Fault Management on Manned Spacecraft From Design to Operations

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Agenda

- Fault Management dimensions
- Fault Management analysis
- Real-time Fault Management
- Learning from Real Failures
- Evolution of on-board Fault Management Approach

Fault Management Dimensions

- Fault Management is accomplished in several dimensions:
  - Spacecraft Fault Tolerance, redundancy and margins
  - Subsystem Hardware, **Firmware and Software capabilities for Failure Detection Isolation and Recovery (FDIR)**
  - System-Level FDIR
  - Role of the Spacecraft Crew and Mission Control Center (MCC) in Fault Management

Spacecraft Fault Tolerance

- How much system degradation can you take, and still accomplish your mission or bring the crew safely home?
  - Independent Strings of HW/FSW for critical functions
    - Power – Generation, storage and distribution.
    - Avionics – Command & Control Computers, On-board Data Network
    - Environmental Control – Cabin Air Revitalization, Pressure Control
    - Guidance, Navigation & Control – Attitude Control, State Determination
    - Thermal Control – Cooling Loops, and Heaters.
    - Communications – Telemetry/Commands & Voice.
    - Mechanisms – Mechanisms for Critical Equipment/Functions
      - Deployment of Solar Arrays, Radiator, Antennas, parachutes, etc
    - Propulsion – Propellant Management, Engines

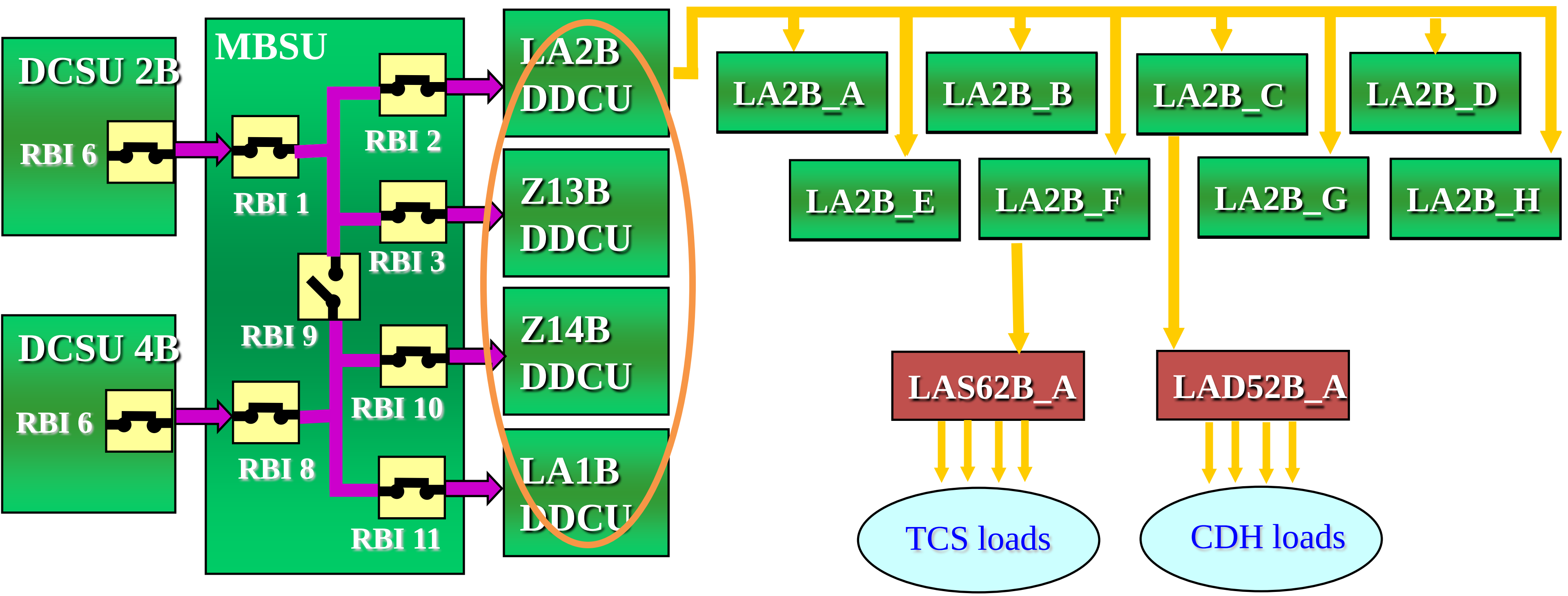
Spacecraft Robustness

- How much system degradation can you take, and still accomplish your mission or bring the crew safely home?
  - Margins of Critical Consumables
    - Power – Ability to accomplish the mission or preserve crew safety with half of power available
    - Thermal –
      - Ability to accomplish the mission or preserve crew safety with half of cooling loops + maximize thermal clocks upon the loss of heating/cooling
      - Ability to survive at different attitudes for some period of time
    - Air –
      - CO_2 removal capability
      - O_2 generation, humidity removal, etc
    - Propellant – Maximizing the options to get to and return from destination (burns)

Subsystem FDIR Responsibilities

- Expectations for Each Subsystem
  - Provide the necessary level of Subsystem FDIR over all components within Subsystem boundary
  - Report all faults and health status
  - Evaluate sensor inputs to determine their validity and infer sensor health
  - Evaluate data inputs from subsystem components to determine validity and respond accordingly
- Key Objectives of Subsystem FDIR
  - To ensure safe operation of the Subsystem
  - To maintain functionality through available local redundancy
  - To prevent fault propagation beyond the subsystem boundary
  - Provide the necessary monitoring and functional tests as determined by safety analysis to identify and report latent faults or hazardous conditions and support:
    - Situational awareness for crew and ground
    - Initiation of system-level and/or higher level recovery actions

System-Level FDIR scenario

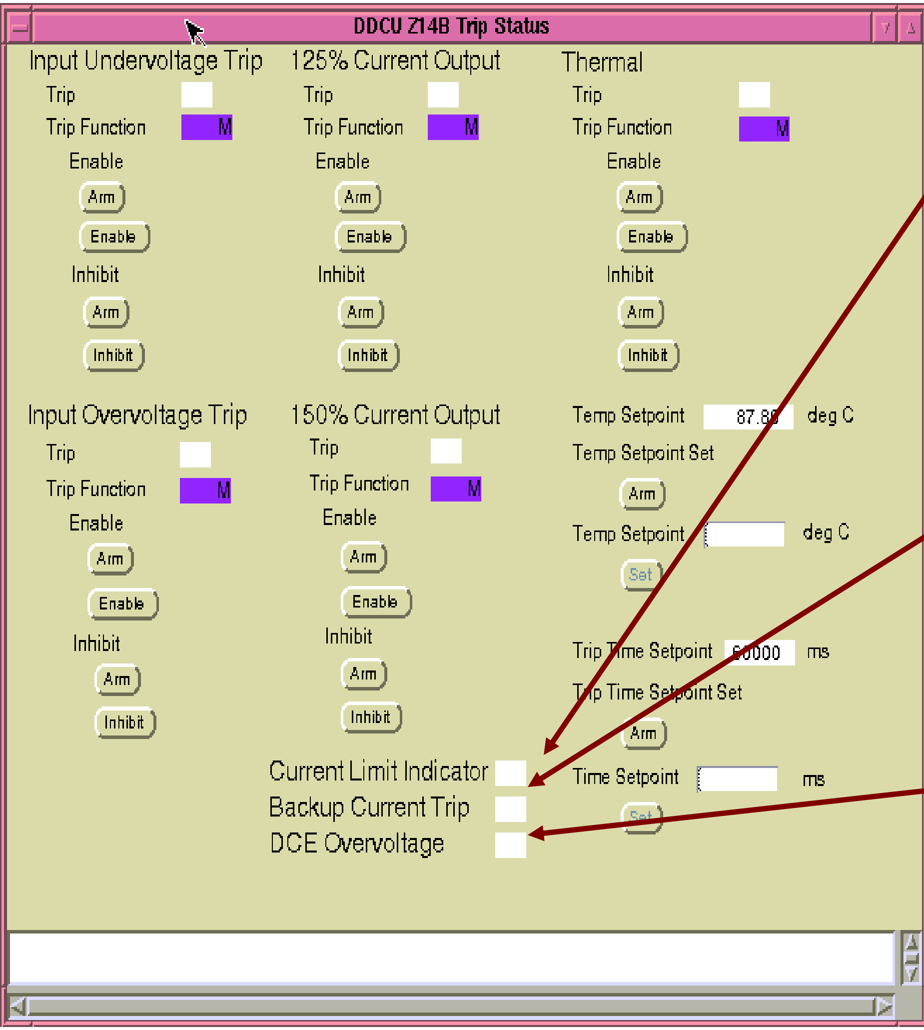


DC-to-DC Converter Unit

Converts Power from Primary Voltage ~150-160 Vdc to 123Vdc

DDCU has several FDIR capabilities due to it's function, and the lack of such up-stream and down-stream

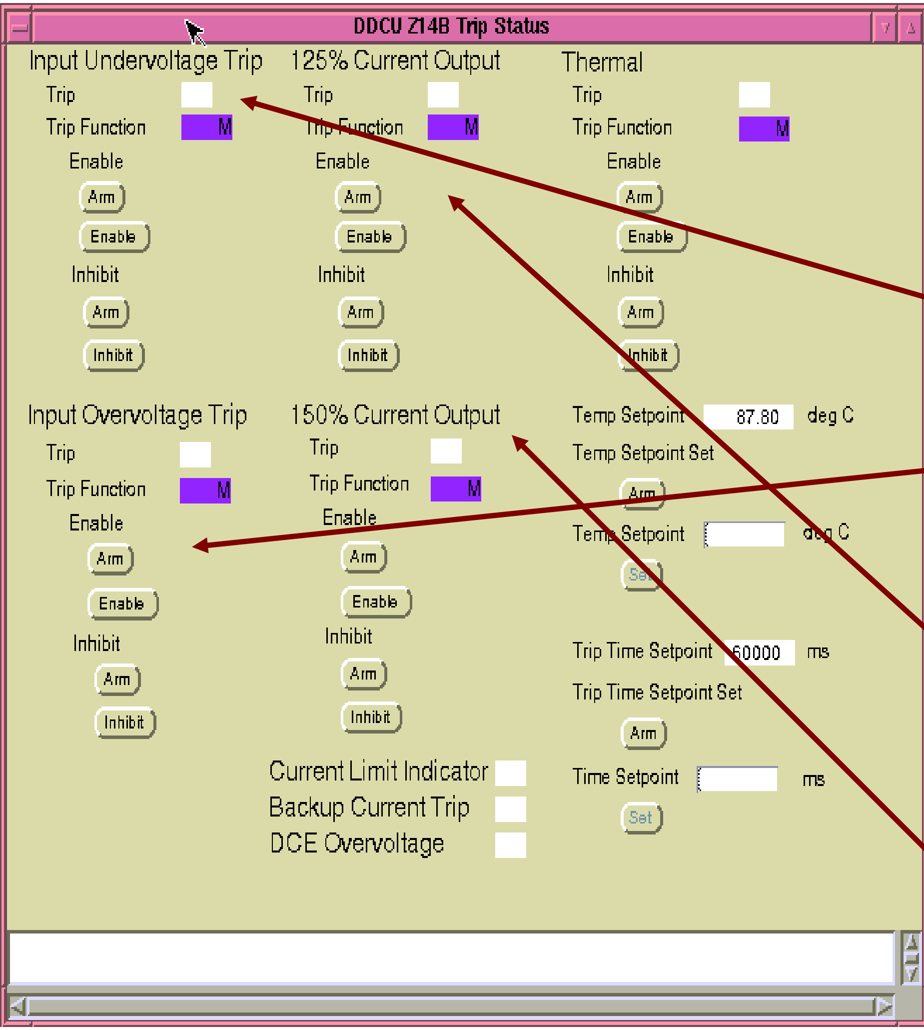
Subsystem FDIR Example- HW



DDCU HW FDIR

- Current Limit = The DDCU will limit the amount of current available to the load (Iout = 78-82 A) rather than regulate the secondary bus voltage.
- Backup Current Trip = Iout > 65A for 95-105 ms or current limit > 50-55ms
- DCE Overvoltage = 153 ± 2 Vdc for 10 µs
- HW FDIR has no functional inhibits

Subsystem FDIR Example- FW

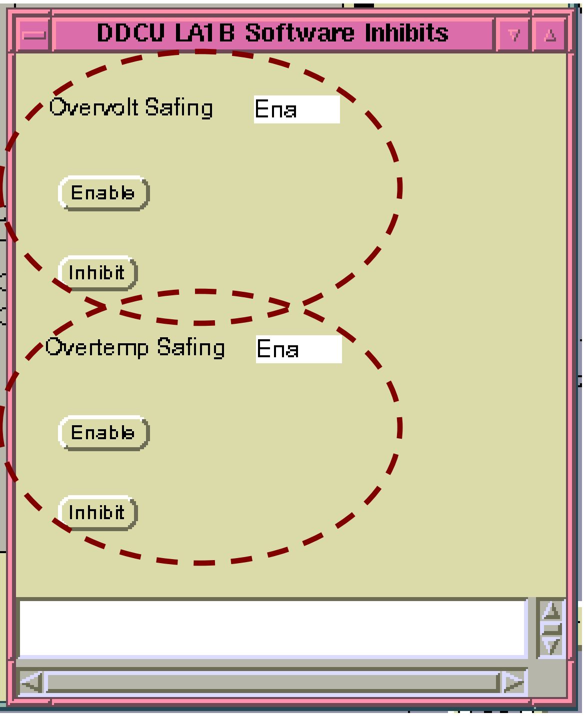


DDCU FW FDIR

DDCU Converter Trips off when:

- Primary (input) under voltage trip= 90 - 115 Vdc for 115 ms ± 4 ms
- Primary (input) Overvoltage trip= 173 - 182 Vdc for 3 ms
- Secondary (output) 125% Overcurrent trip= 57.5A < Iout < 65A for 99 ± 5 ms
- Secondary (output) 150% Overcurrent trip= 78A < Iout < 82A for 52.5 ± 2.5 ms

Subsystem FDIR Example- FSW



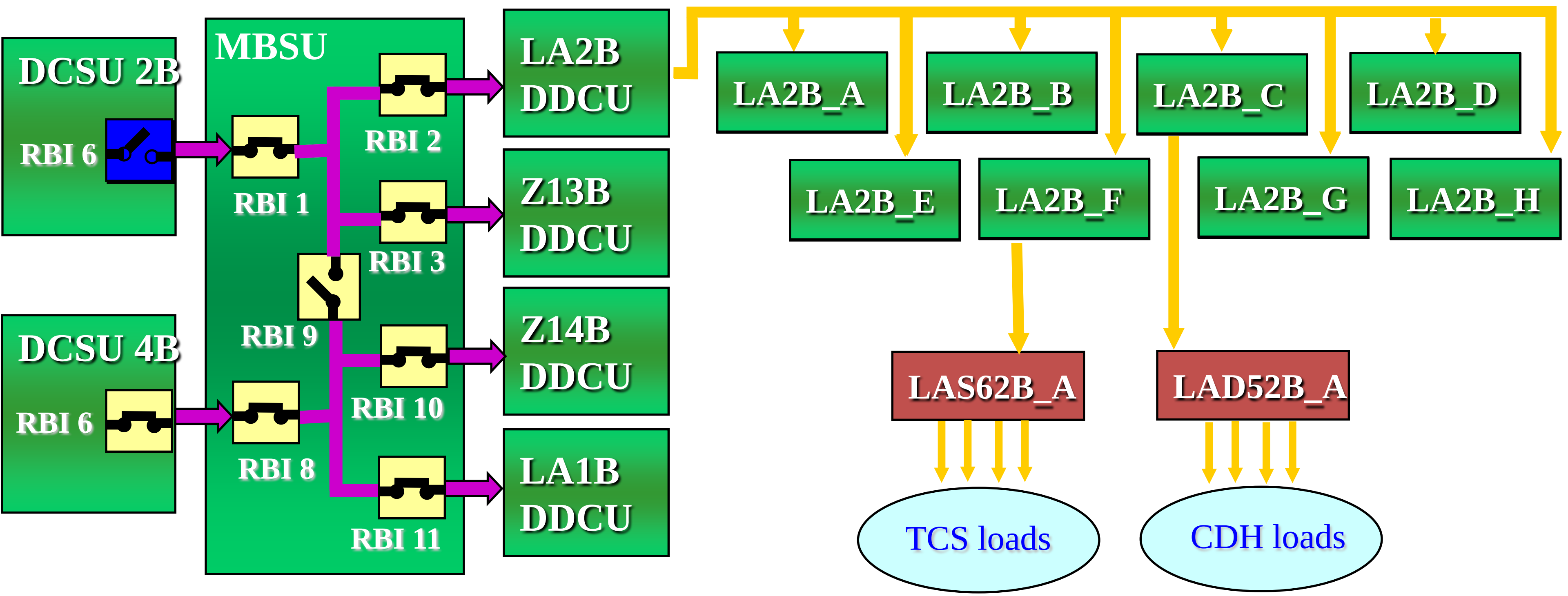
DDCU FSW FDIR

- Secondary (output) Overvoltage trip: 129 Vdc for 6 sec = Converter Off
  - ➢This FDIR action is designed to protect downstream loads sensitive to higher voltage, i.e. computers, electronics
- Overtemperature trip:
  - ➢Conv Temp >190 deg F = Converter Off
  - ➢PS Temp >175 deg F = Converter Off
  - ➢Baseplate Temp >185 deg F = Converter Off
  - ➢FSW Overtemp trip values are changeable
- Both FDIR actions (Voltage and Temperature protection) can be inhibited - see display.

System-Level FDIR

- Correlate subsystem-level information to detect faults that propagate across several subsystems (FDIR)
- Isolate to source subsystem, LRU or LRU component (lowest possible), from multiple subsystem fault indications (FDIR)
- Perform multi-system recovery actions required to mitigate the effects of a fault that affects multiple subsystems (FDIR)

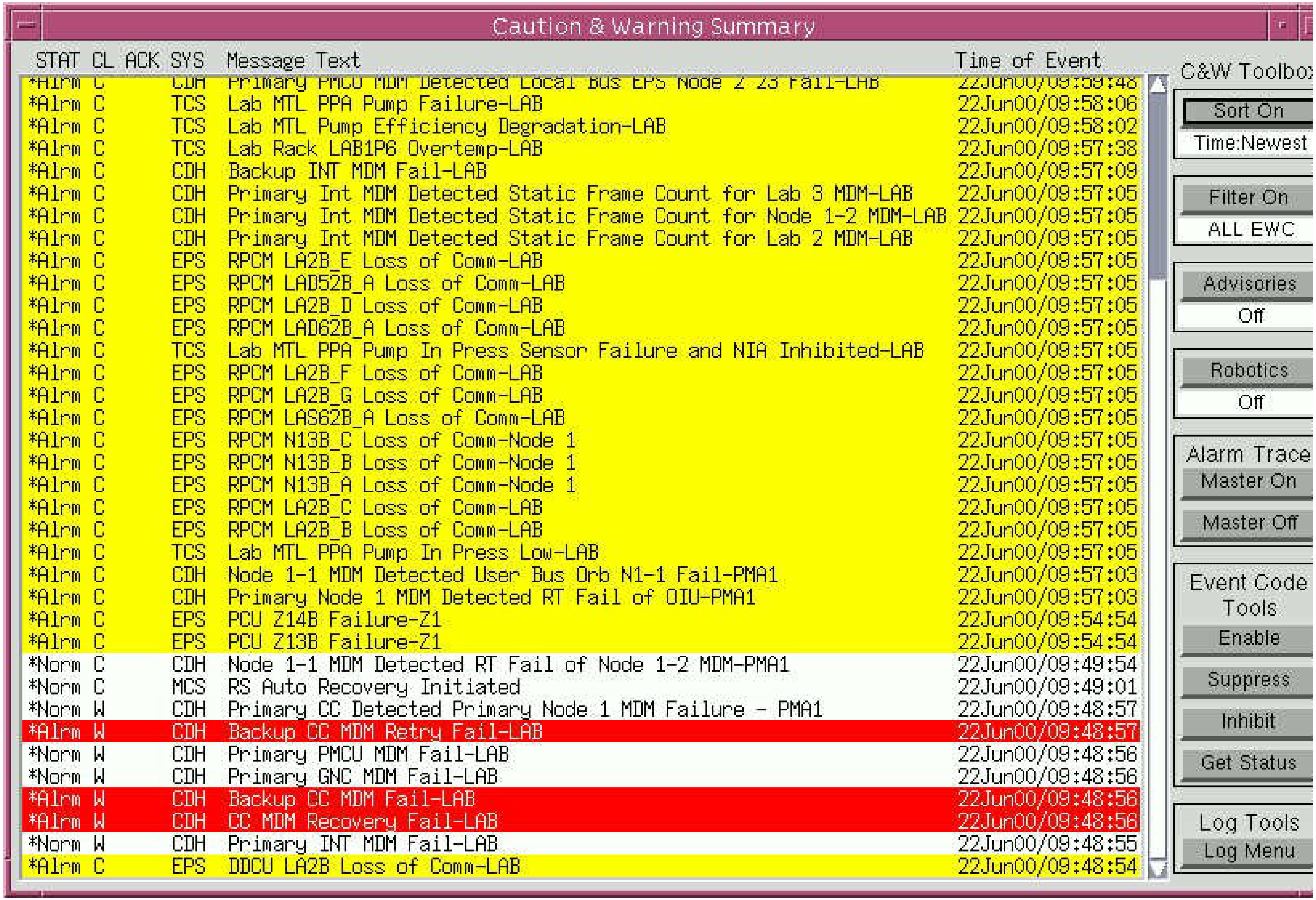
System-Level FDIR scenario



Scenario 1

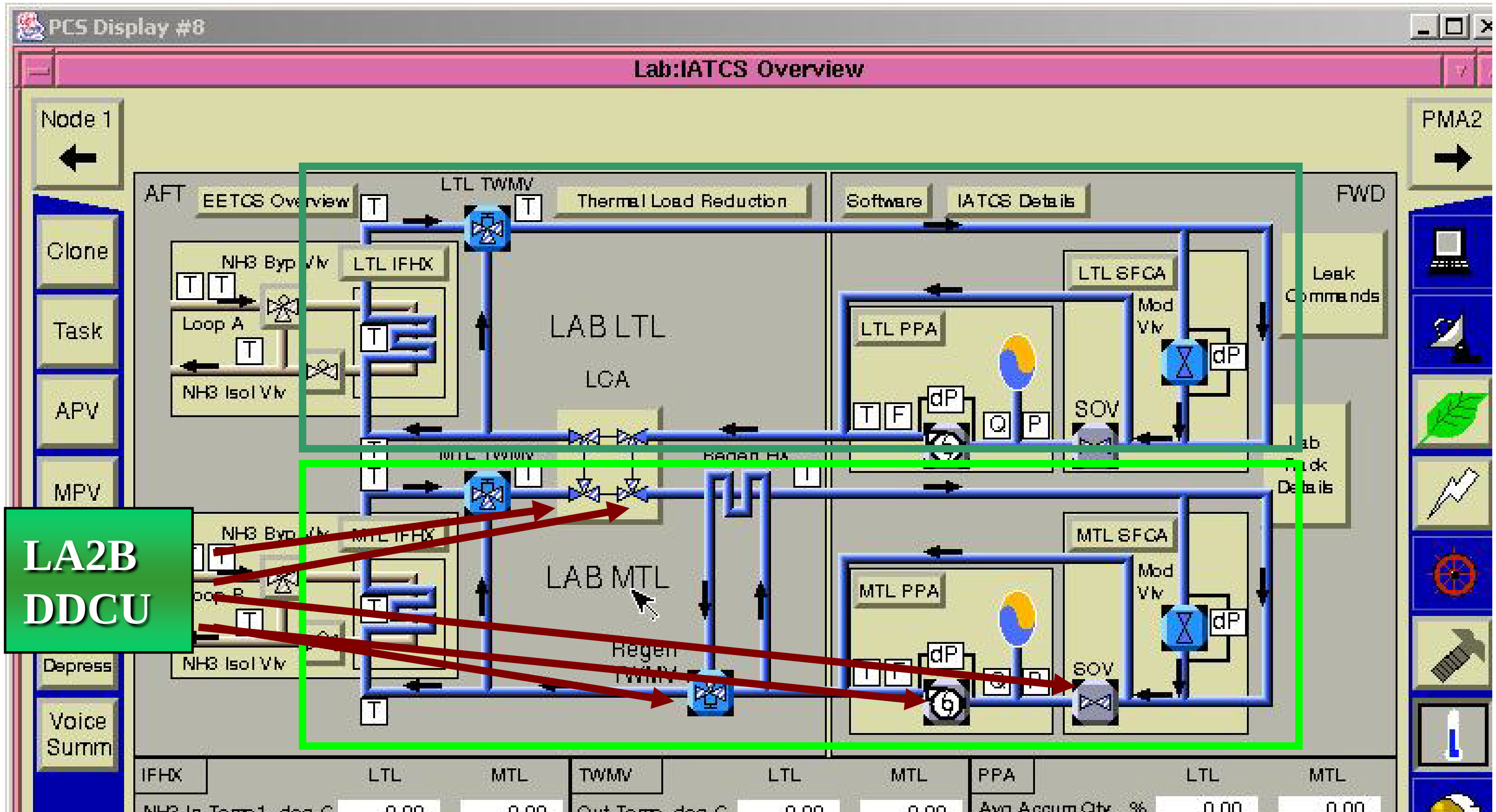
EPS failure –Primary Power switch 6- causes the loss of power to half of the critical US LAB systems. The nature and location of the failure allows system reconfiguration to recover the lost functionality.

Resulting C&W



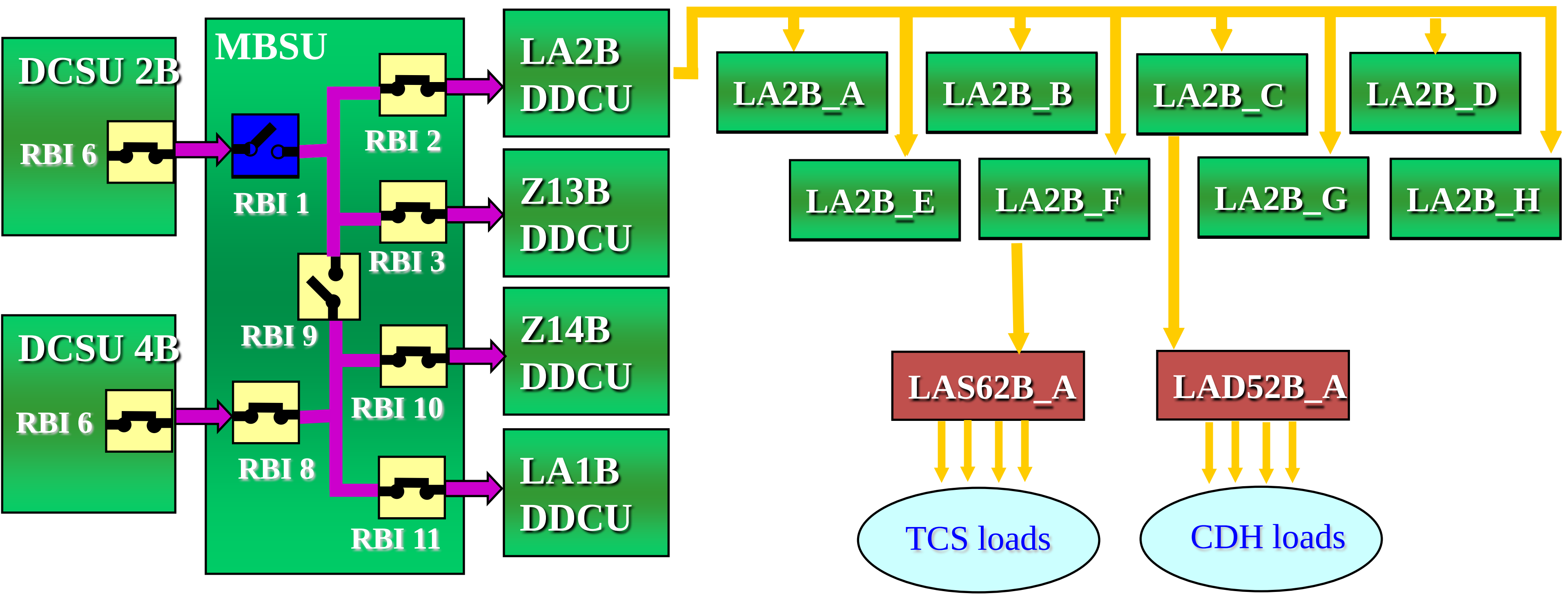
STAT	CL	ACK	SYS	Message Text	Time of Event
*Alrm	C		CDH	Primary PMCU MDM Detected Local Bus EPS Node 2 23 Fail-LAB	22Jun00/09:59:48
*Alrm	C		TCS	Lab MTL PPA Pump Failure-LAB	22Jun00/09:58:06
*Alrm	C		TCS	Lab MTL Pump Efficiency Degradation-LAB	22Jun00/09:58:02
*Alrm	C		TCS	Lab Rack LAB1P6 Overtemp-LAB	22Jun00/09:57:38
*Alrm	C		CDH	Backup INT MDM Fail-LAB	22Jun00/09:57:09
*Alrm	C		CDH	Primary Int MDM Detected Static Frame Count for Lab 3 MDM-LAB	22Jun00/09:57:05
*Alrm	C		CDH	Primary Int MDM Detected Static Frame Count for Node 1-2 MDM-LAB	22Jun00/09:57:05
*Alrm	C		CDH	Primary Int MDM Detected Static Frame Count for Lab 2 MDM-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LA2B_E Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LAD52B_A Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LA2B_D Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LAD62B_A Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		TCS	Lab MTL PPA Pump In Press Sensor Failure and NIA Inhibited-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LA2B_F Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LA2B_G Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LAS62B_A Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM N13B_C Loss of Comm-Node 1	22Jun00/09:57:05
*Alrm	C		EPS	RPCM N13B_B Loss of Comm-Node 1	22Jun00/09:57:05
*Alrm	C		EPS	RPCM N13B_A Loss of Comm-Node 1	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LA2B_C Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		EPS	RPCM LA2B_B Loss of Comm-LAB	22Jun00/09:57:05
*Alrm	C		TCS	Lab MTL PPA Pump In Press Low-LAB	22Jun00/09:57:05
*Alrm	C		CDH	Node 1-1 MDM Detected User Bus Orb N1-1 Fail-PMA1	22Jun00/09:57:03
*Alrm	C		CDH	Primary Node 1 MDM Detected RT Fail of OIU-PMA1	22Jun00/09:57:03
*Alrm	C		EPS	PCU Z14B Failure-Z1	22Jun00/09:54:54
*Alrm	C		EPS	PCU Z13B Failure-Z1	22Jun00/09:54:54
*Norm	C		CDH	Node 1-1 MDM Detected RT Fail of Node 1-2 MDM-PMA1	22Jun00/09:49:54
*Norm	C		MCS	RS Auto Recovery Initiated	22Jun00/09:49:01
*Norm	W		CDH	Primary CC Detected Primary Node 1 MDM Failure - PMA1	22Jun00/09:48:57
*Alrm	W		CDH	Backup CC MDM Retry Fail-LAB	22Jun00/09:48:57
*Norm	W		CDH	Primary PMCU MDM Fail-LAB	22Jun00/09:48:56
*Norm	W		CDH	Primary GNC MDM Fail-LAB	22Jun00/09:48:56
*Alrm	W		CDH	Backup CC MDM Fail-LAB	22Jun00/09:48:56
*Alrm	W		CDH	CC MDM Recovery Fail-LAB	22Jun00/09:48:56
*Norm	W		CDH	Primary INT MDM Fail-LAB	22Jun00/09:48:55
*Alrm	C		EPS	DDCU LA2B Loss of Comm-LAB	22Jun00/09:48:54

Subsystem vs. System-level Response



- DDCU Powers the Loop Pump, but also half of the valves required for subsystem FDIR to perform a proper reconfiguration
- Subsystem FDIR does not understand the nature of the fault (Pump failure) and tries to reconfigure = reconfiguration fails

System-Level FDIR scenario 2



Scenario 2

EPS failure –Primary Power switch 1- causes the loss of power to half of the critical US LAB systems. This failure prevents full system reconfiguration to regain lost functionality. Root cause, affected components and operator actions identified.

Fault Management Design

Integrated FDIR Design

- Integrated FDIR analysis includes three main activities:
  – Bottoms up analysis: Identify all failure modes at subsystem level
    - Functional Fault Analysis
  – Top-down analysis: Identify critical functions and impact of their loss
    - Loss of Crew/Loss of Mission (LOC/LOM) analysis
    - Go/No-Go Tables
    - Operational Functionality Assessment
  – Requirement Allocation: Decomposition of FDIR requirements to:
    - Subsystem-level (HW/FSW/FW)
    - System-Level
    - Crew
    - MCC

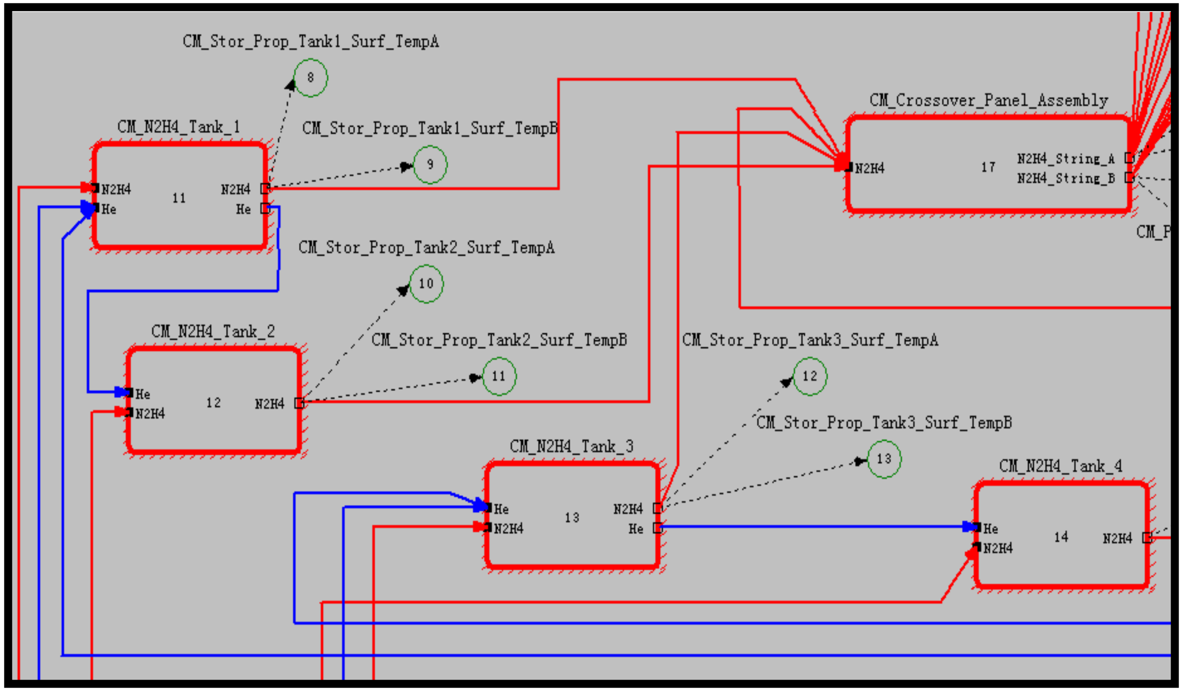
- FFA is "Functional Fault Analysis" captures fault detection and response analysis from the subsystem level to system level FDIR
- Instrumentation Assessment ensures proper fault coverage in design

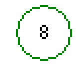
Alternate Methods for FDIR Analysis

- Diagnostic/Testability Analysis tools (just to name two…)
  - QSI TEAMS
  - DSI eXpress
- Description/Benefits:
  - Cause and Effect, Multi-Functional Model of the Failure Behavior of the System
  - Graphical, Understandable way of representing the RM&T aspects of the design for the Life Cycle
  - Testability features enable fault detection, isolation, and diagnosis capabilities
  - Provide metrics of fault detection and fault isolation capabilities, various cases
  - Models can be “recycled” for use in real-time diagnostic systems

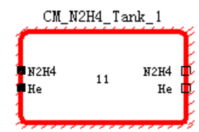
TEAMS Modeling Approach

Sample TEAMS Model for Propulsion Subsystem



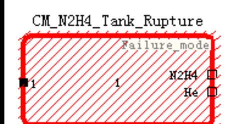


= **Test point (TEAMS)**
= **Sensor**



= **Module (TEAMS)**
= **LRU**

= **Link (TEAMS)**
= **Fault Propagation Path**

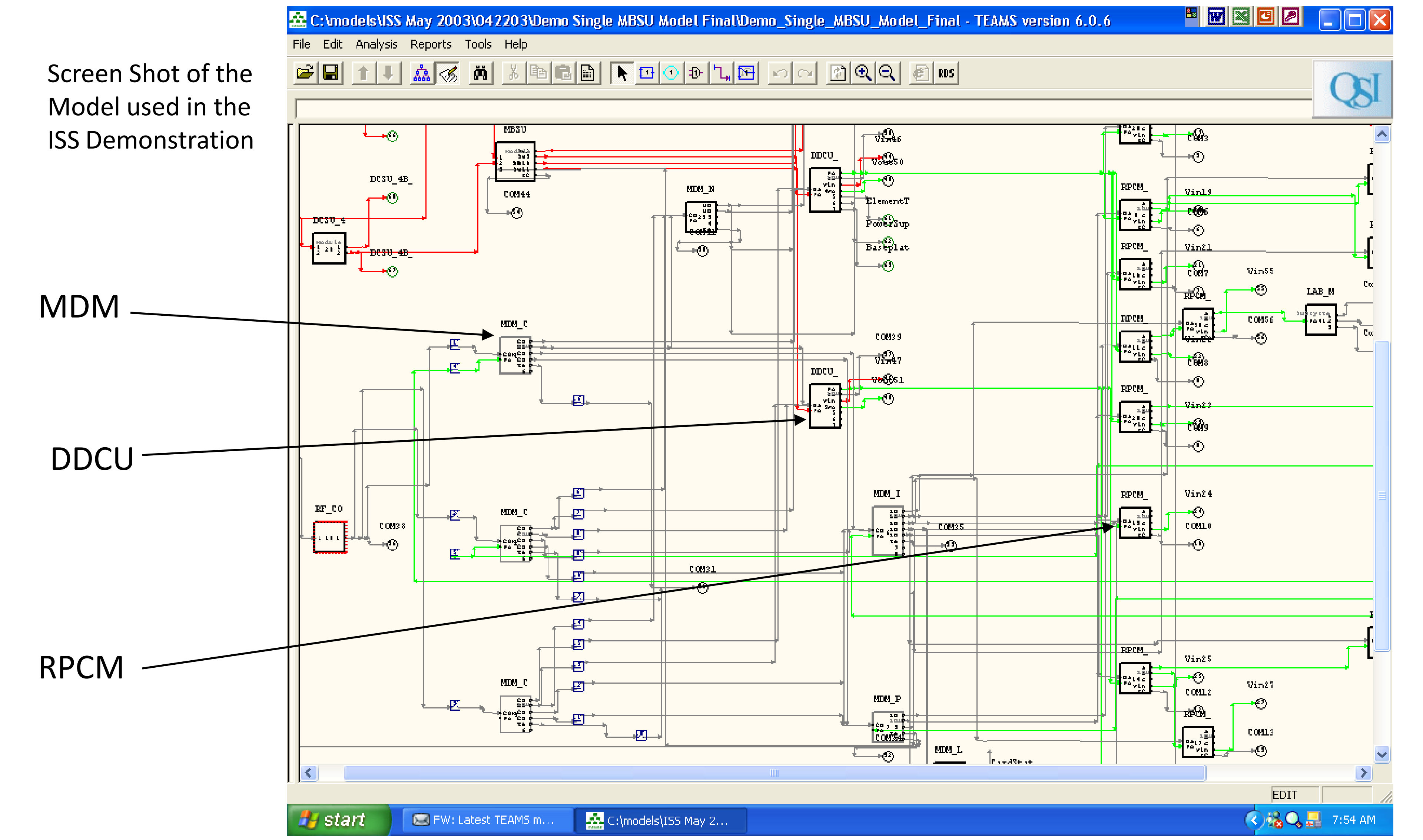


= **Module (TEAMS)**
= **Failure Mode**

- Each module within a subsystem model is designated its own unique color
- Each test point is designated a color based on the source of document used to verify its existence
- Each link is designated its own unique color to differentiate between fluids, power, and data paths
- Each failure mode is designated a “hatched” color pattern

Multi-signal Dependency Modeling

Screen Shot of the Model used in the ISS Demonstration



Fault Isolation Example

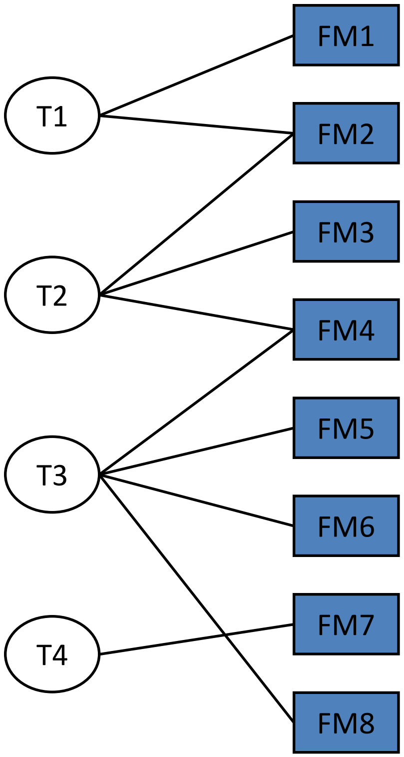
D-matrix

Tests (observables)

Failure Modes (causes)

	T1	T2	T3	T4
FM1	**1**			
FM2	**1**	**1**		
FM3		**1**		
FM4		**1**	**1**	
FM5			**1**	
FM6			**1**	
FM7				**1**
FM8			**1**	

1 = test can detect failure mode



Dependency matrix (D-matrix) is generated from the TEAMS Designer subsystem model

Fault Isolation Example (cont.)

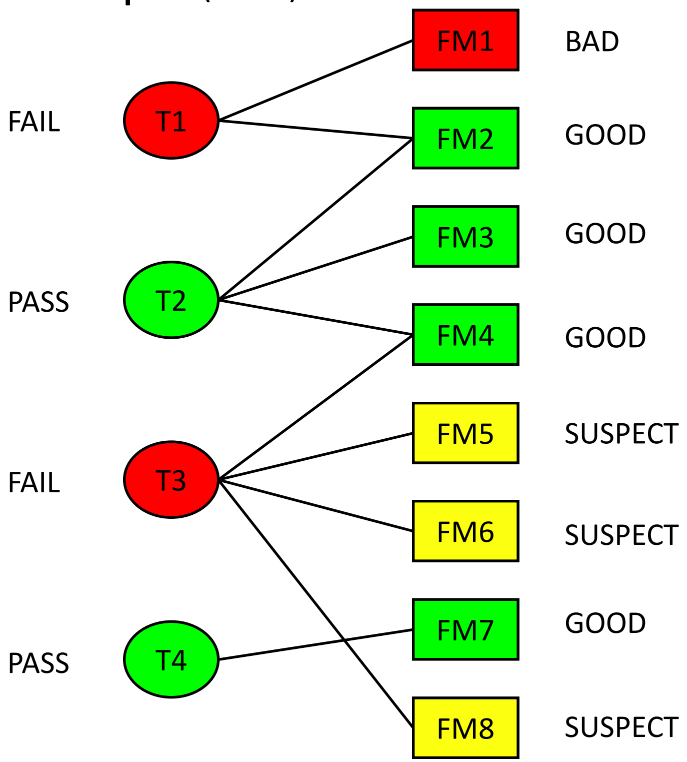
D-matrix

Tests (observables)

Failure Modes (causes)

	T1	T2	T3	T4
FM1	**1**			
FM2	**1**	**1**		
FM3		**1**		
FM4		**1**	**1**	
FM5			**1**	
FM6			**1**	
FM7				**1**
FM8			**1**	

1 = test can detect failure mode

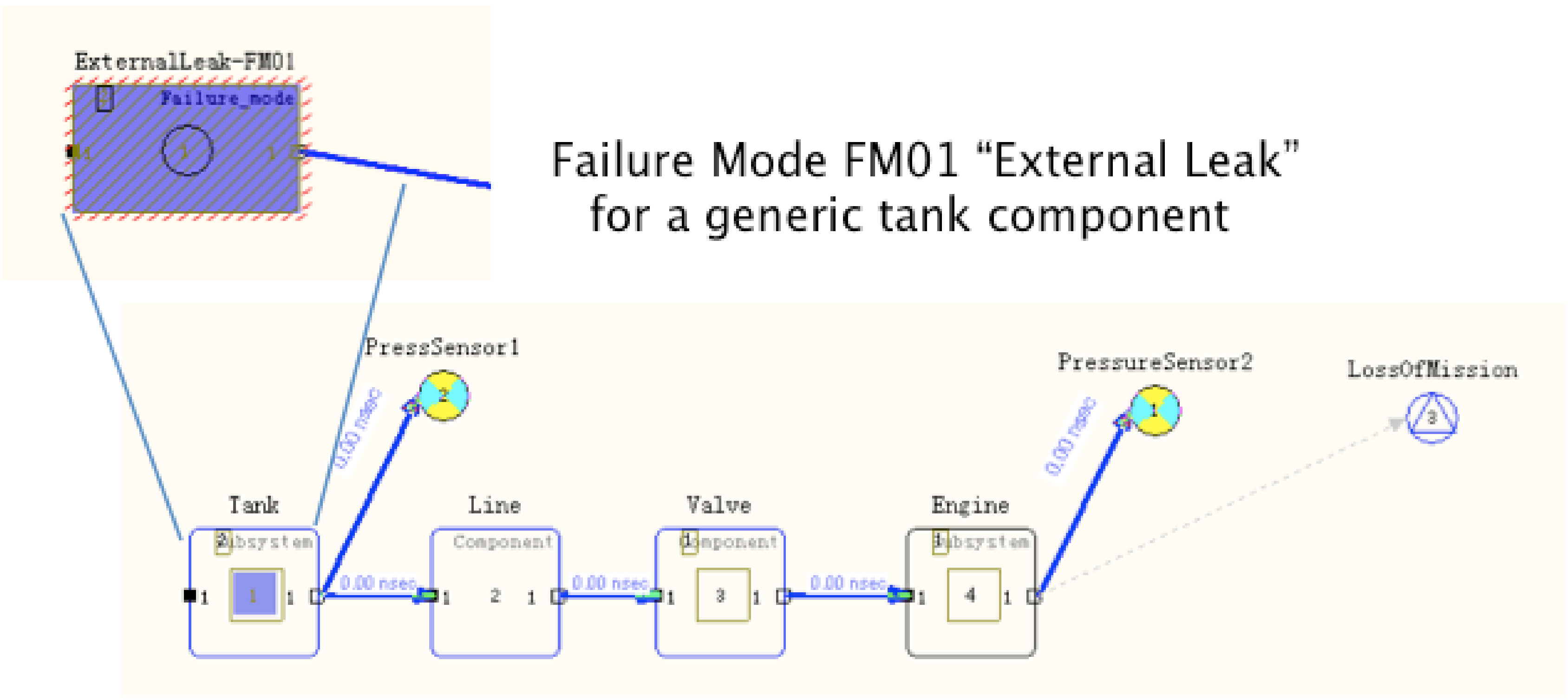


Compute *GOOD* failure modes: Every failure mode connected to a *PASS* test is *GOOD*.

Compute *BAD* failure modes: Every test that is *FAIL* has **at least one** failure mode that is *BAD*.
If there is more than one failure mode that leads to a *FAIL* test, then all failure modes not labeled as *GOOD* are labeled as *SUSPECT*.

All remaining failure modes are labeled *UNKNOWN*: they are connected to tests for which we have no test information.

TEAMS Modeling



Failure Mode FM01 "External Leak"
for a generic tank component

Testability Analysis

TESTABILITY REPORT FOR Vehicle_Model_05

TEST OPTIONS

Test Algorithm NEAR OPTIMAL (Breadth=1, Depth=1)
Test cost weightage = 50.00 %
Test time weightage = 50.00 %
Test dollars per hour = 10.00
Fault Isolated to Failure Modes
System OK probability: 1 %
Mean time to first failure : 4425 (hours)

SYSTEM STATISTICS

Number of failure sources = 188
Number of tests = 85
Number of dependencies = 509
Number of modules at level 1 = 4
Level 2 = 26; Level 3 = 53; Level 4 = 126;
Level 5 = 9;

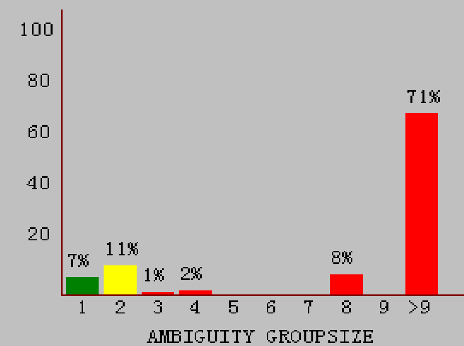
TEST ALGORITHM STATISTICS

Number of tests not used = 54
Number of nodes in tree = 69
Efficiency of test sequence = 26.15 %

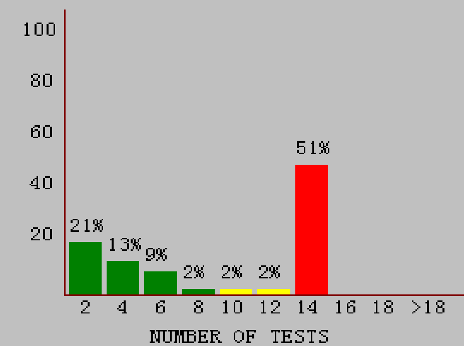
TESTABILITY FIGURES OF MERIT

Percentage Fault Detection = 44.25 % (UW: 51.06 %)
Percentage Fault Isolation = 7.01 % (UW: 8.47 %)
Percentage Retest OK's = 84.36 %
Ambiguity Group Size = 57.78
Mean Weighted Cost To Isolate = 0.00
Dollar Cost = 0.00 Time = 0.00
Mean Cost To Detect = 0.00
Mean Time To Detect = 0.00

HISTOGRAM OF AMBIGUITY SIZE



HISTOGRAM OF TEST USAGE

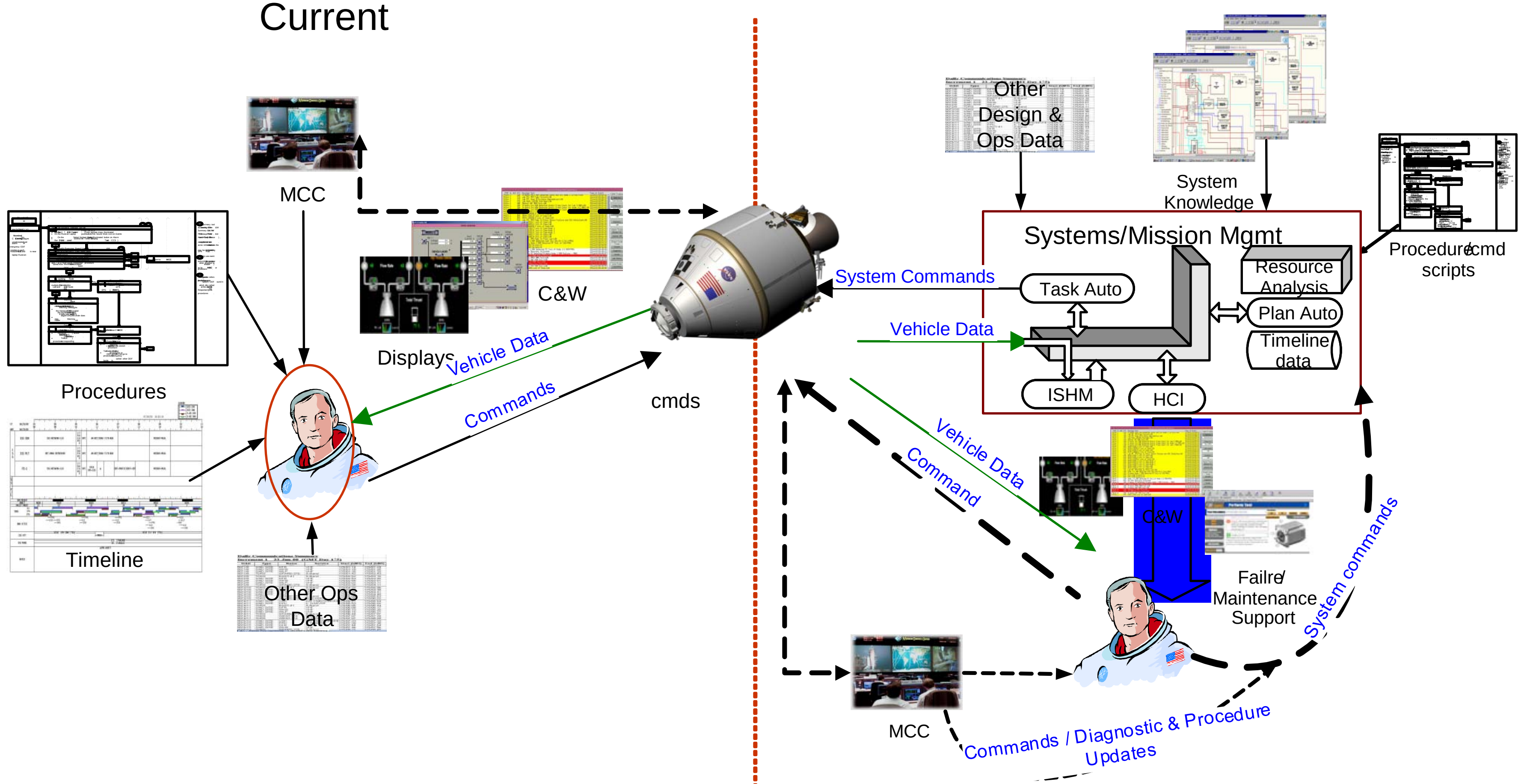


- **Determine % Fault Detection & Isolation – if low, can redesign to add more sensors or others detection or inference means**
- **Identify General System's metrics – Failure modes, Test points, etc**

Real-Time Fault Management

Evolution of Systems/Fault Mgmt on-board

Current



Situational Awareness /System Congnizance			Enhance cockpit Situational Awareness
Crew Workload for Systems Mgmt			Reduced Crew /MCC requirements for systems management actions
Tactical/real-time MCC dependency			Reduced real -time MCC support requirements
Task-Specific Training Requirements			Reduced Crew task training for nominal and off-nominal systems management

On-board Fault Management relevance to Ops

- **Mission Control Center (MCC) -** Level of dependency of the spacecraft and crew on tactical/real-time MCC support during nominal and off-nominal operations.
  - This includes the size of the team required for real-time operations, as well as mission preparation and planning.

- **Crew Training -** Training requirements associated with necessary crew involvement for nominal/routine system management, and response to off-nominal conditions.
  - If the crew is required to actively perform health monitoring, FDIR, and nominal routine system control = significant task and skill training is required.

- **Flight Product development -** Development of flight procedures and other products required by the crew and Flight Control Team (FCT) to manage the system and operate the spacecraft during nominal and off-nominal operations.

On-board Fault Management relevance to Ops

- **Engineering support -** Dependency on engineering teams, outside of the FCT, to provide system expertise during nominal operations and support anomaly troubleshooting.

- **Mission Planning -** Detail required in pre-mission planning to support the execution of a nominal mission and provide sufficient margins for contingency operations.
  - This includes resource analysis, and timeline development, thus on-board capabilities for resource management, or greater availability of resources, reduces granularity required in pre-mission planning.

Key Fault Management Elements

- Vehicle Instrumentation & Displays
  - Provide Crew and MCC insight into system performance, anomalies and current system status
  - Enables identification and response to failures
  - Provides sufficient insight to perform the mission specified for the spacecraft

- Flight Data File
  - Contains nominal, malfunction and reference procedures for the Crew to conduct their mission.
  - Malfunction procedures support Fault detection, Isolation and Recovery when this actions are not performed by on-board systems

- Caution & Warning
  - Alerts the crew to system failures that require their attention
  - Information provided by aural tones, lights, and displayed information
  - Level of information provided by the C&W system determines the crew response to the information.

C&W Message Classification

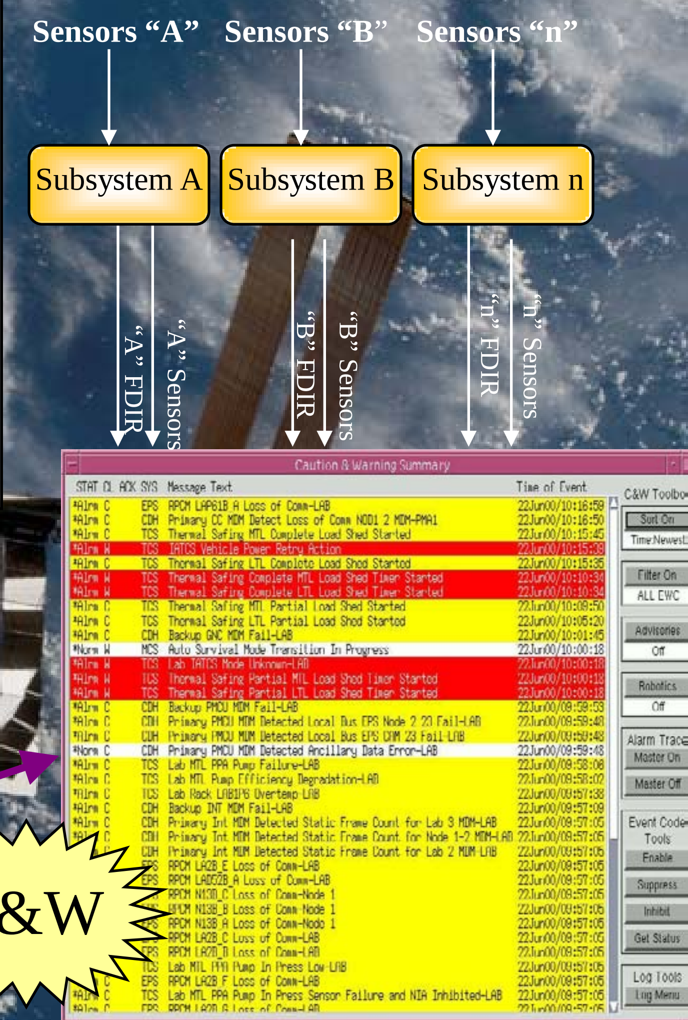
Caution and Warning	**Alert notification system for flight crew and ground that includes Emergencies, Cautions, Warnings, and Advisories.**
Emergency (Class 1 event)	**Any condition that threatens the life of the crew or vehicle and requires immediate action. Three specific conditions (event types) define the emergency class; fire/smoke, rapid change in cabin pressure and toxic atmosphere.**
Warning (Class 2 event)	**Any event that requires immediate correction to avoid loss of or major impact to the vehicle or potential loss of crew.**
Caution (Class 3 event)	**Any event that is not time critical in nature but further degradation has the potential to threaten the loss of crew, or the loss of redundant equipment such that subsequent failure could result in a Warning condition.**
Advisory (Class 4 event)	**A non Caution and Warning message which provides information about systems status and processes.**

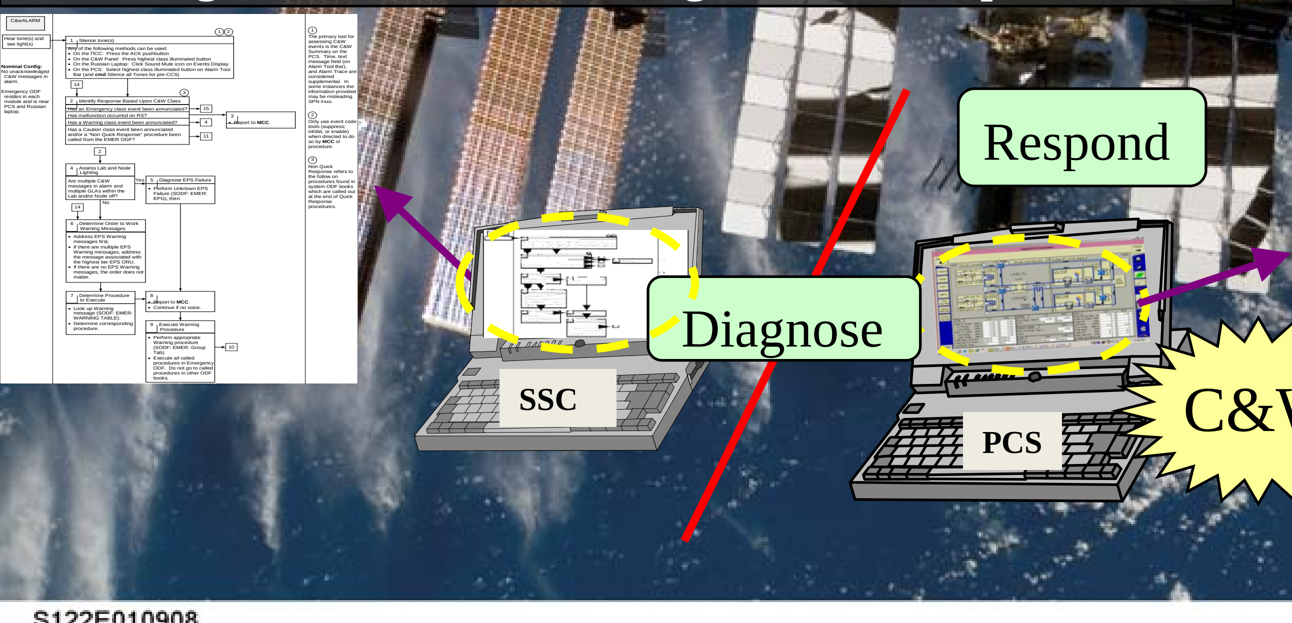
Fault Management on-board Orbiter

- Annunciator Matrix and On-board Fault Summary data based on individual conditions or pre-defined “hard-coded” rules = no dynamic correlation
- Failures that impact multiple components result in the generation of many seemingly unrelated messages that the crew needs to isolate = cryptic C&W
- Generated alerts are often not indicative of the real failure. E.g. ‘EPS bus ‘undervolt’ failure generated ‘Fuel cell Ph low’ = crew diagnosis required

Fault Management on-board ISS

- H&S driven from individual subsystem-level health mgmt data, not vehicle-level health state
- C&W data only one “piece of the puzzle” to determine the nature of the failure, and system propagation
- H&S data does not directly provide failure response information, or system impact severity
- Each C&W message has associated procedures for crew or ground execution. Diagnosis within procedures





Key FM Elements– Decision Support

- Decision Support Information
  - Generation of actionable information for the Crew or Flight Controllers
  - Required information to make a failure response decision
  - Typical information required:
    - **Affected Components** - System components that have lost partial or all functionality as a consequence of the root cause failure.
      - Power failure that also affects thermal control: all components that have lost power + all components that start getting hot.
    - **System-level impact** - Components or functionality that performs critical functions and has been affected by, or is the root-cause failure.
      - A power failure cuts power to 4 loads: light 1, light 2, light 3, and main air conditioning unit. Affected components are all four and system-level impact is the loss of air conditioning.
    - **Redundancy of Critical Components** – Level of redundancy degradation of critical components
      - In the Internal Measurement Unit (IMU) in the Shuttle, for example, the system is 2-fault tolerant, since there are 3 IMUs, and only one is necessary to perform the IMU system functions. Upon the loss of one IMU, the system would be 1-fault tolerant.
    - **Critical-to Information** - A system is “Critical to” any component that if failed, will prevent the system from performing its functions.
      - The IMU system is two-fault tolerant for individual IMU failures. If two IMUs have failed, then the IMU system is critical to the non-redundant components that keep the last IMU functioning.

Learning from System Anomalies - STS

- STS 93 Electrical Short During ascent
  - Seven seconds after lift-off, the Orbiter suffered a transient AC electrical short circuit
  - Failure Indications Onboard: ‘Fuel Cell pH’ message generated by the computer. This message occasionaly occurs during ascent as a transient condition.
  - Root-cause: electrical short had momentarily dropped the AC bus voltage and a built-in self-check of the pH sensor had caused the message when the power was restored.
  - The crew was unaware of the real issue and the impact to the the health of critical systems for ascent.
    - **Affected Components** – equipment powered by shorted AC bus
    - **System impact** – none
    - **Redundancy of critical components** – 2 main engine controllers 0 Fault Tolerant to MEC, power and data
    - **Critical to**: MEC, Power and data components for affect MECs
  - Crew Situational awareness based on sysem indications - none

Learning from System Anomalies - ISS

- ISS US C&C Failure
  - STS-100/ISS 6A assembly mission in April 2001, the ISS suffered failures within the hard drive mass storage system of each of the 3 Command and Control (C&C) flight computers over several days.
  - Result: no command & control capability, no insight in system telemetry
  - Factors that contributed to recovery:
    - The ISS architecture comprised of US and RS segments – RS maintained critical capabilities
    - The Space Shuttle was docked to ISS – providing additional comm capabilities and ATT control
    - Systems Management functions in the ISS architecture are distributed
      - power generation, atmosphere control, attitude control, thermal control) are allocated within the subsystem control, between HW, firmware, tier 2 and local tier 3 computers.

Learning from System Anomalies - ISS

- ISS RS C&C Failure
  - At GMT 164:14:57, during ISS Assembly flight 13A, all six Russian computers (TsVMs & TVMs) became unavailable.
  - Both sets of RS computers TsVM & TVM, are triplex systems, but a single design feature caused all six computers to fail
  - The following functions provided by RS segment became un-available:
    - Oxygen generation (Elektron),
    - CO2 removal (Vozdukh)
    - Propulsive attitude control, necessary in the event US MM is unavailable or unable to maintain control.
    - Power to SOYUZ severely limited, since US to RS power converters were off at the time of failure
  - Factors that contributed to recovery:
    - The ISS architecture comprised of US and RS segments – RS maintained critical capabilities
    - The Space Shuttle was docked to ISS – providing additional communications capabilities and ATT control
    - Systems Management functions in the ISS architecture are distributed

Questions/comments?

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