



25 years

Content and Representation of Information Needed to Support Time-Constrained Problem Solving



2025 Human Research Program
Investigators' Workshop

IWS 2025 - SESS-437

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Earth-Dependent Operational Paradigm

Near-complete, **real-time dependence on a ground team** to manage the combined state of the mission, vehicle, and crew.



Apollo, 1961 - 1973



ISS, 2000 - present



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



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- **~660** years combined on-console experience
- **22** unique console disciplines



Amount of data monitored by a single Flight Controller (SPARTAN)

Earth-Dependent Operational Paradigm

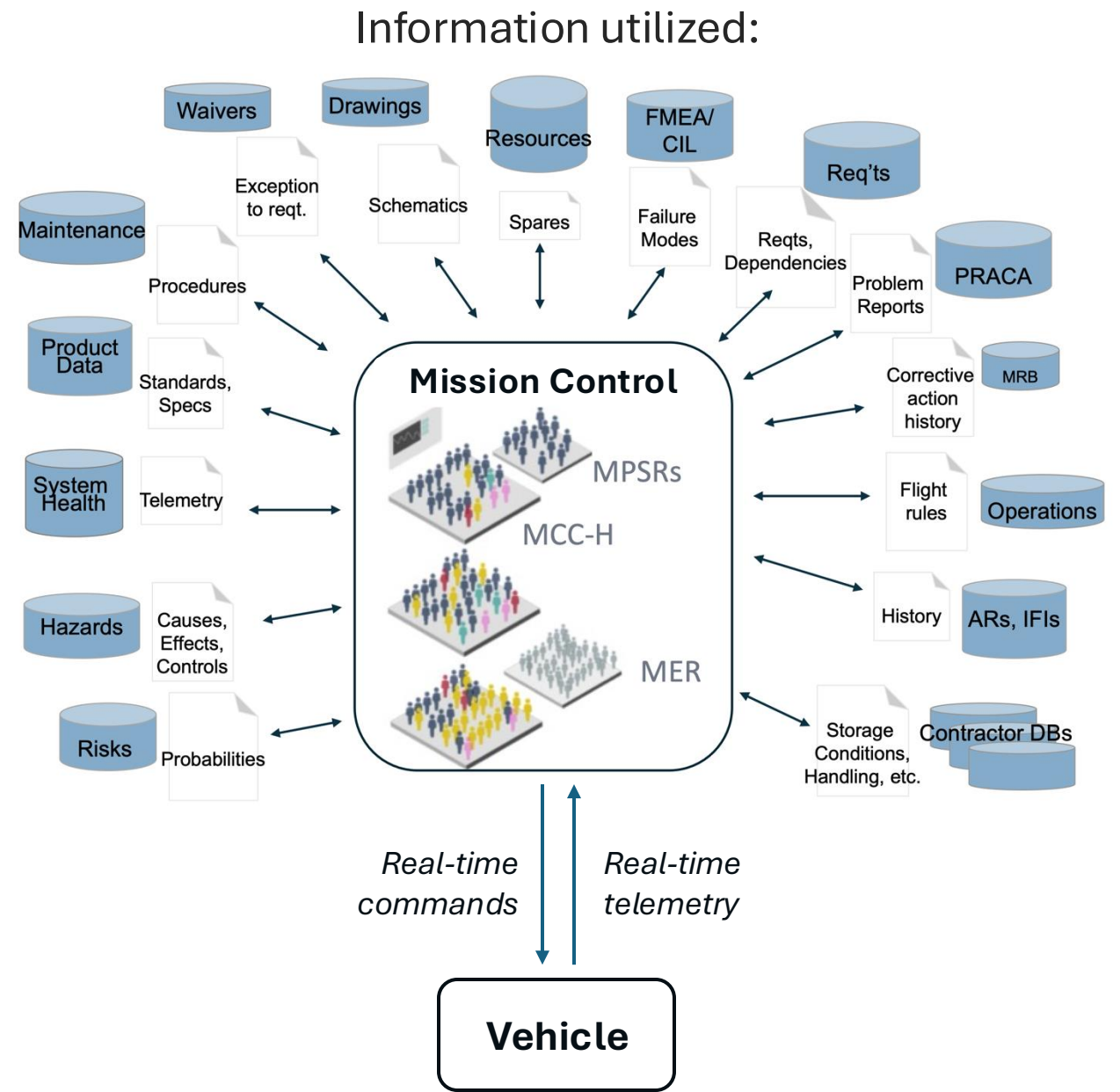
Near-complete, **real-time dependence on a ground team** to manage the combined state of the mission, vehicle, and crew.



Apollo, 1961 - 1973



ISS, 2000 - present



Earth-Independent Missions Beyond LEO

A new operational paradigm is needed as distances and communication latencies increase.



Apollo, 1961 - 1973



ISS, 2000 - present



Moon to Mars

**Crew will need to independently
respond to anomalies historically
handled by a team 20x their size**



With limited attention and expertise

ISS Anomaly Rates (2000 – 2019)

Reported Anomalies

~10k

Anomaly Reports
(in MCC Gateway, ISS
Increments 4 – 60 +
shuttle ISS missions)

Average of 161/
ISS increment

Average of 58 / shuttle
mission to ISS

Items for Investigation

~4500

Items for Investigation
(Created by MER)

Critical / significant

64

High priority IFIs
(Marked high priority)

10

Significant Incidents and
Close Calls, Z-Card

Require urgent diagnosis

33

Vehicle incidents requiring
urgent diagnosis
(Determined by SME)

Average of 1.7 / year
(but higher during the
burn-in phase!)

Earth-Independent Missions Beyond LEO

A new operational paradigm is needed as distances and communication latencies increase.



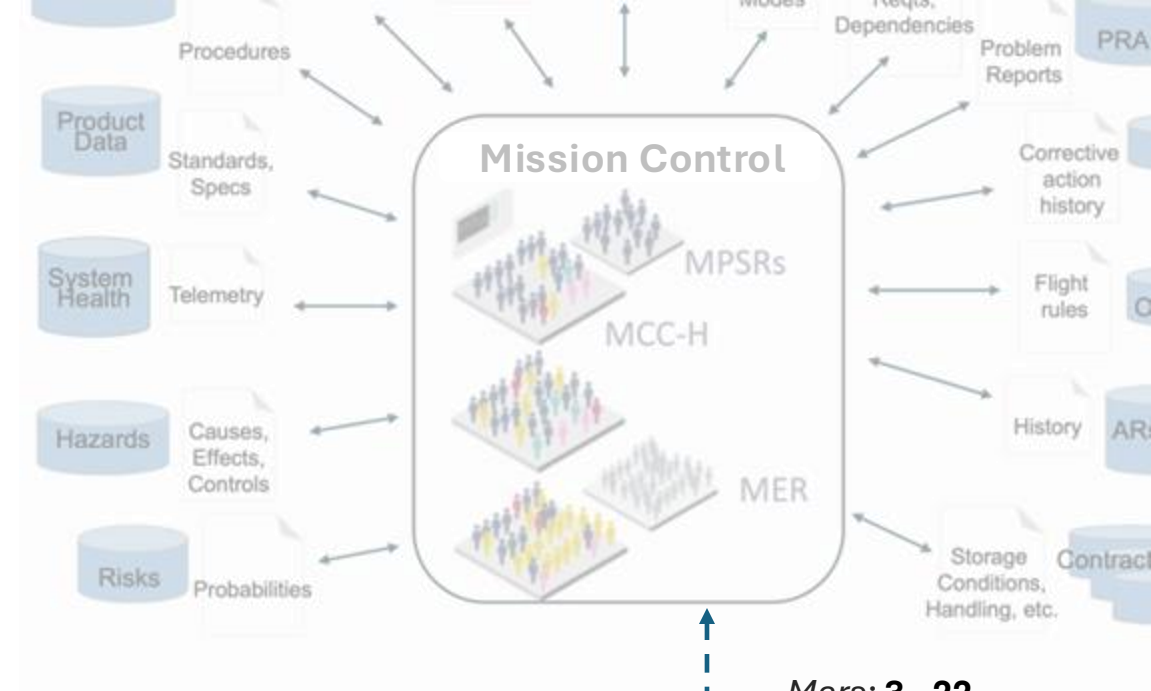
Apollo, 1961 - 1973



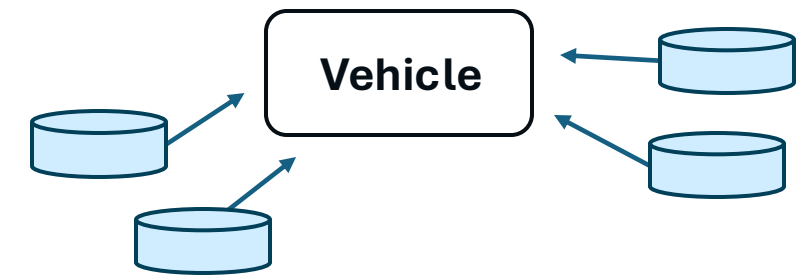
ISS, 2000 - present



Moon to Mars



Comm delay
Mars: 3 - 22 minutes one-way

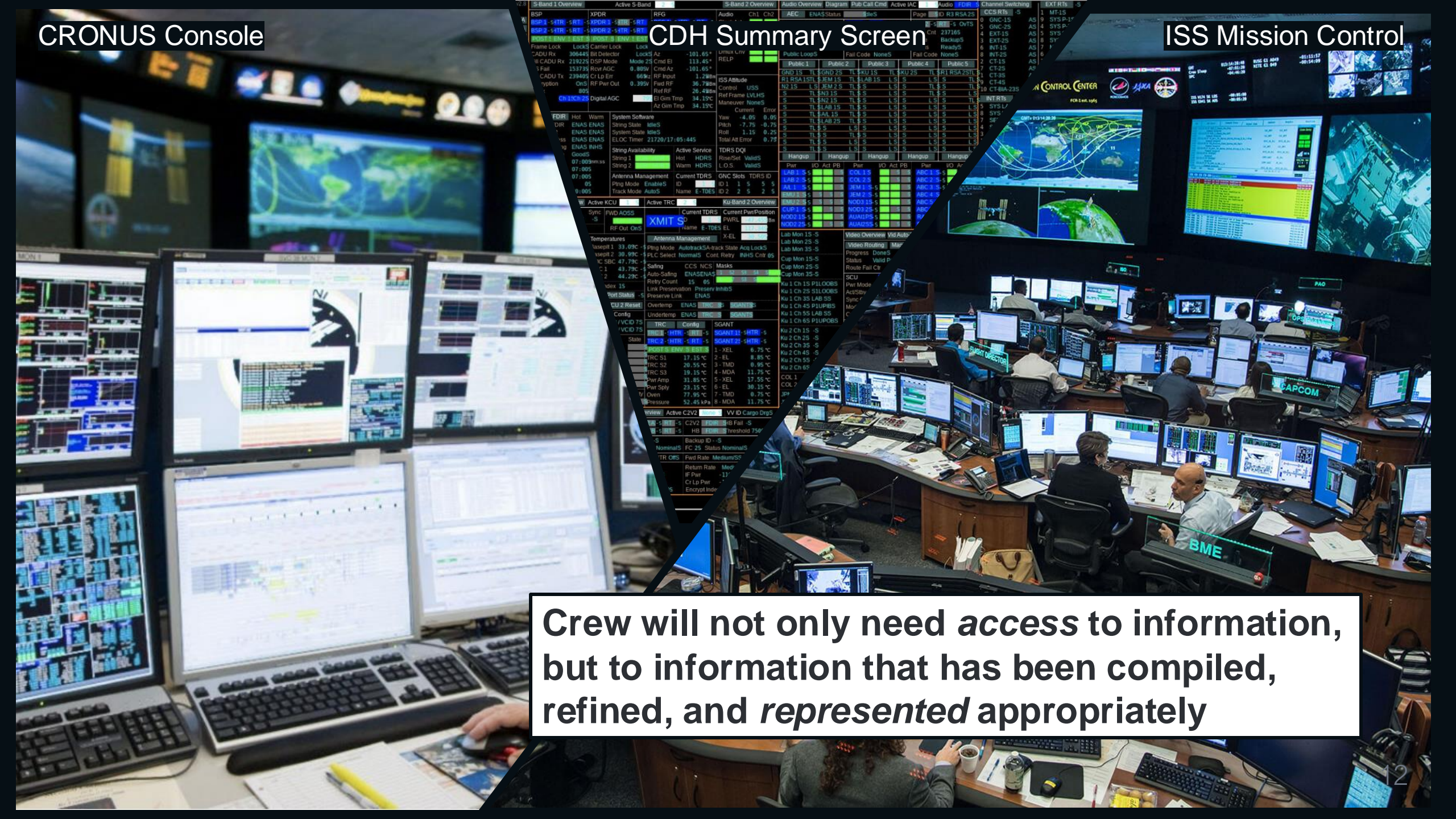


Need for onboard access to data!

CRONUS Console

CDH Summary Screen

ISS Mission Control

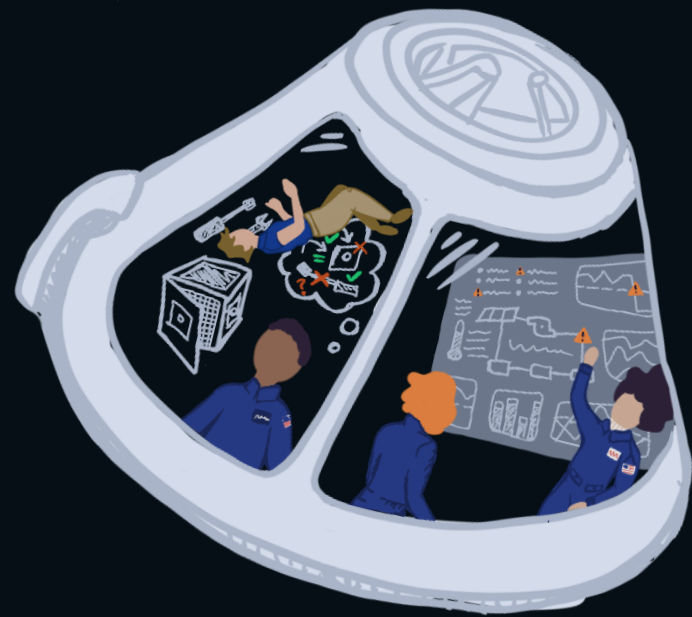


Crew will not only need access to information, but to information that has been compiled, refined, and *represented* appropriately



How can a crew of four monitor (and understand) the same amount of data as 20+ experts?

They can't (on their own)



Task: Content and Representation of Information Needed to Support Time-Constrained Problem Solving

Purpose: Assess the content and representation of information needed to support time-constrained problem solving and decision-making during procedure execution and anomaly resolution by the crew under conditions of reduced and/or intermittent communication with the ground team.

Goals:

- Determine specific information accessed and assembled for problem solving, including declarative (e.g., facts), procedural (e.g., rules), schematic (e.g., principles) and strategic (e.g., heuristics) types
- Understand how to organize and integrate this information into appropriate mental models that can then be exercised to produce solutions



The users:

- Small crew (~4)
- Limited attention
- Limited expertise
- Generalists

Approach

- Literature review
- Problem-solving modeling
- Information classification/mapping
- Interviews (spaceflight SMEs, analogous domain experts, operators, etc.)
- UI reviews and requirements
- Exploratory designs

Analogous Domains

We interviewed expert problem solvers and surveyed information systems in safety-critical industries:

- Hospital command centers
- Air traffic control
- Nuclear industry ops

To understand how experts solve critical problems under time pressure



“...by and large, you know, you're just kind of doing a more high-level general monitoring of things and relying on, you know, either catching the trends deviating or, you know, an enunciator to call out your attention.”

- Nuclear SME



“...being able to look at things in that way where it becomes visually obvious ...would be a very helpful way to help the crew understand what's wrong...there are many different ways to group things: by power, by cooling, by data path, or by physical location, and any one of those could provide you the clue...as to what the common factor is.”

- Crew Member

ISS Lessons Learned

- Interviewed flight operations personnel
- Investigated real ISS anomaly scenarios
- Reviewed training resources and processes for flight controllers

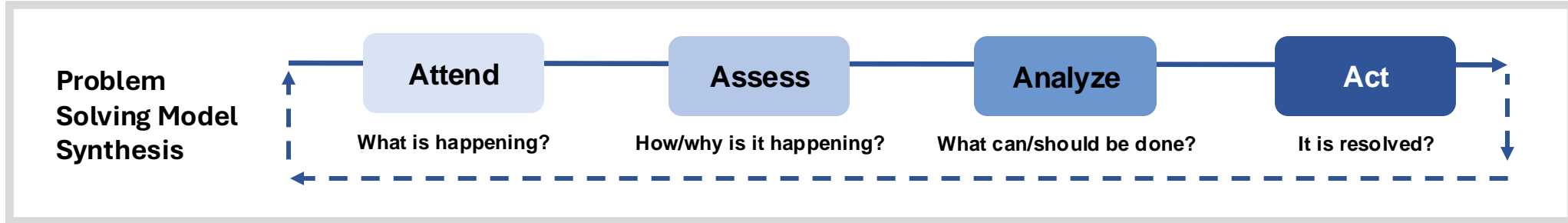
To understand:

- How MCC solves problems
- Key challenges for anomaly response beyond LEO
- Skills/tools needed by crew



What information do crew need on board to support problem solving?

Types of Problem-Solving Information



Types of Information

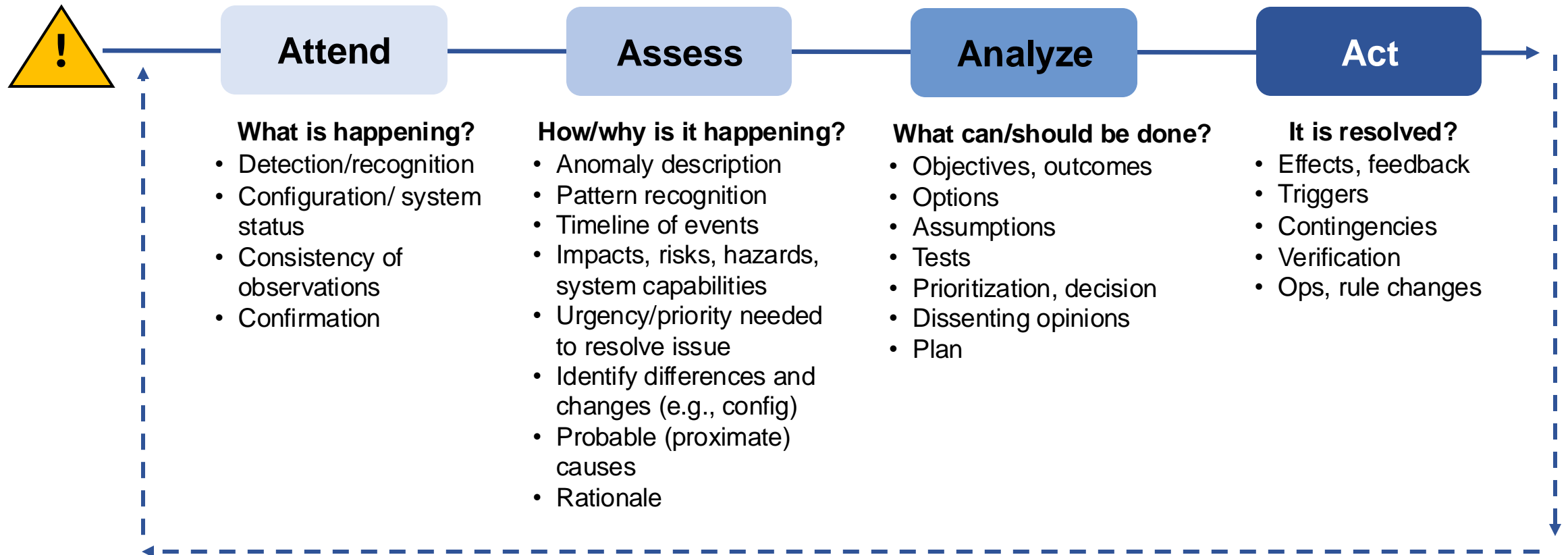
Declarative Knowledge: *Knowing “that”*
e.g., definitions, descriptions, etc.

Procedural Knowledge: *Knowing “how”*
e.g., sequences, rules, etc.

Strategic Knowledge: *Knowing “applicability”*
e.g., heuristics, judgement, etc.

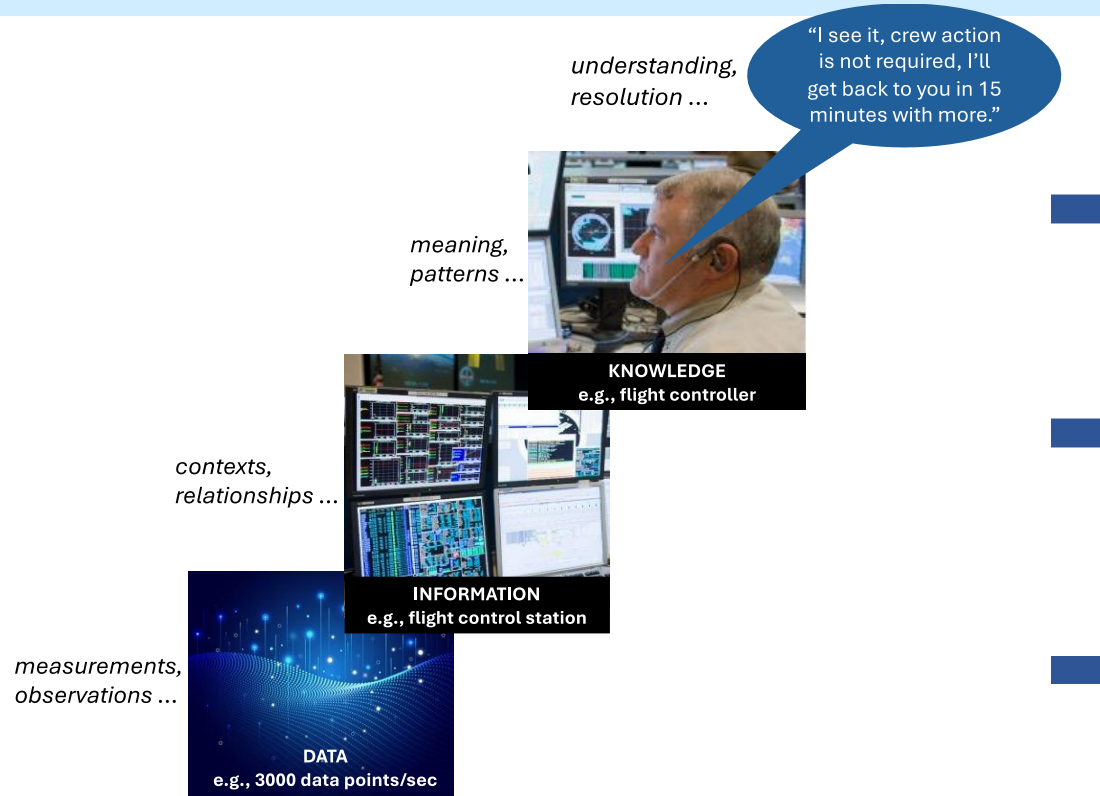
Schematic Knowledge: *Knowing “why”*
e.g., principles, schemes, etc.

Problem Solving Model: Information Needs

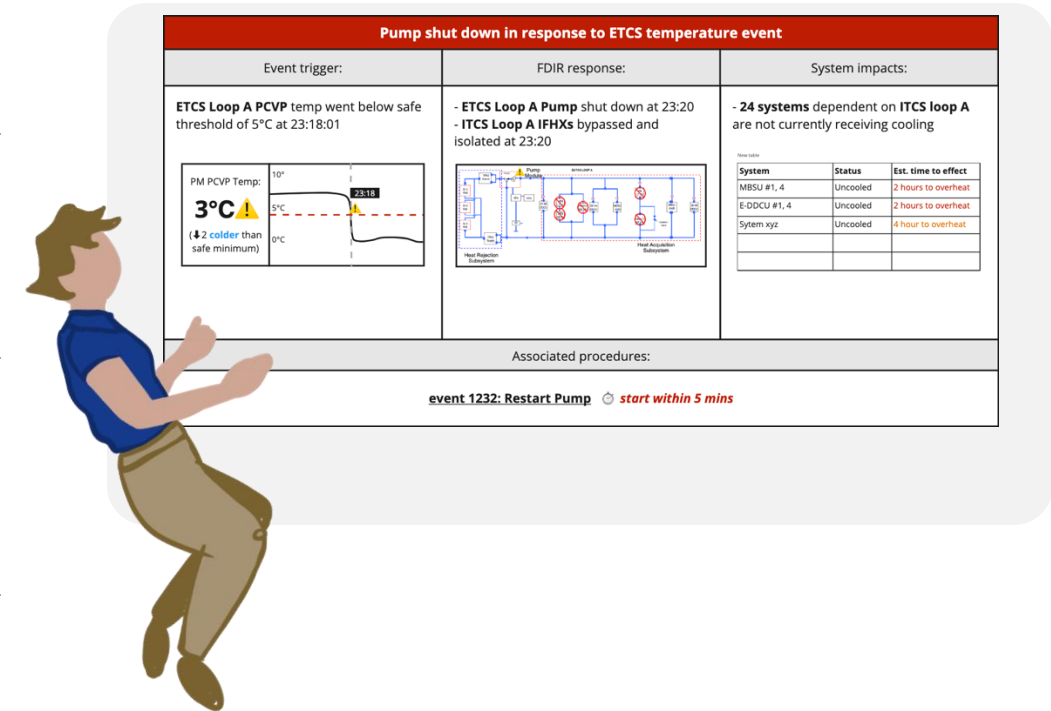


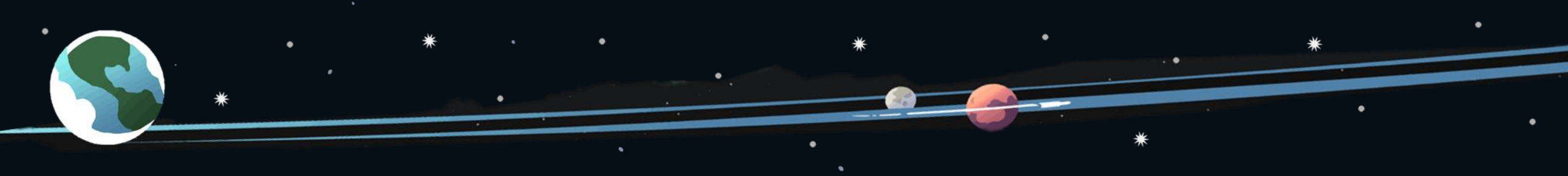
Enabling crew to think like experts: system design

GROUND TEAM-SYSTEM



ONBOARD CREW-SYSTEM





How should this information be integrated and organized?

Prioritized Needs

	Problem solving model	Prioritized needs	Maps
ATTEND	<ul style="list-style-type: none"> • Detection/recognition • Configuration/ system status 	<p>System Status and Health Overview:</p> <ul style="list-style-type: none"> • Information on system status and availability • information on current configuration and constraints imposed • detect/display unusual trending <p>Caution and Warning Data Management:</p> <ul style="list-style-type: none"> • alerts for anomalous events • FDIR limits and their implications • parent-child relationships noted; triaged 	<ul style="list-style-type: none"> • Physical • Functional
ASSESS	<ul style="list-style-type: none"> • Urgency/Time to effect • History/timeline of events • Impacts, risks, hazards, system capabilities • Probable (proximate) causes 	<p>Detailed Event Analysis and Drill-Down Capabilities:</p> <ul style="list-style-type: none"> • Information on downstream impacts and time frame • Information on norms and ranges • System manuals, logs • Troubleshooting “cheat sheet” • Information on possibly relevant past anomalies 	<ul style="list-style-type: none"> • Temporal • Contextual • Evidential • Causal

	Problem solving model	Prioritized needs	Maps
ANALYZE	<ul style="list-style-type: none"> • Objectives, outcomes • Options 	<p>Trial Action Options/Plans:</p> <ul style="list-style-type: none"> • Information on available resources • Information on constraint-based timeline options • Information on possible consequences of actions • Information on sequence of actions determined to be executed (based on then information) 	<ul style="list-style-type: none"> • Tactical • Resource • Capability • Procedural
ACT	<ul style="list-style-type: none"> • Effects, feedback • Triggers 	<p>Automated Procedure Execution Oversight and Feedback:</p> <ul style="list-style-type: none"> • Real-time feedback on procedure effects • Automated alerts for rule violations or threshold breaches • Status tracking to ensure successful execution and monitoring of procedures 	

Countermeasure Areas

Caution and Warning Data Management



Detailed Event Analysis and Drill-Down Capabilities

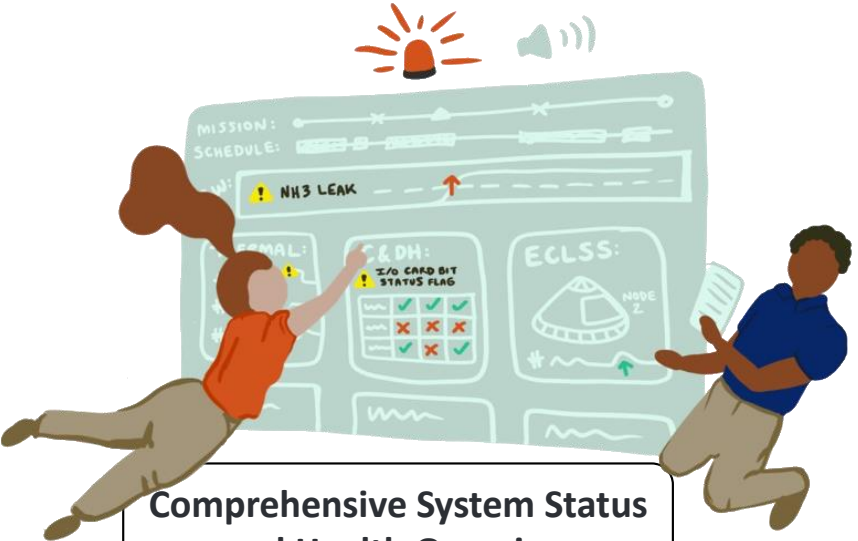


Should we depress and/or vent ETCS loop B?

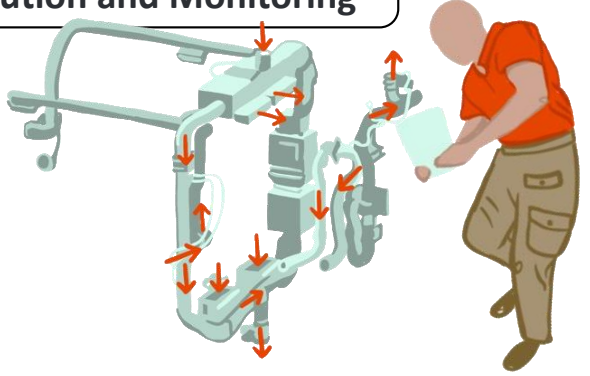
Actions	Risks / Impact
Depress loop	Uses consumables
Vent ETCS Loop B	Irreversible

Trial Action Plans/Options

Comprehensive System Status and Health Overview



Real-Time Procedure Execution and Monitoring



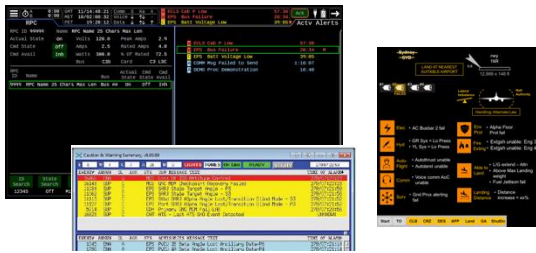


How should this information be represented?

Design Process

	Problem solving model	Prioritized needs	Maps	Problem solving model	Prioritized needs	Maps
ATTEND	<ul style="list-style-type: none"> Detection/recognition Configuration/system status 	System Status and Health Overview: <ul style="list-style-type: none"> Information on system status and availability (3) Information on current configuration (4) and constraints imposed detect/display unusual trending (1) Caution and Warning Data <ul style="list-style-type: none"> alerts for anomalous events FDIR limits and their implications parent-child relationships noted/triggered 	<ul style="list-style-type: none"> Physical Functional 	<ul style="list-style-type: none"> Objectives, outcomes Options 	Trial Action Options/Plans: <ul style="list-style-type: none"> Information on available resources Information on constraint-based timeline options (16) Information on possible consequences of actions (14) Information on sequence of actions determined to be executed (based on then information) 	<ul style="list-style-type: none"> Tactical Resource Capability Procedural
ASSESS	<ul style="list-style-type: none"> Urgency/Time to effect History/timeline of events Impacts, risks, hazards, system capabilities Probable (proximate) causes 	Detailed Event Analysis and Drill-Down Capabilities: <ul style="list-style-type: none"> Information on downstream impacts and time frame (7) Information on norms and ranges System manuals, logs (9) Troubleshooting "troubleshoot sheet" (10) Information on possibly relevant past anomalies (8,11) 	<ul style="list-style-type: none"> Temporal Contextual Evidential Causal 	<ul style="list-style-type: none"> Effects, feedback Triggers 	Automated Procedure Execution Oversight and Feedback: <ul style="list-style-type: none"> Real-time feedback on procedure effects Automated alerts for rule violations or threshold breaches Status tracking to ensure successful execution and monitoring of procedures 	

Prioritized Needs



Literature Review

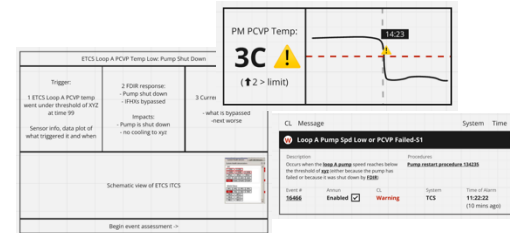
- Interfaces in analogous domains
- Existing ISS interfaces
- Data viz best practices
- Requirements

Data needs, features, tools

Iterative design



Storyboards



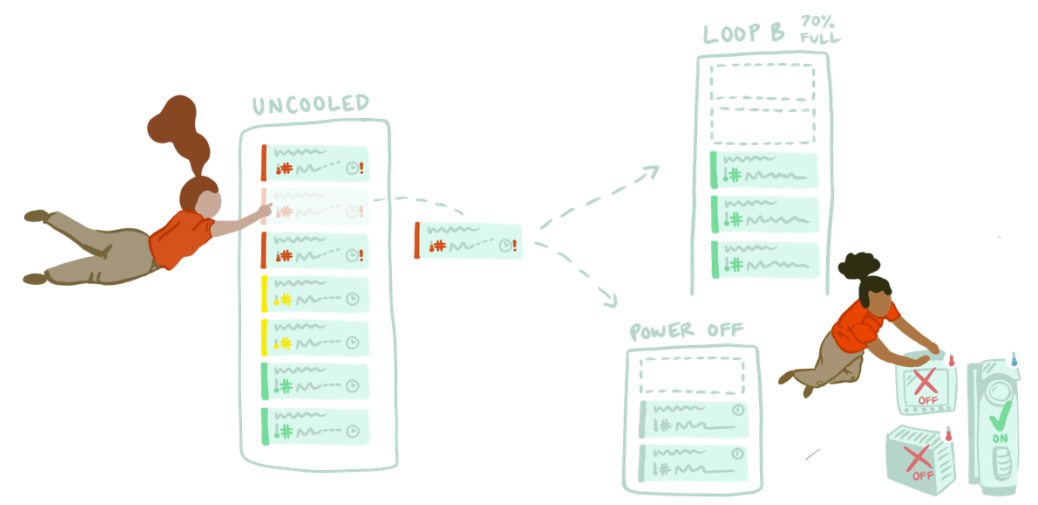
Sketches / Wireframes

Pump shut down in response to ETCS temperature event														
Event trigger:	FDIR response:	System impacts:												
ETCS Loop A PCVP temp went below safe threshold of 5°C at 23:18:01 	ETCS Loop A Pump shut down at 23:20 ETCS Loop A IFHXs bypassed and isolated at 23:20 	- 24 systems dependent on ITCS loop A are not currently receiving cooling <table border="1"> <thead> <tr> <th>System</th> <th>Status</th> <th>Max. time to effect</th> </tr> </thead> <tbody> <tr> <td>ISSU #1, 4</td> <td>Uncooled</td> <td>2 hours to overheat</td> </tr> <tr> <td>ISSU #1, 4</td> <td>Uncooled</td> <td>2 hours to overheat</td> </tr> <tr> <td>System xpt</td> <td>Uncooled</td> <td>3 hours to overheat</td> </tr> </tbody> </table>	System	Status	Max. time to effect	ISSU #1, 4	Uncooled	2 hours to overheat	ISSU #1, 4	Uncooled	2 hours to overheat	System xpt	Uncooled	3 hours to overheat
System	Status	Max. time to effect												
ISSU #1, 4	Uncooled	2 hours to overheat												
ISSU #1, 4	Uncooled	2 hours to overheat												
System xpt	Uncooled	3 hours to overheat												
Associated procedures: event 1232: Restart Pump ⏱ start within 5 mins														

Exploratory Design Concepts

UI patterns, best practices

ISS Cooling Loop A Anomaly Case Study



50+ alarms in the first two hours...

ISS Current State

- Some alarms are impacts (“children”) of other alarms
- Some alarms are repeated at intervals, or duplicated across systems
- Some alarms are just notifications of (anticipated) FDIR actions
 - **ETCS Loop A Pump Spd Low or PCVP Failed-S1**
- Some alarms are just (anticipated) effects of FDIR actions
 - **ETCS Loop A PCVP Loss of Comm-S1**

ETCS Loop A PCVP Temp Low: Pump Shut Down	C	ETCS Loop A PCVP Temp Low-S1	54	TCS	ETCS	14:23:18
	W	ETCS Loop A Pump Spd Low or PCVP Failed-S1	55	TCS	ETCS	14:23:30
FCV not at required position	C	ETCS Loop A FCV Not At Required Posn Following Pump Shutdown-S1	56	TCS	ETCS	14:23:39
Pump shutdown cmds feedback	A	S1 1 MDM Detect RT Loss of Comm - ETCS Pump Ctrl Vlv Pack A-S1	57	CDX	MDM	14:23:40
	C	ETCS Loop A PCVP Loss of Comm-S1	59	TCS	ETCS	14:23:42
	C	ETCS Loop A PCVP Temp Low-S1	58	TCS	ETCS	14:23:42
	C	ETCS Loop A Pump Shutdown Command Sequence Failed-S1	60	TCS	ETCS	14:24:05
ITCS warming up because pump is shut down	C	TCA L LTL Temp Out Of Limits-JPM	61	TCS	ITCS	14:26:06
	A	Node 3 MTL TWMV Overtemp-NODE3	62	TCS	ITCS	14:26:13
	C	LTL IFHX Out Temp High-JPM	63	TCS	IFHX	14:26:18
	A	Node 3 MTL REGEN TWMV Overtemp-NODE3	64	TCS	ITCS	14:26:32
	C	TCA L LTL Temp Abnormal-JPM	65	TCS	ITCS	14:28:47
	C	Node 3 MTL REGEN TWMV Overtemp-NODE3	66	TCS	ITCS	14:29:03
SARJ cmd feedback	A	SARJ DLAs Engaged and Locked-P3	67	EPS	SARJ	14:31:09
ITCS impacts	C	Node 3 MTL REGEN TWMV Overtemp-NODE3	68	TCS	ITCS	14:32:06
	A	Node 3 MTL REGEN TWMV Overtemp-NODE3	69	TCS	ITCS	14:32:08
	A	Node 3 MTL REGEN TWMV Undertemp-NODE3	70	TCS	ITCS	14:32:13
	C	Node 3 MTL REGEN TWMV Undertemp-NODE3	71	TCS	ITCS	14:32:15
	C	Node 3 MTL REGEN TWMV Undertemp-NODE3	72	TCS	ITCS	14:33:07
	A	Node 3 MTL REGEN TWMV Undertemp-NODE3	73	TCS	ITCS	14:33:22
	A	Node 3 MTL TWMV Overtemp-NODE3	74	TCS	ITCS	14:33:37

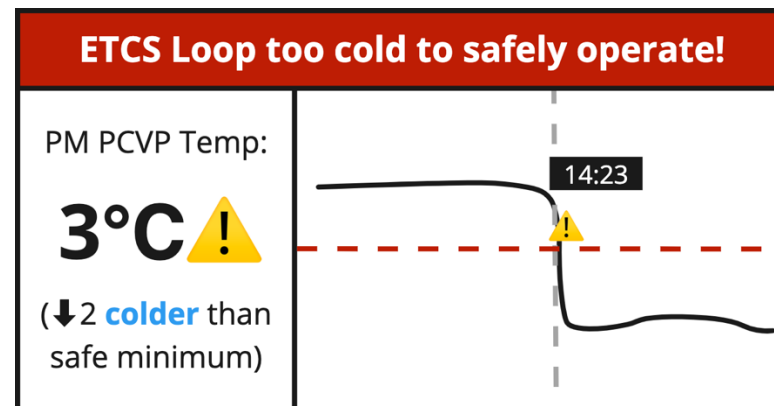
Contextualizing alarms with telemetry

- Some alarms could benefit from additional context of telemetry

ISS Current State

ETCS Loop A PCVP Temp Low-S1

Proposed for BLEO



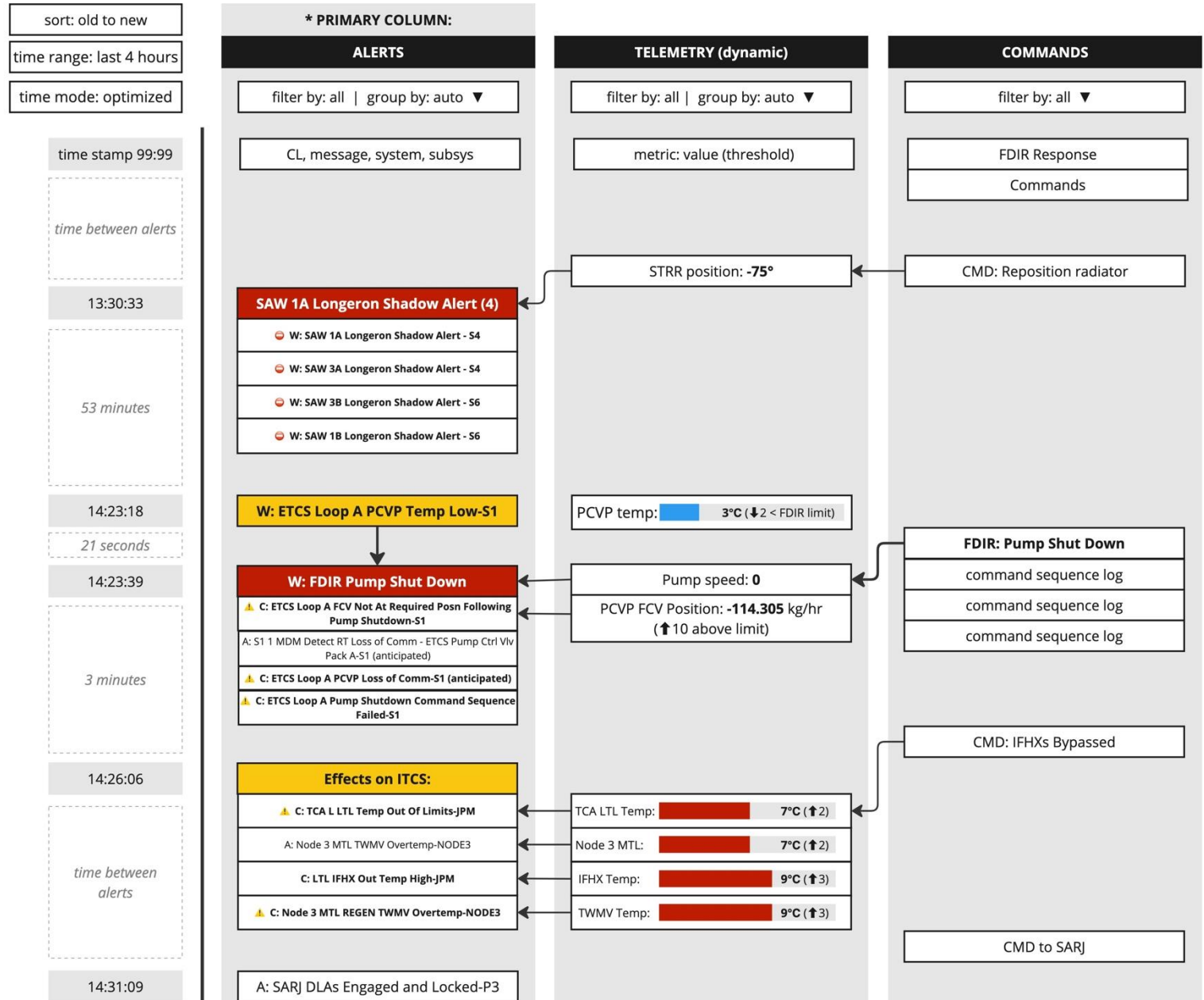


Attend: What is happening?

Caution and Warning Data Management

- Alerts for anomalous events
- FDIR limits and their implications
- Parent-child relationships noted; triaged

Mapping: *temporal*





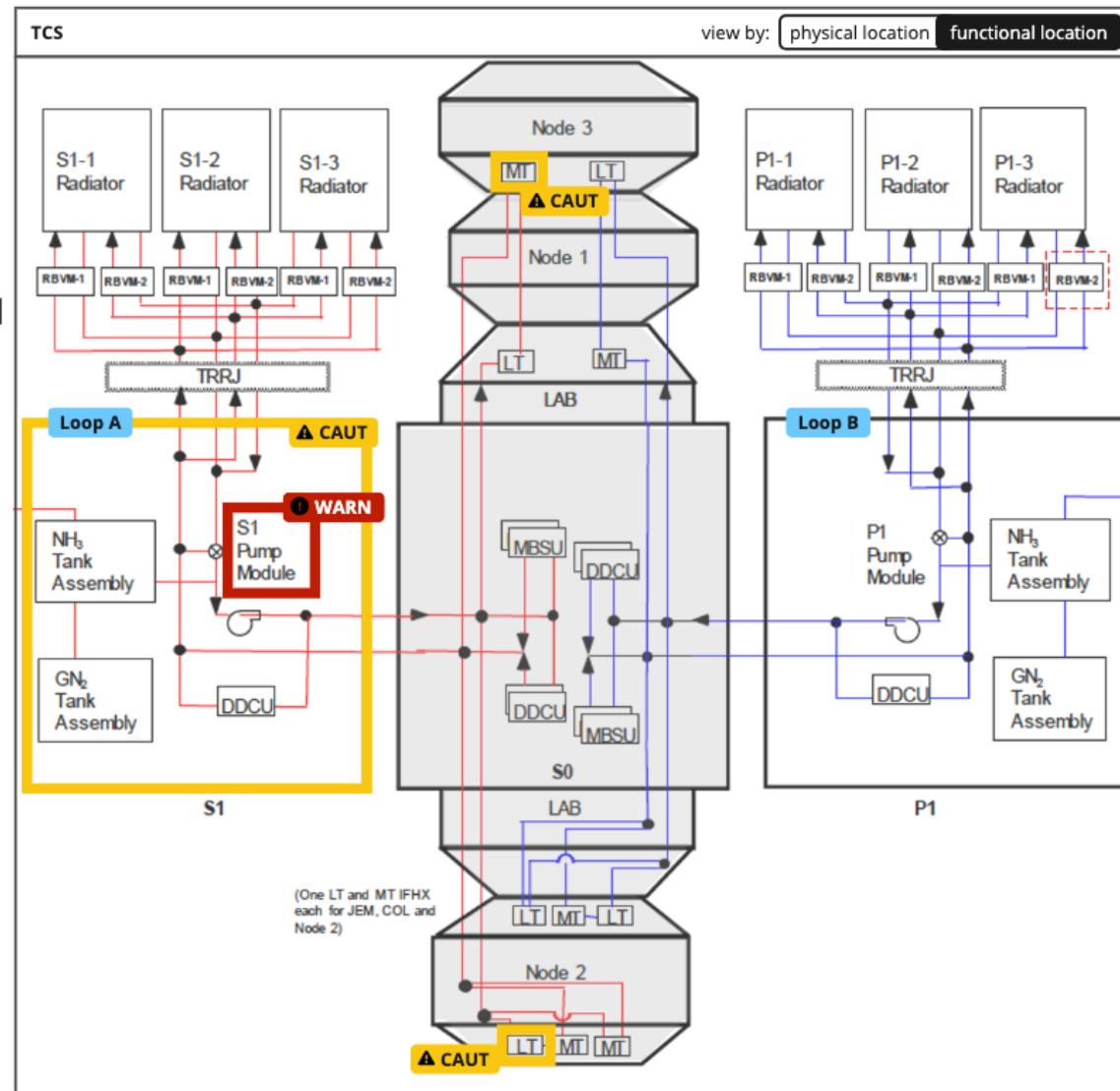
Attend: What is happening?

Caution and Warning Data Management

- Alerts for anomalous events
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Mapping: functional

Event in the TCS	
<p>CAUT Code 1644 TCS</p> <p>ETCS Loop A PCVP Temp Low-S1</p> <p>Enabled <input checked="" type="checkbox"/> Ack <input checked="" type="checkbox"/> 22 minutes ago</p>	23:18
<p>WARN Code 1644 TCS</p> <p>Loop A Pump Spd Low or PCVP Failed-S1</p> <p>Enabled <input checked="" type="checkbox"/> Ack <input checked="" type="checkbox"/> 22 minutes ago</p>	23:30
<p>CAUT Code 4444 TCS</p> <p>Loop A FCV Not At Required Posn Following Pump Shutdown-S1</p> <p>22 minutes ago</p>	23:39
<p>CAUT Code 4159 TCS</p> <p>Loop A PCVP Loss of Comm-S1</p> <p>22 minutes ago</p>	23:42
<p>CAUT Code 4444 TCS</p> <p>Loop A Pump Shutdown Command Sequence Failed-S1</p> <p>22 minutes ago</p>	24:05
<p>CAUT Code 11660 TCS</p> <p>TCA: LTL TEMP Out of Limits - JPM</p> <p>22 minutes ago</p>	26:06
<p>CAUT Code 15717 TCS</p> <p>MTL REGEN Overtemp - Node 3</p> <p>22 minutes ago</p>	29:03





Attend

Assess: How/why is it happening?

Detailed Event Analysis and Drill-Down Capabilities

- Information on downstream impacts and time frame
- Information on norms and ranges
- System manuals, logs
- Troubleshooting “cheat sheet”
- Information on possibly relevant past anomalies

Event Assessment Panel

Initiating alert:
C) ETCS Loop A PCVP Temp Low-S1

Event trigger:
ETCS Loop A PCVP temp went below safe threshold of 5°C at 23:18:01

FDIR Response:
- ETCS Loop A Pump shut down at 23:20
- ITCS Loop A IFHXs bypassed and isolated at 23:20

System Impacts:
- 24 systems dependent on ITCS loop A are not currently receiving cooling

Redundancies / contingencies:
Loop B 50% redundant

Related procedures:
event 1232: restart pump asap -->

Related documentation:
5.102 Lab and Airlock Component Thermal Constraints

Related past incident reports:
5.102 Lab and Airlock Component Thermal Constraints

System	Status	Est. time to effect
MBSU #1, 4	Uncooled	2 hours to overheat
E-DDCU #1, 4	Uncooled	2 hours to overheat
Sytem xyz	Uncooled	4 hour to overheat

ETCS Loop A

Loop A Pump Status: Off
Speed: 0
PCVP Temp: --
Accum Qty: --

ETCS Loop A Mode: --
Status: Shut Down
Temp: 3°C (& 2 below limit)
Flow rate: 0 (stopped)

ITCS Dependencies

Node	LT Temp	MTL Temp	Equipment list	Status	Est. time to effect
Lab ITCS	3°C	5°C	Equipment list	Uncooled	2 hours to overheat
Node 2 ITCS	3°C	5°C	Equipment list	Uncooled	2 hours to overheat
Node 3 ITCS	3°C	5°C	Equipment list	Uncooled	2 hours to overheat

Mapping:
Temporal
Contextual
Evidential
Causal

Event Assessment Panel

caution, 11:20:00, TCS

ETCS Loop A PCVP Temp Low-S1
Occurs when the ETCS loop A temp reaches below the threshold of xyz. Indicates loop is too cold to operate safely, risk of freezing IFHX.

related alerts:
warning, 11:20:00, TCS
Loop A Pump Spd Low or PCVP Failed-S1

triggered by:

PM PCVP Temp: 3°C
nominal: x-y
FDIR limit: z

FDIR response:
11:21: pump shut down to prevent potential freezing
- mitigated immediate threat of freezing IFHX
- pump is now off, equipment xyz no longer receiving cooling

assoc. procedures:
event 1232: restart pump asap -->

Alert Trigger view by: physical location functional location

Sensor p11 reliability: 87% installed: 109 days ago
Sensor p12 reliability: 87% installed: 109 days ago

sensor processing data flow: sensor p12 → channel 8 → MDM 2

Event assessment: information architecture concepts



Attend

Assess

Analyze: What can/should be done?

Trial Action Options/Plans

- Information on available resources
- Information on constraint-based timeline options
- Information on possible consequences of actions
- Information on sequence of actions determined to be executed (based on then information)

<i>Trial Options Planner</i>					
Failure: Loop A shut down					
Current objective: mitigate impacts of loss of cooling					
Recommended plan: options A + B Transfer all <u>priority level 1 systems</u> to contingency cooling, and raise the flow limit. Power down all <u>level 2 and 3 systems</u> .					
Option A: Transfer critical systems to loop B	Time: ~2 hours	Solution: Temporary	System Recommends		
Risks: Loop B will exceed capacity if all heat loads are transferred (time to effect: 2 hours)	Workarounds: <table border="1" style="width: 100%;"> <tr> <td>✓ Only transfer priority level 1 loads</td> </tr> <tr> <td>✓ Raise limit of Loop B 20%</td> </tr> </table>		✓ Only transfer priority level 1 loads	✓ Raise limit of Loop B 20%	<input checked="" type="checkbox"/> ^ ^
✓ Only transfer priority level 1 loads					
✓ Raise limit of Loop B 20%					
Option B: Shed heat loads	Time: ~1 hour	Solution: Temporary	System Recommends		
Option C: Use loop as is	Time: Immediate	Solution: Temporary	Not Recommended		
Accept Plan and Continue -->					

Decision support planning tool concept



Attend

Assess

Analyze

Act: It is resolved?

Automated Procedure Execution Oversight and Feedback

- Real-time feedback on procedure effects
- Automated alerts for rule violations or threshold breaches
- Status tracking to ensure successful execution and monitoring of procedures

ETCS Loop A pump successfully restarted

Loop A system configuration:

Status:	Run time:	Flow rate:
● Startup Mode	1 minute	99

Allows for minimal loop functions with Ammonia temps below 1.7°C and heat exchangers bypassed.

i Startup mode is not designed for long term use.

Loop Temperature:	Heat exchangers:
0°C	bypassed
nominal: -35 to -20	heaters: off

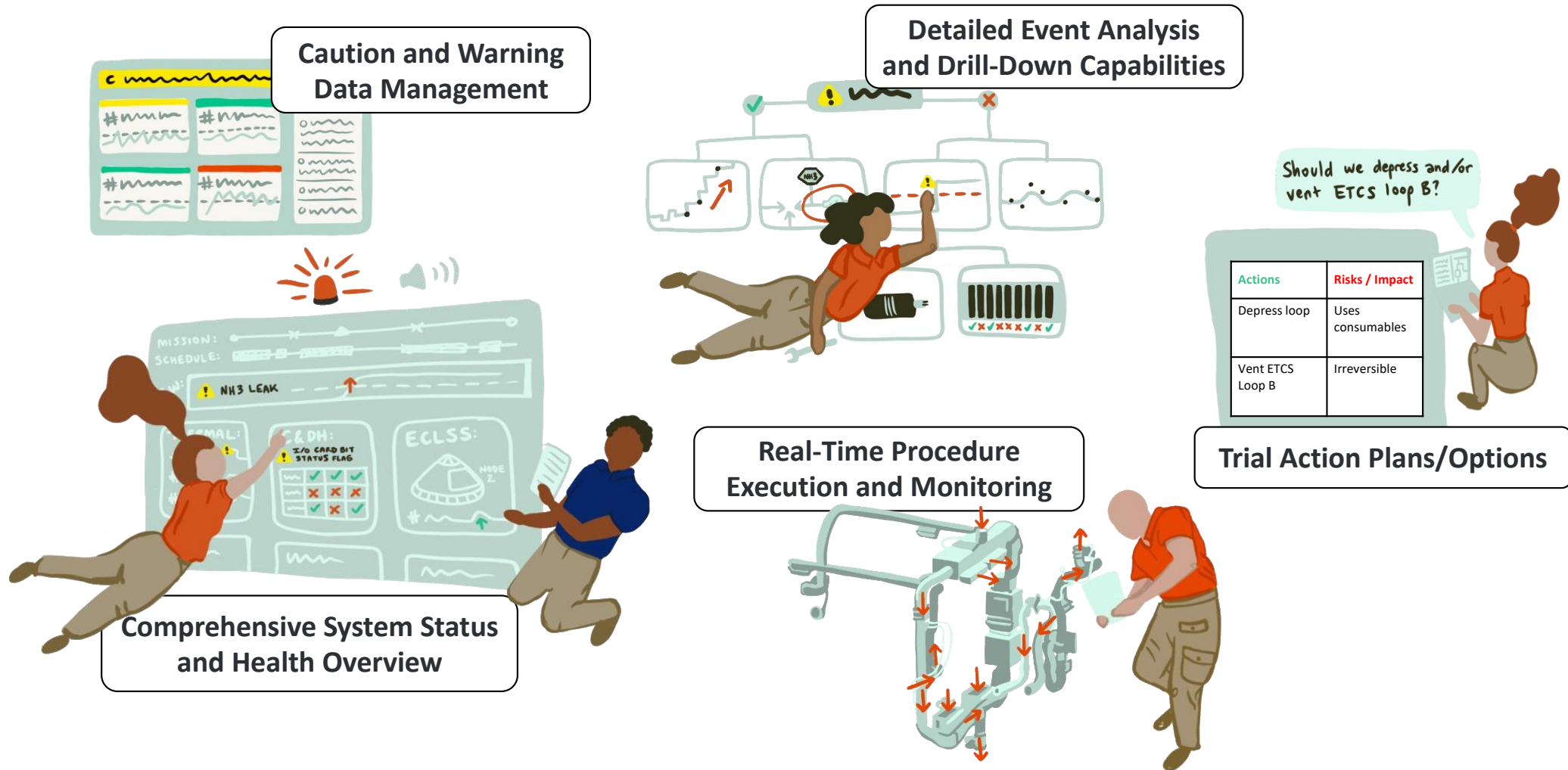
i Pump module low temp shutdown FIDRs inhibited	i Ammonia being routed through <u>bypass line</u>
--	--

Associated procedures:
Startup mode safety checklist

Next worse failure:
EATCS Loop A ammonia depress

Procedure effects dialogue

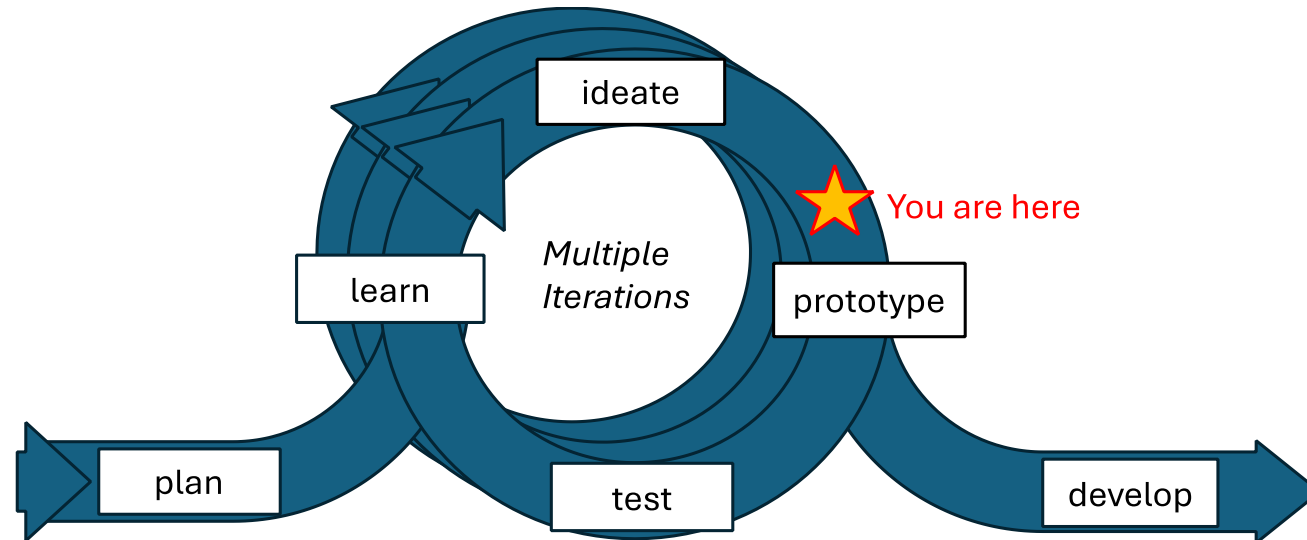
Content and Representation of Information Needed to Support Time-Constrained Problem Solving



Summary: Deliverables

- ✓ 1. Annotated literature search on information needed/used for problem solving
- ✓ 2. Common themes and features of problem-solving models used in time-constrained contexts
- ✓ 3. Conceptualization of information content and representation incorporating these problem-solving themes/features and informed by ISS data model
- ✓ 4. Countermeasure concepts and requirements to support time-constrained, crew-reliant problem solving and decision-making during procedure execution and anomaly resolution
- ✓ 5. Findings integrated with deliverables from Mapping BLEO Task (i.e., beyond LEO HSIA anomaly response specifying crew roles and responsibilities, teaming, and interactions with onboard systems and delayed ground support)

Summary



- Concepts firmly grounded by substantial research (problem solving and solvers, mental modes, etc.) and needs analyses
- Some questions still remain (e.g., How much info is too much? How much context is too much?)
- Testing and maturation now needed to progress designs



Thank you!