the capability should be available

RECOMMENDATION #5

Research and technology capabilities to focus on

Simulation capabilities for determining requirements and validating concepts for Earth-independent crew anomaly resolution and complex operation execution.

Data integration, data architecture, and data visualization to support crew in vehicle diagnostic processes.

Artificial intelligence (AI) to aid the crew in data monitoring, analysis, and trend identification for vehicle systems.

Asynchronous communication support to mitigate effects of delays and intermittency.

Advanced **sensors** and sensor fusion to support crew diagnosis and repair of vehicle systems.

Advanced **maintainability standards** and sparing approaches (e.g., additive manufacturing) that support crew in both routine operations and conditions requiring critical repairs.

Virtual/augmented reality for crew execution support.

PRE-PHASE A: **Concept Studies**

PHASE A: **Concept Development**

PHASE B: **Preliminary Design**

PHASE C: **Final Design and Build**

PHASE D: **System Assembly, Integration, Test**

PHASE E: **Deployment, Operations, Sustainment**

LETS (Lunar Exploration Transportation Services) for HLS

Gateway

ORION