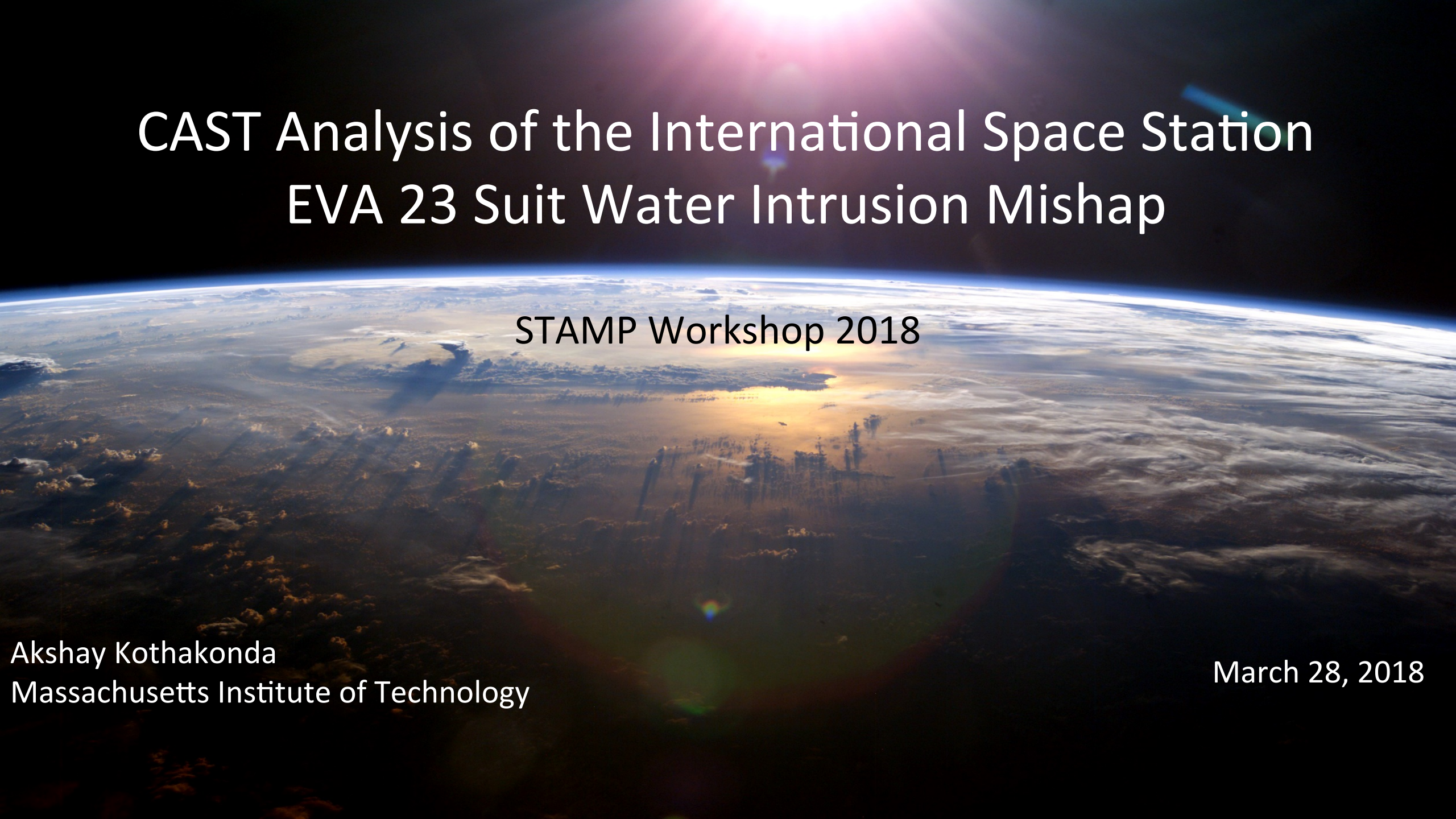

CAST Analysis of the International Space Station EVA 23 Suit Water Intrusion Mishap

STAMP Workshop 2018

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Background and Events Leading up to EVA 23

EVA 23 Crew

EV1 (Chris Cassidy) had completed five EVA's, totaling almost 30 hours and EV2 (Luca Parmitano) had completed one EVA, lasting 6 hours

EVA 21

During EVA 21 on May 12, 2013, the suit that leaked was **used without any issues**

EVA 22

- EVA 22 on July 9, 2013 **had the same crew and suits as on EVA 23**
- **½ to 1 liter of water** was found in EV2's helmet post EVA
- EV1 reported not seeing any water in EV2's helmet during airlock repress and EV2 was looking down and leaning forward during this time
- Based on this, the **crew incorrectly concluded** the water entered the helmet during repress as EV2 pressed the drink bag with his chest and pinched bite valve open with his chin
- The ground team accepted this theory and there was **no further investigation**
- **There was no discussion** of water leakage during EVA 23 pre-briefs

Events During EVA 23

EVA 23

- Roughly 38 minutes into the EVA 23 (July 16, 2013), Parmitano had a "**CO2 Sensor Bad" alarm**
- Another 6 minutes later, he **reported feeling water** on the back of head and neck
- The water was **reported to increase** over the next 10 minutes
- Cassidy **visually confirmed** the pooling of water
- The **source of the water was not identified** by the EVA crew or the ground and the EVA crew continued to work
- The ground eventually called for an **EVA Termination 23 minutes after Parmitano first reported water**
- During translation back to airlock, **water migrated to front of the face**, covering his eyes, nose, and ears; and soaking his communications cap
- This **caused severe visibility, breathing, and communication issues**
- After repress, the suit was doffed expeditiously and **1 to 1.5 liters of water was found**

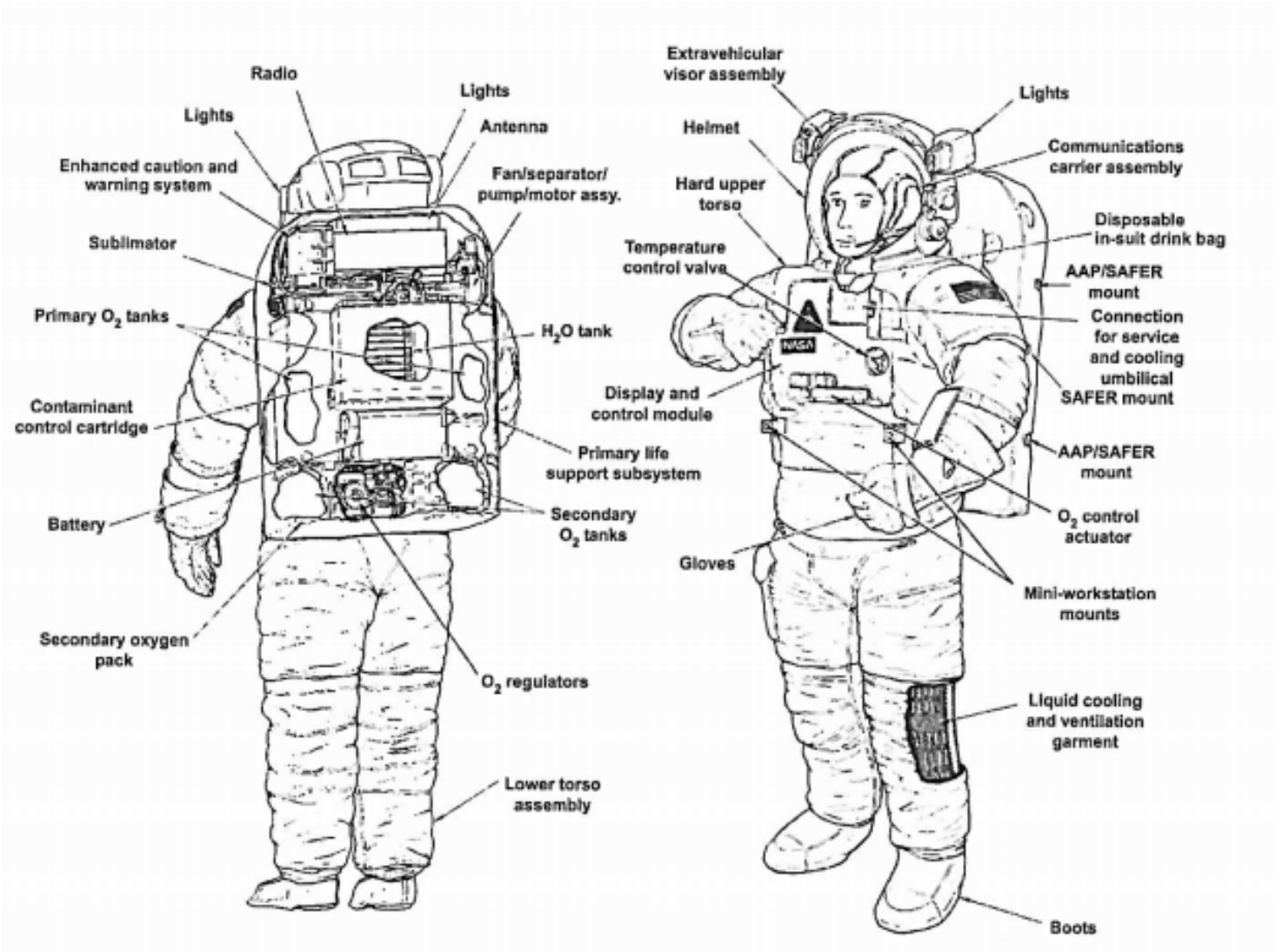
NASA Investigation

- Initial troubleshooting was performed by the flight crew
- The ISS Program convened a Mishap Investigation Board (MIB) to investigate this **High Visibility Close Call** (HVCC)
- **Event and Causal Factor Tree (ECFT)** was developed which identified proximate, intermediate, and root causes, and contributing factors
- **Several observations were made** through course of investigation that could improve ISS operations
- **Recommendations were drawn** from these tasks
- **Human factors analysis performed** using DoD Human Factors Analysis and Classification System (HFACS)
- Mishap was found to be due to **inorganic materials** blocking the drum holes in the EMU water separator, resulting in water spilling into the vent loop
- **Source of inorganic materials has not been found**
- MIB report and this study focus on **why water intrusion after EVA 22 was not investigated** and **why EVA 23 was not immediately terminated**

Why do a CAST Analysis?

- Enables one to **better dissect the complex interconnected organizational and real time flight operations structure** of the ISS Program
- This gives a more **realistic and transparent picture** of why this incident occurred
- It allows for generation of a **more comprehensive list of recommendations**
- Overall, it offers a **clearer understanding of the mishap**
- Provides an opportunity to **compare the results of an event based approach with a systems theory based one**

Extravehicular Mobility Unit



Safety Control Structure

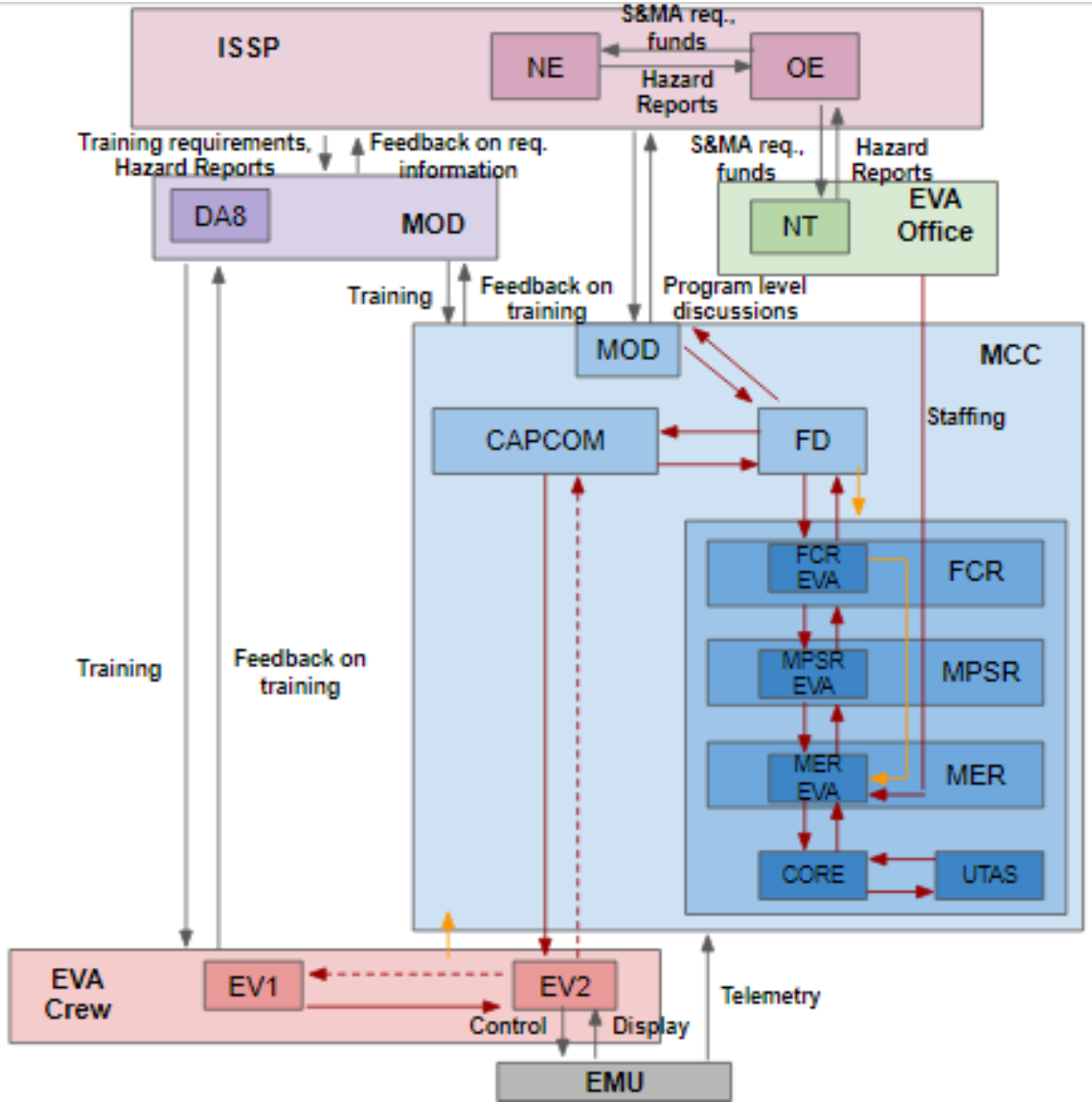
Acronyms:

EVA	Extravehicular Activity
EMU	Extravehicular Mobility Unit
EV1	Extravehicular Crew 1 (Chris Cassidy)
EV2	Extravehicular Crew 2 (Luca Parmitano)
MCC	Mission Control Center
FD	Flight Director
CAPCOM	Capsule Communicator
MOD	Missions Operations Directorate
FCR	Flight Control Room
MPSR	Multi-Purpose Support Room
MER	Mission Evaluation Room
CORE	Central Operations Room for EVA
UTAS	United Technologies Aerospace Systems
DA8	Flight Safety Office
NT	EVA Safety and Reliability Group
ISSP	ISS Program
NE	ISS Safety Division
OE	ISS S&MA/Program Risk Office
S&MA	Safety and Mission Assurance

Voice

Interrupted Voice

Voice Loop (one way)



Physical Safety Controls

Constraints Violated	• Filter impurities in EMU • Keep water from getting into vent loop
Safety Equipment	• CO2 Sensor • EMU Helmet Purge Valve
Failure/Inadequate Controls	• Inadequate filtration of impurities • Fan-Pump-Separator failure due to impurities
Physical Contextual Factors	• EMU initially certified for single Shuttle mission, is now certified for six years on board ISS • Erroneous CO2 sensor reading normalized over time

EVA Crewmembers

Safety Responsibilities	• Diagnose EMU problems • Make judgement call to abort/terminate
Context	• Training did not cover water in helmet • Water intrusion after EVA 22 not investigated
Unsafe Decisions/ Control Actions	• Did not communicate water temperature • Did not request termination immediately
Process Model Flaws	• Crew influenced by drink bag leakage theory • Concurred with ground's recommendation to continue with EVA

Mission Control Center

Safety Responsibilities	• Diagnose problems during EVA operations and investigate post-EVA • Constantly refresh training and system knowledge
Context	• Under extreme time pressures to prepare for EVA23 after EVA 22 • Water in helmet normalized and training did not cover this • There were multiple simultaneous communication loops
Unsafe Decisions/ Control Actions	• Did not investigate water leak after EVA 22 • Did not terminate EVA 23 as soon as water was reported
Process Model Flaws	• There was an unsubstantiated perception that drink bags leak • There was a feeling that investigation into EVA 22 water leak would be time consuming

Mission Operations Directorate

Safety Responsibilities	• Create operational procedures • Train and provide simulations to Flight Control
Context	• Consequences of water leakage was not understood and normalized • Simulations expected finding solutions instead of terminating
Unsafe Decisions/ Control Actions	• Failure mode of water leakage not covered in flight rules and training • MOD EVA Lessons Learned Archive lacks descriptions of failures prior to STS-88
Process Model Flaws	

EVA Office

Safety Responsibilities	• Identify hazards and provide QA in EMU and EVA • Integrate safety actions with rest of ISS
Context	• Ground testing of behavior of water in EMU was less severe • ISS Program had no requirement to review EMU FMEA/CIL • Attrition in suit expertise
Unsafe Decisions/ Control Actions	• Did not understand severity of water in EMU • Updates to FMEA/CIL not comprehensive • Water in helmet and CO2 sensor errors normalized
Process Model Flaws	• Based on ground tests, water in EMU was deemed to not be a hazard

ISS Program

Safety Responsibilities	• Ensure all ISS systems have completed SMA processes • Chairing ISS Safety Review Panel
Context	• Budget cuts affected planned review of EMU FMEA/CIL • SMA process for EVA separate from rest of ISS and is managed by EVA Office
Unsafe Decisions/ Control Actions	• Emphasized maximizing crew time for mission over safety tasks • Did not require periodic review of EMU FMEA/CIL • No requirement for EVA/EMU training of MER Safety Team
Process Model Flaws	• Updating FMEA/CIL was thought of as mere paperwork and did not receive the attention warranted

Recommendations

- MOD to develop flight rules for water intrusion and train accordingly. This includes investigating helmet purge valve operation and reviewing and detailing procedures that require crew to contact ground
- MOD should train FCT and EVA crew in prior EMU failures including using simulations
- MOD should train MER Safety Team in EVA systems and be made a requirement by ISS Program
- Simulations should allow for FCT to terminate/abort an EVA
- MOD should implement channels to allow lower level flight control elements to have a more direct access to Flight Control Room and Flight Director
- Flight Safety Office should enforce best practices to address known failure modes and normalized deviations within MOD SMA program

Recommendations (continued)

- Possibility of asphyxiation should be included in FMEA/CIL by EVA Office and enforced by ISS Program
- ISS Program along with MOD and EVA Office should review cases where deviations are normalized (for instance presence of small amounts of water in helmet causing fogging) and address them. This should be done for wider ISS Program. Other examples include CO2 sensor and sublimator inefficiency.
- ISS Program along with MOD and EVA Office should review and update FMEA/CIL and address failures. With resources from ISS Program, EVA Office should update and release EMU lessons learned, system development, design and flight procedure rationales. These may be included in training programs.
- ISS Program should have better oversight over FCT in reporting anomalies
- ISS Program should encourage culture of prioritizing astronaut safety and of anyone being able to voice safety concerns to higher management

Recommendation (continued)

- ISS Program should review implications of changing water quality and chemistry on ISS systems
- ISS Program should review acceptability of EMU's six year certification
- ISS Program should require periodic review of FMEA/CIL of ISS systems

Conclusion

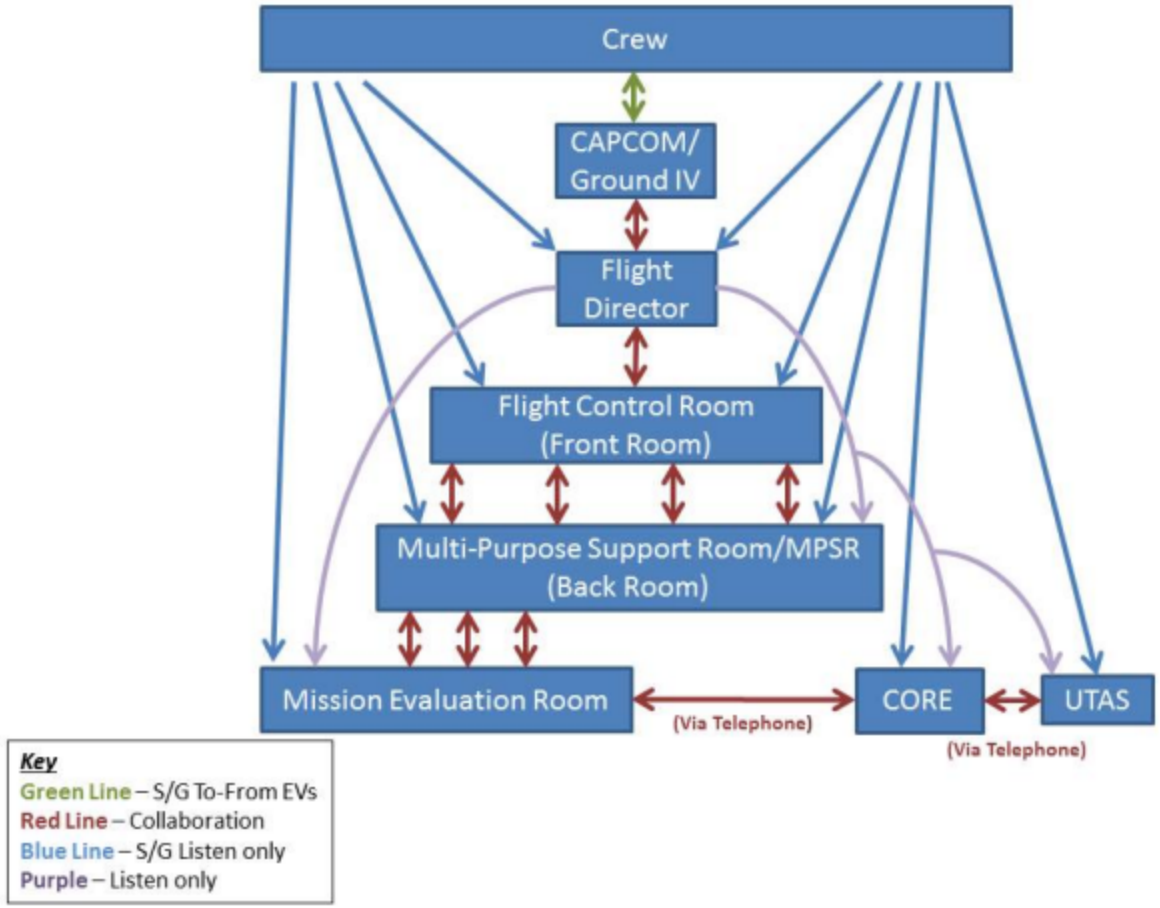
- CAST provided a **highly systematic analysis process** for a very complex socio-technical system
- This resulted in a **highly efficient** process
- **More number of significant safety recommendations** were generated using CAST than that using event-based approach

References

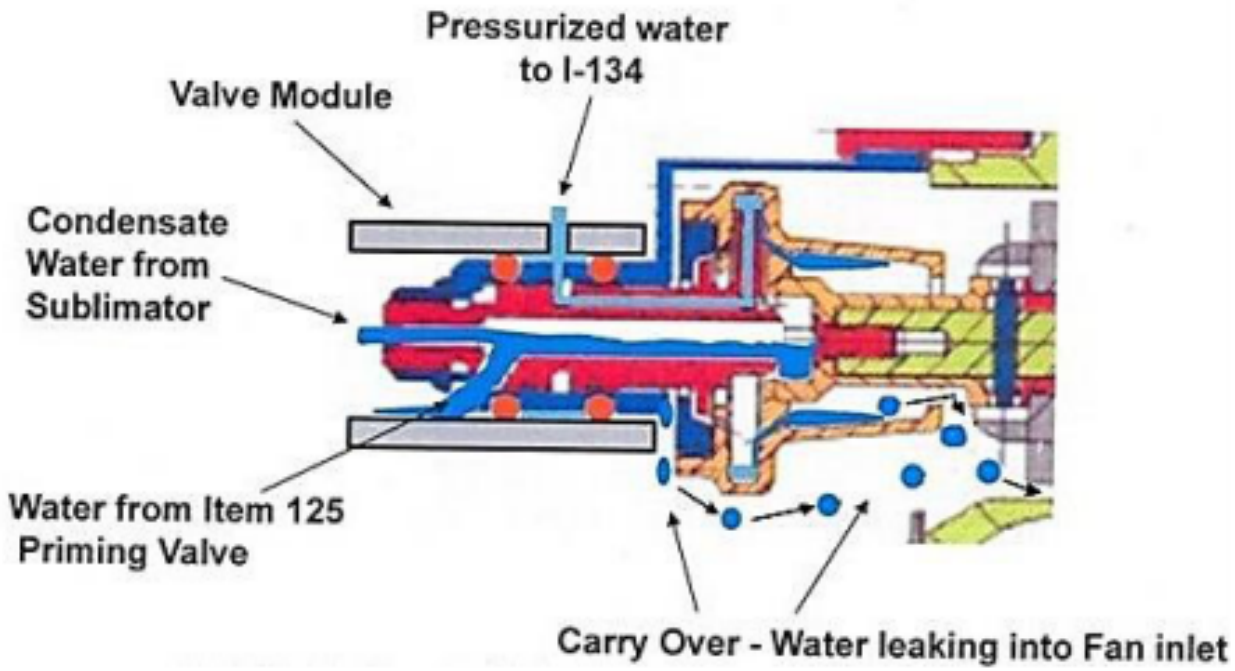
- *NASA Mishap Investigation Report: ISS EVA Suit Water Intrusion High Visibility Close Call, IRIS Case Number: S-2013-199-00005*
- *Hansen, C., Cassidy, C. (2014) Mishap Investigation Board Summary of Extravehicular Activity 23: Lessons Learned From a Spacewalk Close Call. Journal of Space Safety Engineering, Vol. 1, pages 32-39*
- *Kothakonda, A. (2015). Design of Sensor System to Detect Presence of Anomalous Water in Air Lines in the Extravehicular Mobility Unit. Journal of Space Safety Engineering, 2(2), 74-78.*

BACKUP SLIDES

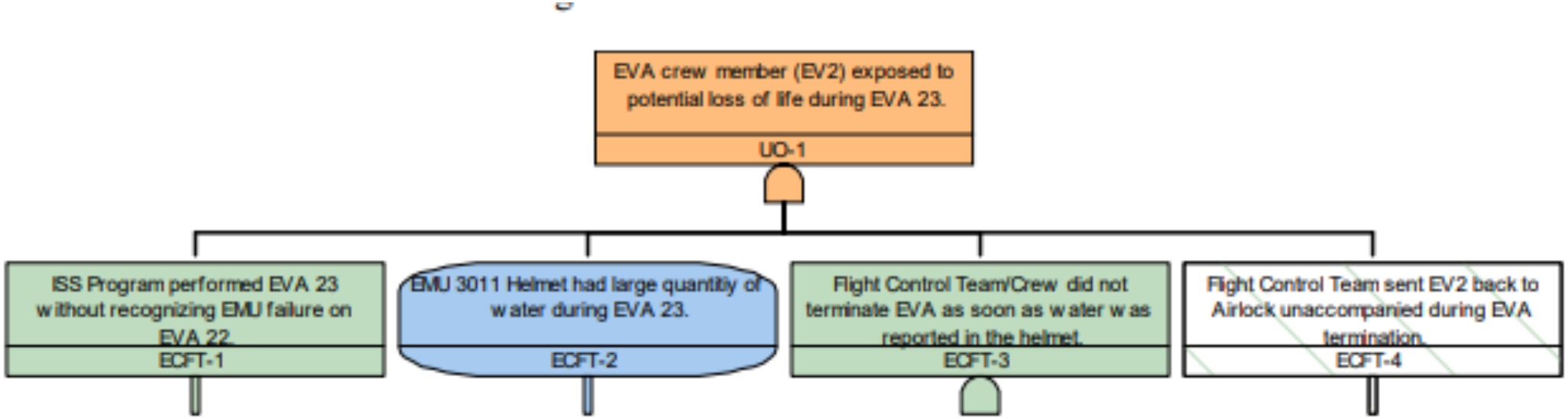
EVA Communication Paths



Water Separator Spinning Drum and Pitot Components



ECFT Proximate Causes



Physical Safety Controls

Safety Requirements and Constraints Violated:

- Filter impurities in the Extravehicular Mobility Unit (EMU) so that they do not adversely affect system performance
- Keep water from getting into the vent loop
- Provide accurate information of the system and suit environmental condition

Emergency and Safety Equipment:

- CO2 Sensor (although not meant for this purpose, it gives an indication of moisture and water in the vent loop)
- EMU Helmet Purge Valve

Failures and Inadequate Controls:

- Inadequate filtration of impurities in the suit
- Inadequate CO2 sensor design
- Fan-Pump-Separator failure due to impurities
- Inadequate provisions in the EMU helmet system to keep water from causing visibility, breathing, and communication issues

Physical Contextual Factors:

- The EMU was initially designed for the Space Shuttle Program. With its purpose of serving as a backup system in the event of certain Shuttle failure modes, it was designed as a single fault tolerant system with abort capability within time to effect. It later evolved into a workhorse for ISS construction, Hubble Repair Missions and other Extravehicular Activity (EVA) requirements. Although system changes took place to support this new role, much of the fault tolerance from the legacy system remained.
- The erroneous off-scale reading of CO2 sensor in presence of moisture was normalized over time
- There was uncertainty regarding the safety and effectiveness of using the Helmet Purge Valve to remove free water from the helmet. The concern was that the water passing through it would freeze and damage the valve. The operation of purge valve to remove water was never investigated.
- The 6 year certification of EMU's may not be practical. EMU is not maintainable on orbit.
- Changing water quality on ISS affects EMU.

EVA Crewmembers

Safety Related Responsibilities:

- Communicate all relevant information on the status of the EMU suit and the development of the failure to the ground
- Make judgement calls to terminate/abort or continue with EVA in a possible hazardous condition
- Use training and knowledge in the EMU system to try to diagnose a problem

Context:

- EVA training did not cover the possibility of a significant amount of water in the helmet. Flight Rules were inadequate to respond to this event.
- The discovery of water at the end of EVA 22 was falsely attributed to the drink bag and was not investigated further. The same assumption influenced EVA crew's actions.

Unsafe Decisions and Control Actions:

- Did not communicate important critical information like the temperature of the water, which could have helped the ground to focus on a source other than the drink bag
- EVA crew did not request EVA termination as soon as a significant amount of water was felt by EV2 (Parmitano).

Process Model Flaws:

- EV2 was relatively inexperienced in EVA's and did not see the presence of water as being particularly abnormal or hazardous at the end of EVA 22 and during EVA 23 (EVA 22 was Parmitano's first EVA)
- The EVA crew were influenced by the prior assumption and also from ground communications that the source of water was the drink bag, although EV2 later realized that it was likely not the case
- Before EV1 (Cassidy) got a visual on EV2's helmet, the EVA crew concurred with the ground team's recommendation to continue with the EVA as they thought the quantity of water was not increasing

Mission Control Center

Safety Related Responsibilities:

- Use crew communications and telemetry, system and safety knowledge to diagnose a problem and instruct crew accordingly with regards to safe EVA operations, all in a given time
- Investigate anomalies that carry a hazard to the crew
- Ensure systems are adequately safe for crew operations
- Constantly refresh training and system knowledge, as well as keep updated on trends in system safety

Context:

- The ground team was under extreme time pressures to prepare for EVA 23 after EVA 22
- Shifts were changing after EVA 22 and many questions pertaining to the water intrusion may not have been followed up on
- Training and flight rules did not cover the failure mode of water leakage in EMU and a small amount of water in the helmet was normalized.
- CO2 sensors usually erroneously show an off scale high reading due to presence of moisture in the vent loop towards the end of an EVA
- As this failure was not encountered before, the ground team was unprepared and it quickly led to task oversaturation
- Due to multiple communication loops active simultaneously, the ground team was unable to adequately comprehend EV2's remarks on water source

Unsafe Decisions and Control Actions:

- Did not invoke an investigation into the source of water in the helmet when it was discovered at the end of EVA 22. Accepted the EVA crew's theory that the source of water was the drink bag.
- The presence of water in the helmet at the end of EVA 22 was not discussed during EVA 23 pre-briefs
- Failed to pay attention to the CO2 sensor failure; doing so could have led to an earlier EVA termination
- Did not terminate the EVA as soon as water was reported in the helmet during EVA 23
- Failed to ask critical questions like the temperature of water (and focussed for the most part on drink bag), which could have helped understand the severity of the situation sooner

Process Model Flaws:

- There was a wide perception that drink bags leak, which is unsubstantiated. This led to channelized attention to that as the water source and failure to explore other possible sources. This also led to not recognizing the severity of the situation because if the source was the dring bag, it was self limiting and could be expended by drinking.
- The reluctance to initiate an investigation into the water leakage after EVA 22 was due to the feeling that such a formal investigation is resource intensive and is not worth taking time away from the EVA 23 preparations as it would probably turn out to be a non issue
- Faulty CO2 sensor reading was normalized and was not thought of being indicative of a bigger problem, despite failing at the start of the EVA as opposed to towards the end when they usually fail
- The ground team thought the water in the helmet was not increasing

Mission Operations Directorate

Safety Related Responsibilities:

- Create operational procedures
- Train and provide simulations to the Flight Control Team
- Provide comprehensive and updated technical resources to the Flight Control Team

Context:

- Although EMU Failure Mode Effects and Analysis (FMEA) / Critical Items List (CIL) contain the failure modes of Portable Life Support System (PLSS) water entering vent loop and the helmet, they did not identify the catastrophic nature of the failure (due to incorrect assumptions of behaviour of water in the EMU suit in zero-gravity). The EVA community did not understand the consequences of water carryover in the EMU suit.
- Minor amounts of water in the vent loop from sublimator was normalized
- EVA simulations are very expensive and in order to maximize output, simulation situations usually require the Flight Control Team to find a solution instead of terminating early. This creates a mindset to tend to not terminate an EVA especially if a failure occurs towards the beginning.

Unsafe Decisions and Control Actions:

- The failure mode of water leakage was not covered by flight rules and training/simulations to handle such a scenario are not carried out. The procedure that addresses the failure mode of excess water in helmet most closely applies in the event of substantial amount of LiOH contaminated water entering the EMU helmet. Even this procedure is inadequate and simply requires the EV crew to contact Mission Control.
- Although EMU FMEA/CIL contained several instances of EMU vent loop/water loop interface causing water leakage into vent loop, studying the failure modes by the EVA flight controllers is given very little importance by MOD. Very little training in EMU is available to the safety team and is not required.
- The MOD EVA Lessons Learned Archive document lacks the detailed description of past failures, especially those prior to STS-88.

Process Model Flaws:

EVA Office

Safety Related Responsibilities:

- Identify hazards and provide quality assurance in EVA and EMU. Make the information available to the ISS community
- Identify trends in EVA/EMU safety and apply corrective actions. Document these actions and rationale and make them available to the ISS community.
- Take steps to ensure EVA/EMU systems and their hazards are integrated with rest of the ISS systems, including but not limited to providing support to the ISS Safety Review Panel
- Provide staffing to Mission Evaluation Room (MER) EVA and support ISS Safety in MER during EVA's

Context:

- Ground testing of behaviour of water in an EMU showed a less severe picture than what was seen in the zero-g environment.
- ISS Program had no requirement to perform periodic review of EMU FMEA/CIL. Budget cuts also added to why FMEA/CIL was not reviewed and updated. Many of the EMU design and failure related documentation are incomplete or not updated.
- There has been an attrition in suit expertise caused due to many experienced personnel retiring and the suit reaching maturity. The workforce in general has diminished. Attempts to counter the loss in expertise by documenting the lessons learned and capturing the knowledge of the suit's legacy and development possessed by the suit experts has been limited due to shortage of budget and time. Moreover, departure of experts occurs faster than the information can be captured.
- The remaining staff within EVA Office are stretched thin with covering mission related tasks and availability to capture backlog of EMU lessons learned is extremely limited

Unsafe Decisions and Control Actions:

- Did not understand the severity of water carryover in EMU and hence the possibility of asphyxiation by the astronaut is not mentioned in FMEA/CIL
- Updates to FMEA/CIL are not comprehensive and usually only minimal changes are made
- Did not address the issues of small amounts of water in helmet from sublimator due to slurper inefficiency (which can cause eye irritation due to its interaction with anti-fog agents and also cause visor fogging). Also did not address frequent off-scale failures of CO_2 sensor towards the end of an EVA due to moisture in the vent loop. Both of these issues were normalized which contributed to the not understanding the severity of the hazard during EVA 23.

Process Model Flaws:

- Based only on ground tests, the behaviour of free water in the complex environment of an EMU was deemed not to be a hazard, which turned out to be false in the case of a zero-g operation

ISS Program

Safety Related Responsibilities:

- Carry out Safety and Mission Assurance (S&MA) tasks for non-EVA ISS systems
- Ensure all ISS hardware and software have successfully completed the Safety and Mission Assurance (S&MA) processes in order to minimize risk to crew and vehicle by providing integration across ISS program
- Chairing the ISS Safety Review Panel
- Provide staffing for ISS Safety position in MER (ISS Safety Division)
- Sustaining Engineering provides engineering support in MER

Context:

- Budget cuts adversely affected the planned review of EMU FMEA/CIL
- S&MA process for EVA is separated from that of all other systems and is managed by the EVA office
- ISS Program requires EMU's to meet a six year certification and the suit is not maintainable on orbit

Unsafe Decisions and Control Actions:

- Emphasized maximizing crew and ground team time and resources for mission related activities over safety and troubleshooting
- Did not require periodic review of FMEA/CIL- in this case for EMU
- Funding for an underway comprehensive review and updating of EMU FMEA/CIL and hazard reports was cut
- There was no requirement for EVA/EMU training of the Safety Team supporting MER

Process Model Flaws:

- Updating FMEA/CIL was thought of by many in the ISS community as a mere paperwork exercise and did not receive the attention that was warranted