Structural Health Monitoring Analysis for the Orbiter Wing Leading Edge

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Keng C. Yap, Ph. D.
Project/Technical Lead, Loads & Dynamics
Boeing Defense, Space & Security (BDS)
Keng.C.Yap@Boeing.com

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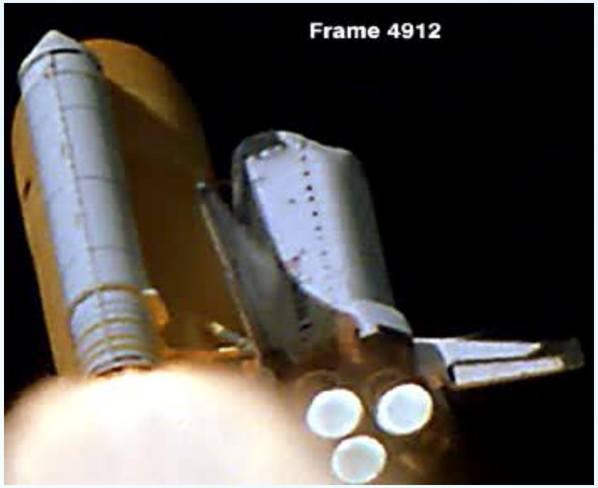
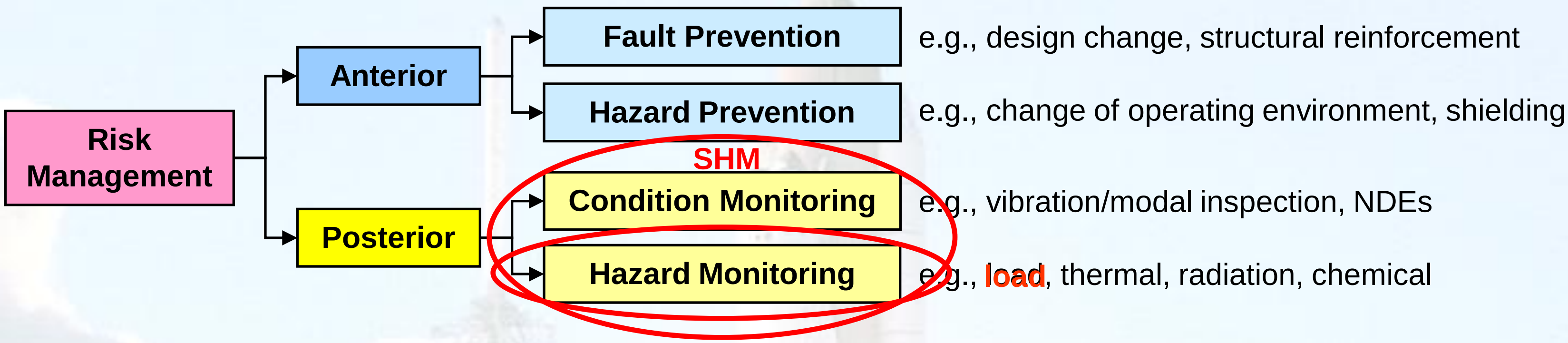
Introduction

- **Wing Leading Edge Impact Detection System (WLE IDS)**
  - Columbia re-entry breakup (STS-107) was caused by External Tank (ET) foam release and subsequent impact on the WLE
  - Structural health monitoring (SHM) system was developed under Return-to-Flight (RTF) to monitor WLE debris threat
  - System development led by NASA-JSC, supported by LaRC & ARC, Invocon, USA, Boeing, LM, ESCG
  - Goal is to detect foam/ice & micrometeoroid/orbital debris (MM/OD) impacts, and help make critical mission decisions



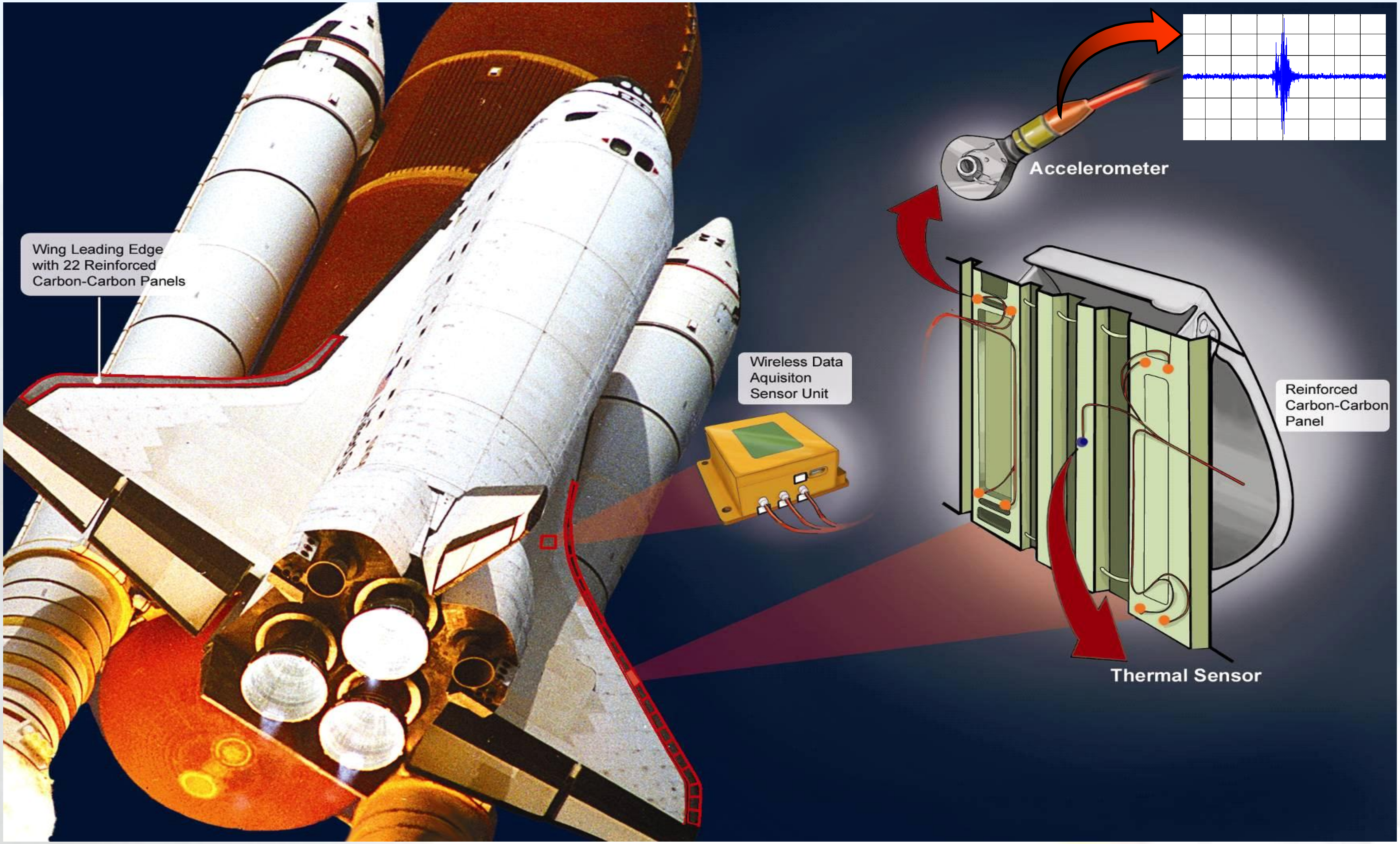
- **Impact Analysis Process**
  - Starts with searching for potential impacts in summary data
  - G-time history data are then downloaded for detail analysis
  - Impact criteria were established based on extensive impact testing conducted after the accident
  - Seek for typical shock response with localized high-frequency transient and damped oscillation
  - Primary impact criteria were extended to improve MM/OD monitoring
    - Orbiter funded Boeing to explore new impact criteria (damping, multi-sensor, and nonlinear characteristics)
    - The development had greatly enhanced the ability to discern MM/OD impacts from false positives
  - Analysis capability was extended to provide severity assessment
    - Helped establish reporting threshold and determine the level of concern
    - Supported by elaborate Orbiter Vehicle testing and NASTRAN modeling efforts

Risk Management via SHM

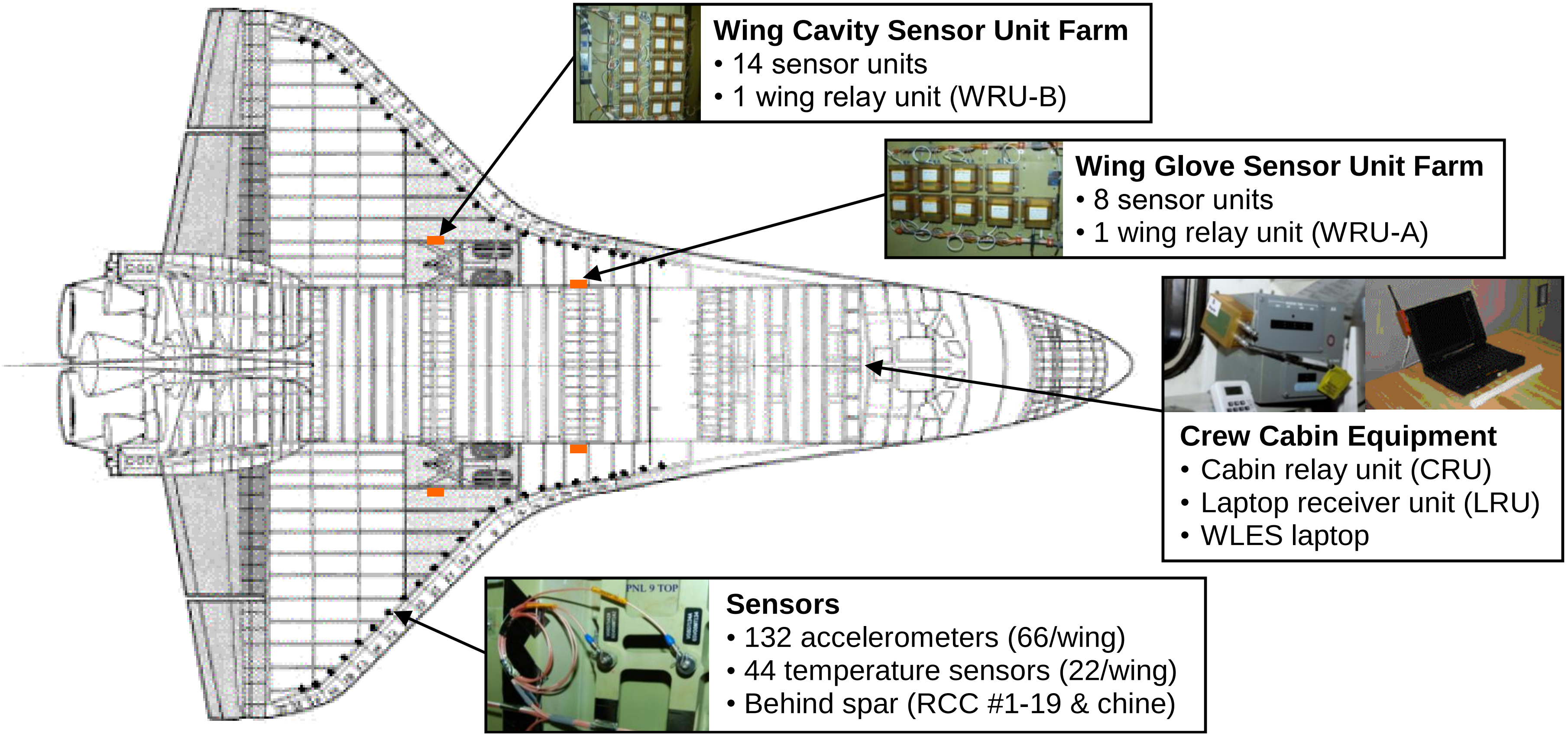


- **Risk Management**
  - Possible to prevent or reduce the occurrence of structural fault or hazard event
  - It may not be feasible or cost-effective to completely prevent fault or eliminate hazard
  - SHM can reduce the catastrophic failure risk after a fault condition or hazard event has occurred
- **Risk Mitigation**
  - Goal is to mitigate risk between the time of detection and the time of potential catastrophe
  - "*. . . the reason for time is so everything doesn't happen at once*"
- **Cost-benefit Study**
  - How much can you benefit from SHM? (trade study, design requirements, system goals)
  - How much useable lead-time will you get? (application specific, instrumentation, analysis capability)
  - What can you do within this limited amount of time? (repair options, operation changes)

Hardware Overview



Instrumentation



Wing Spar

- Sensors

Wing Cavity/Glove

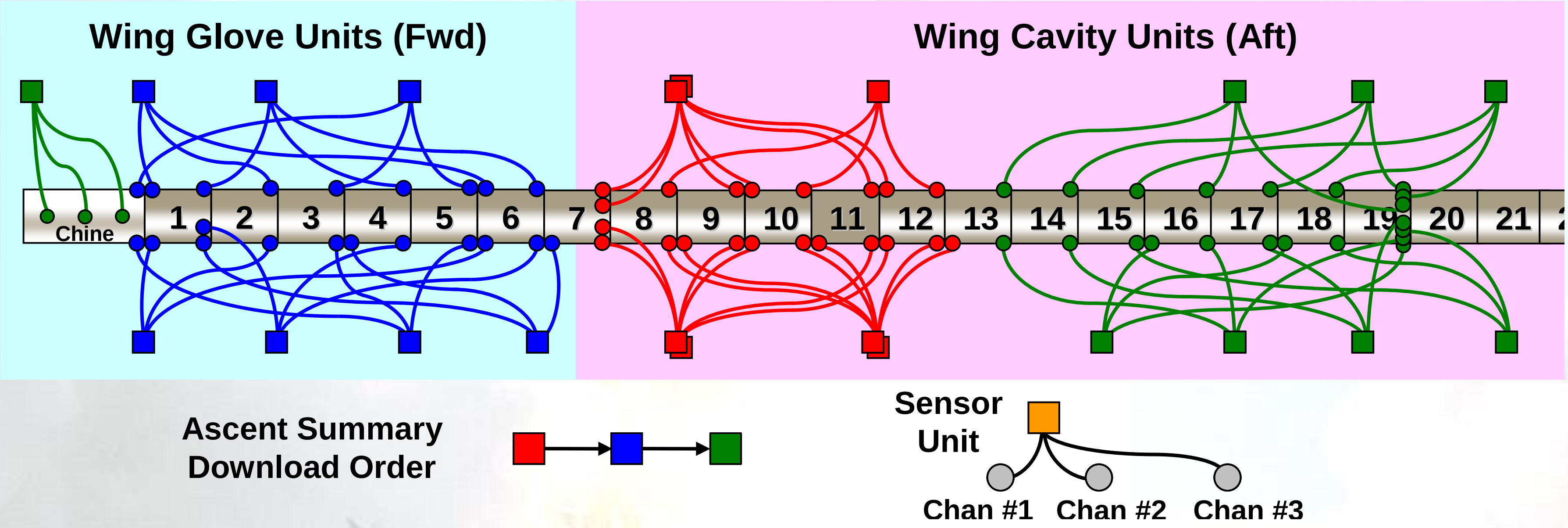
- Data Acquisition Units — RF — Wing Relay Units

Crew Cabin

- Cabin Relay Units — RF — Laptop Receiver Unit — Laptop

Sensor Configuration

- **Accelerometer Locations**
  - 3 channels per data acquisition (sensor) unit, typically distributed 2 panels apart
  - Sensor units are mounted at two separate "farm" areas (wing glove and cavity)
- **Ascent Summary Download Priority**
  - 3 groups of data are downloaded according to a prioritized order
  - Download priority is based on the criticality of re-entry aeroheating of the panels monitored



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Debris Hazard Monitoring

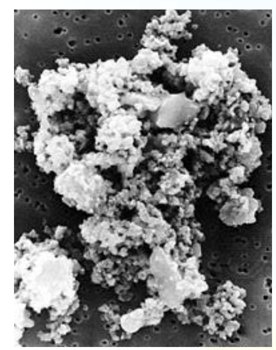
- **Ascent Monitoring**
  - Debris (foam & ice)
    - Foam insulates ET, protects it from ascent aeroheating, and reduces ice formation
    - Study conducted after STS-107 prompted bipod redesign and NDE closeout
    - Foam shedding from multiple locations reduced but continued to occur
  - Ascent Operation
    - WLEIDS continued to operate with 10-min data take through ascent flight monitoring
    - Main challenge is to determine when and where an impact occurred and its severity

- **On-orbit Monitoring**
  - Micrometeoroid & Orbital Debris (MM/OD)
    - Micrometeoroids are interplanetary particles broken off from larger debris
    - Man-made orbital debris (e.g., fragments from satellites/rockets) also pose serious risk
    - Small MM/OD damage craters are commonly found (e.g., RCCs, thermal tiles, radiator)
  - On-orbit Operation
    - After ascent analysis is completed, sensor units cycle through idle and trigger modes intermittently for the remaining flight
    - Main challenge is impact discernment

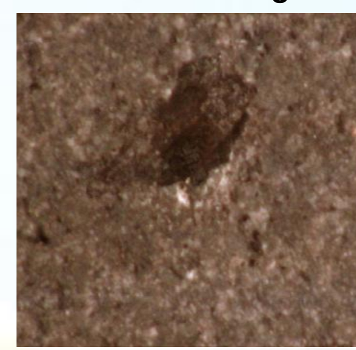
Various Foam Types

Ballistic Impact Test

Micrometeoroid

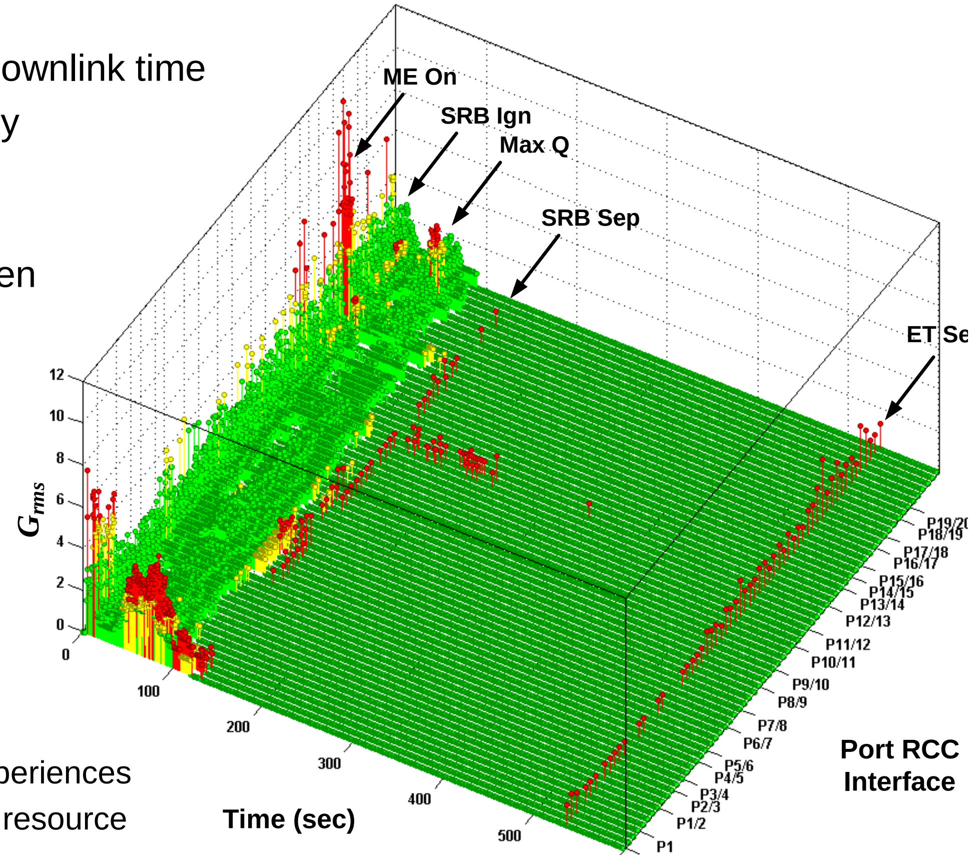


Crater Damage



Ascent Response Summary

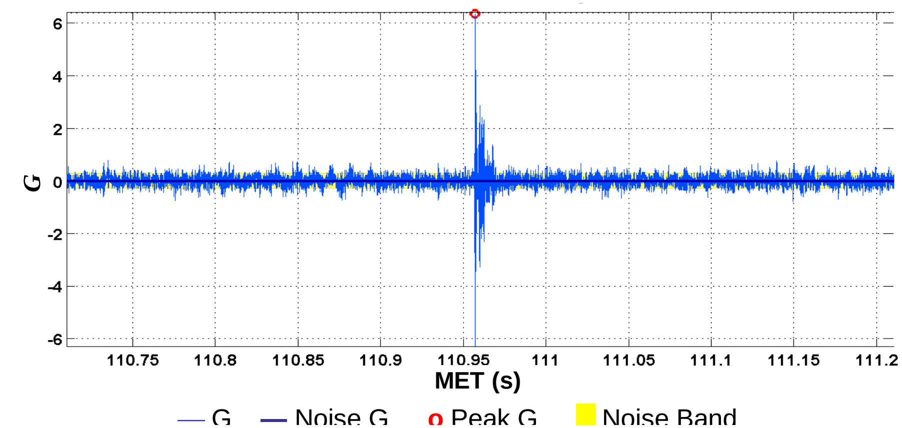
- **Summary Data**
  - Data summarized to optimize storage & downlink time
  - 312.5 Hz high-pass periodic G_{rms} summary
  - 10-min 20 kHz data down to 1200 points
  - ME & SRB ignition are most pronounced
  - SRB and ET separations are distinctly seen
  - Chine shows higher response sensitivity
  - Higher noise at certain panel interfaces (foil-wrapped spar insulation batting)
- **Summary Analysis**
  - Screened data for potential impacts
  - Process can be slow & labor intensive
  - Auto-detection
    - Tried using data mining methods
    - Adopted expert systems[†] approach
    - Incorporated test, simulation, and flight experiences
    - Resulted in significant savings in time and resource
    - Safeguards against possible visual prevalence



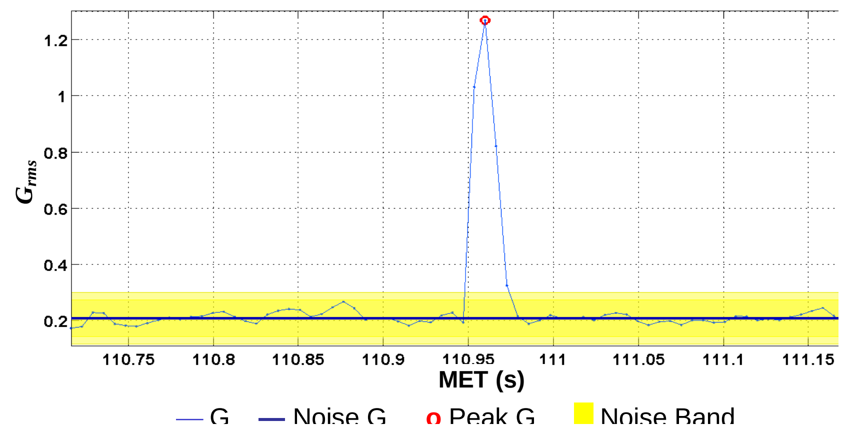
[†] **An artificial intelligence (AI) approach that captures the expert's knowledge base via representation formalism, so that the engineered system can serve as an aid to human in the same problem solving setting as the expert**

Response Signal

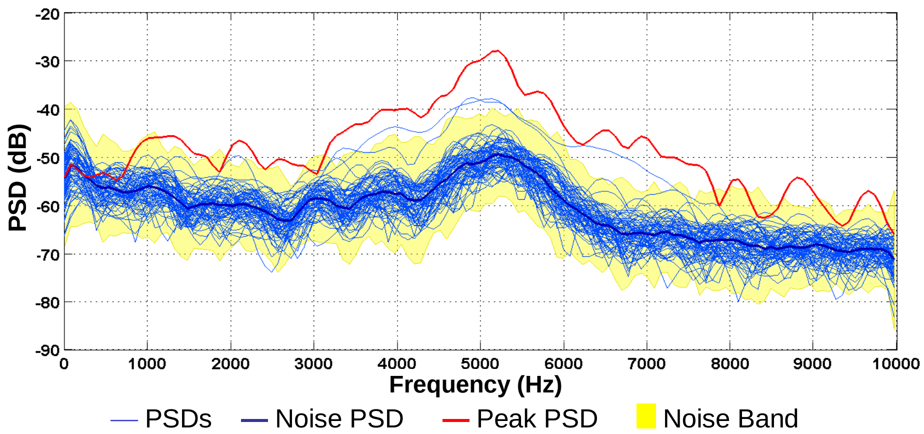
G-time History



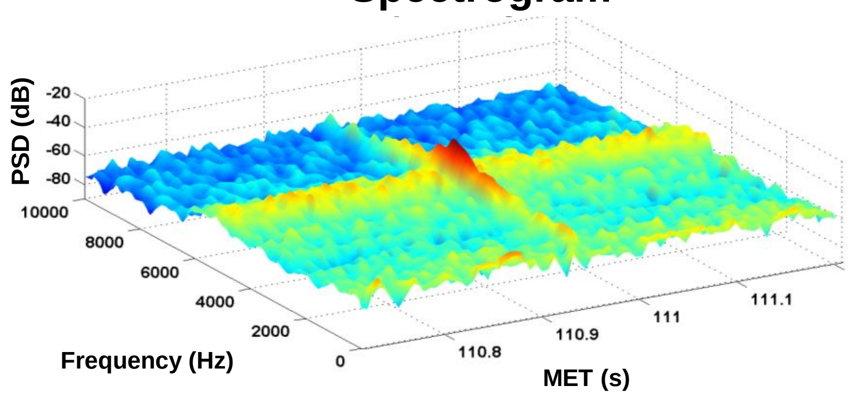
G_{rms}-time History



Power Spectral Density

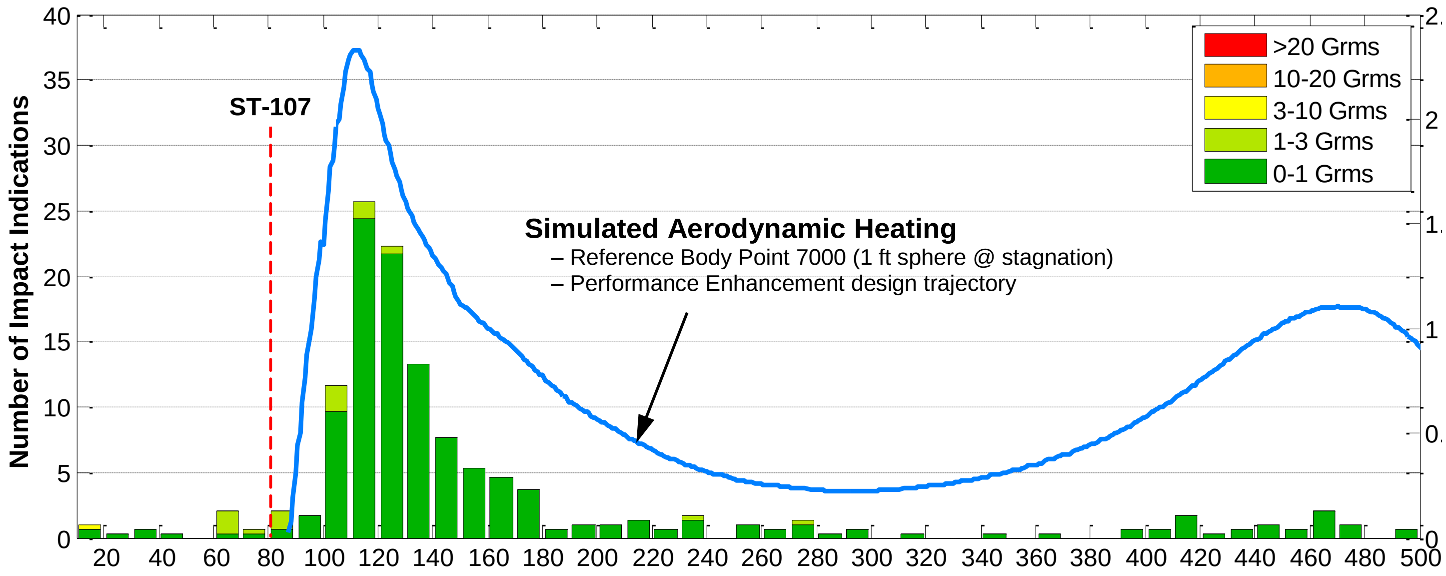


Spectrogram



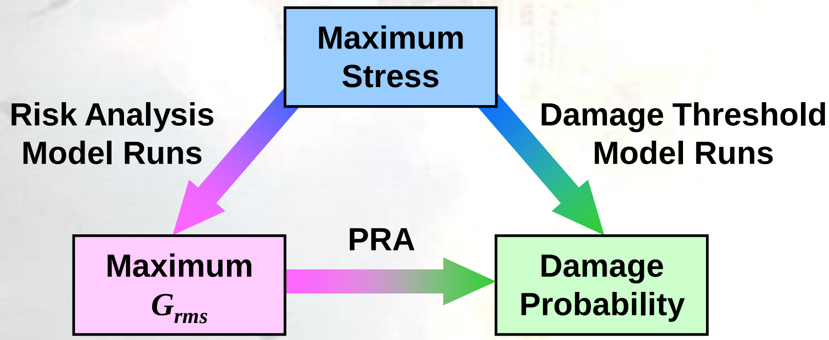
Distribution of Flight Indications

- **Data Trend**
  - System detects as many as 100 indications (low energy, non-damaging, small "popcorn" foam)
  - Distribution shows high correlation with ET aero-heating (second hump is less pronounced)
  - ET aero-heating causes internal pressure build-up and burst of small pores in foam insulation
- **Significance**
  - Provided the first strong evidence of the system registering real impacts
  - Helped establish confidence in the system's sensitivity to detect more severe foam impacts
  - The discovery confirmed the well-known ascent flight phenomenon of popcorn foam release

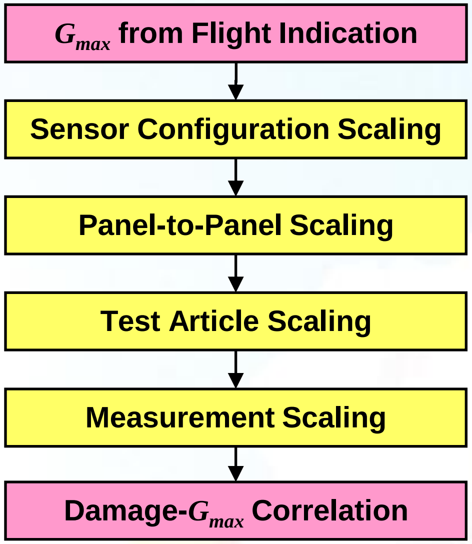


Probabilistic Risk Analysis (PRA)

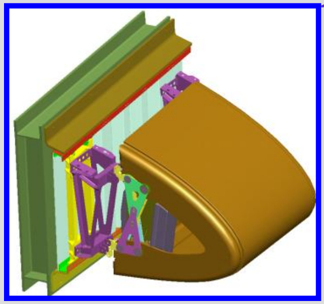
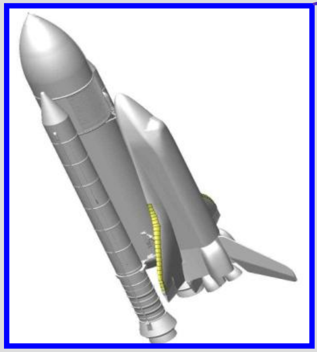
- **Ascent PRA**
  - Analysis Goals
    - Discern impacts from aero-acoustic loads
    - Address situational risk due to an indication
    - Determine the level of concern
  - Analysis Process
    - Characterize impact indications by time, location, and severity
    - Use PRA to determine severity and produces “decisionable” information
    - Account for varying response sensitivity across the wing, and uncertainty (location, angle, velocity, debris type)
    - Elaborate effort involving vehicle thumper testing, model simulation, and risk analysis



- **On-orbit PRA**
  - Analysis Goals
    - Discern impacts from spurious triggers
    - Address situational risk due to an indication
    - Determine the level of concern
  - Analysis Process
    - Estimate impact and damage probability
    - Relate flight response to damage from test
    - Scale flight response to account for higher test article response sensitivity
    - Model the statistics of these scaling factors



Model Correlation

Structure / Test	Test Article	Operating Structure
	 	 
Ballistic Impact Test 	• Correlate test article model at high loads • Realistic test conditions • Full-scale test article used • No damage risk to operating structure **Accident Investigation & RTF**	~~• Correlate hi-fi model at high loads~~ ~~• Most realistic test conditions~~ ~~• Potential damage to the structure~~ ~~• Prohibitive cost & damage risk~~
Thumper Test 	• Correlate test article model at low loads • Thumper simulated impact conditions • Full-scale test article used • No damage risk to operating structure **PRA Pretest Planning**	• Correlate hi-fi model at low loads • Thumper simulated impact conditions • Minimal risk of damaging the structure • Manageable cost & damage risk **Probabilistic Risk Analysis**

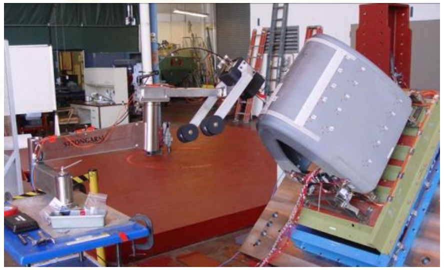
Impact Tests

Thumper Test on OV-105 at KSC

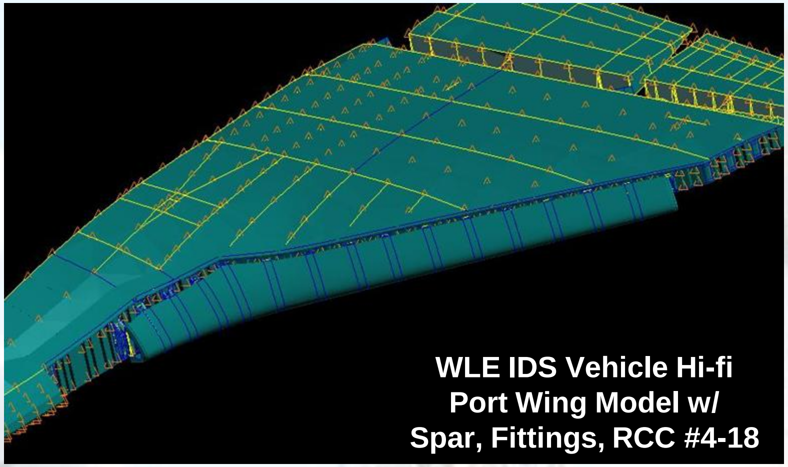
Hypervelocity Impact Test

Ballistic Impact Test

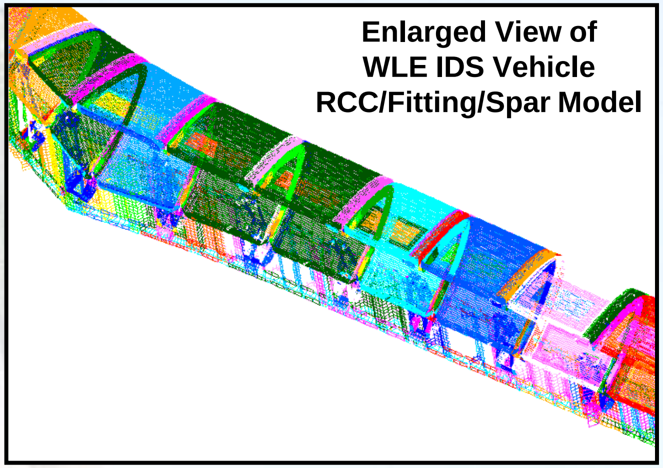
Test Article Thumping



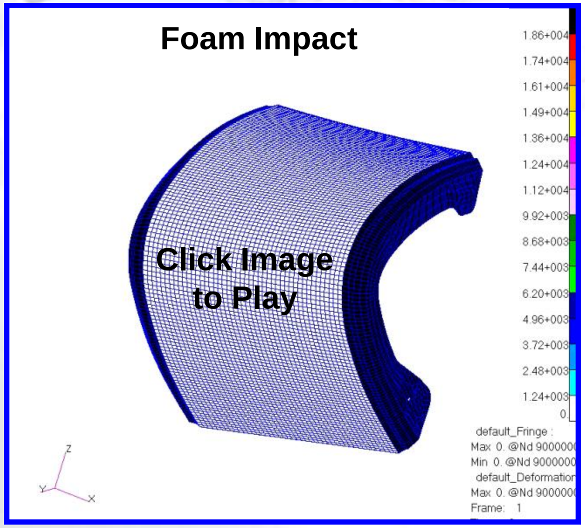
Wing Leading Edge Modeling

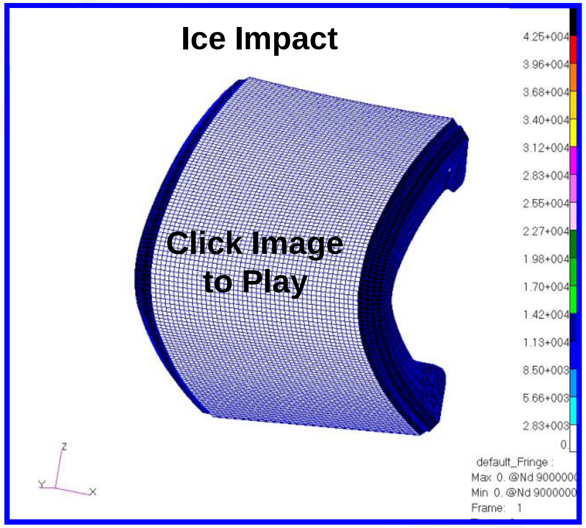


WLE IDS Vehicle Hi-fi
Port Wing Model w/
Spar, Fittings, RCC #4-18



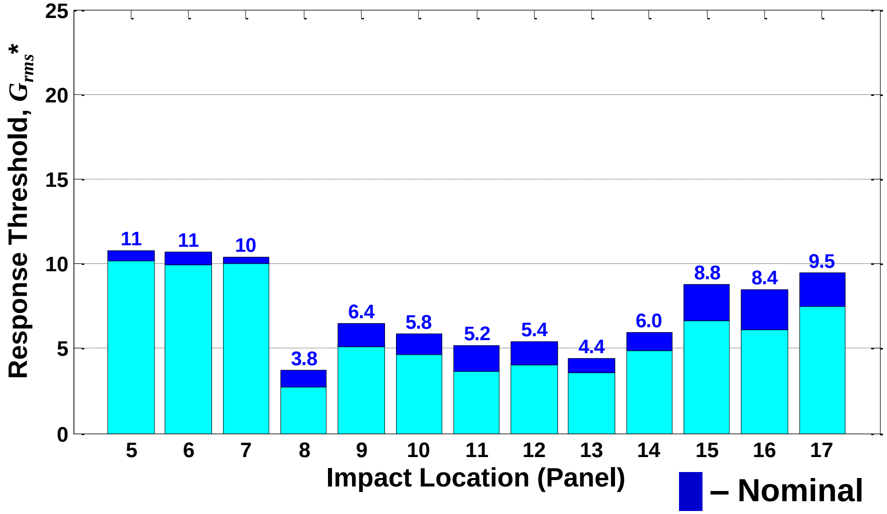
Enlarged View of
WLE IDS Vehicle
RCC/Fitting/Spar Model



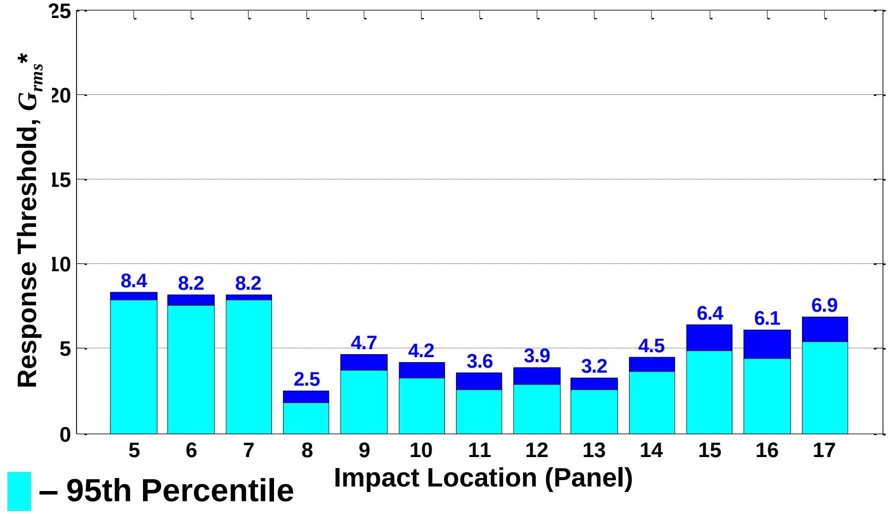


Ascent Debris PRA Results

Foam Impact on Apex, P=1/100

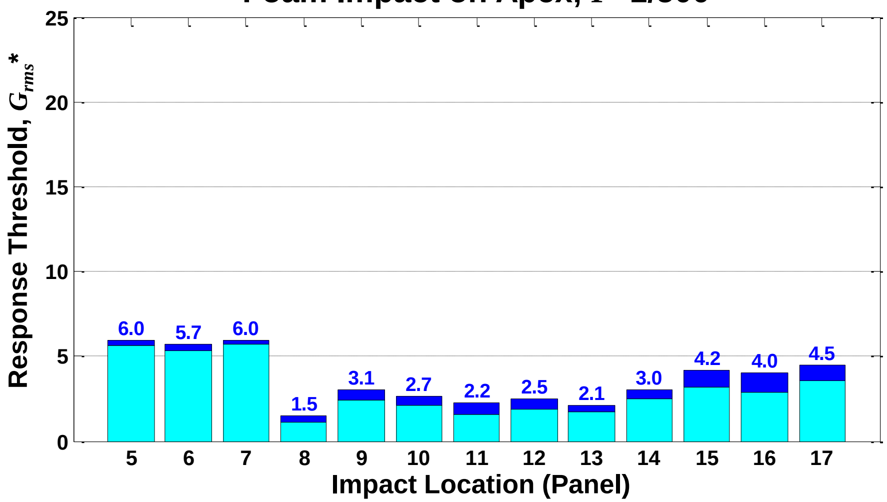


Foam Impact on Apex, P=1/200

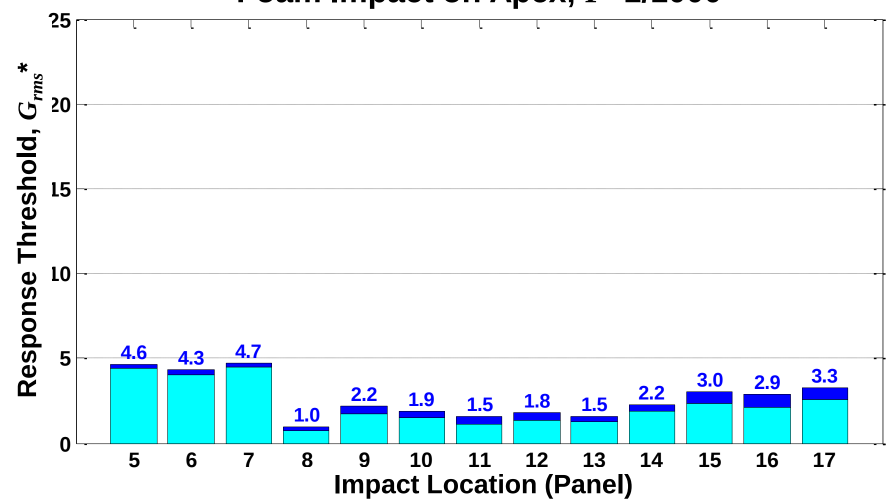


– Nominal – 95th Percentile

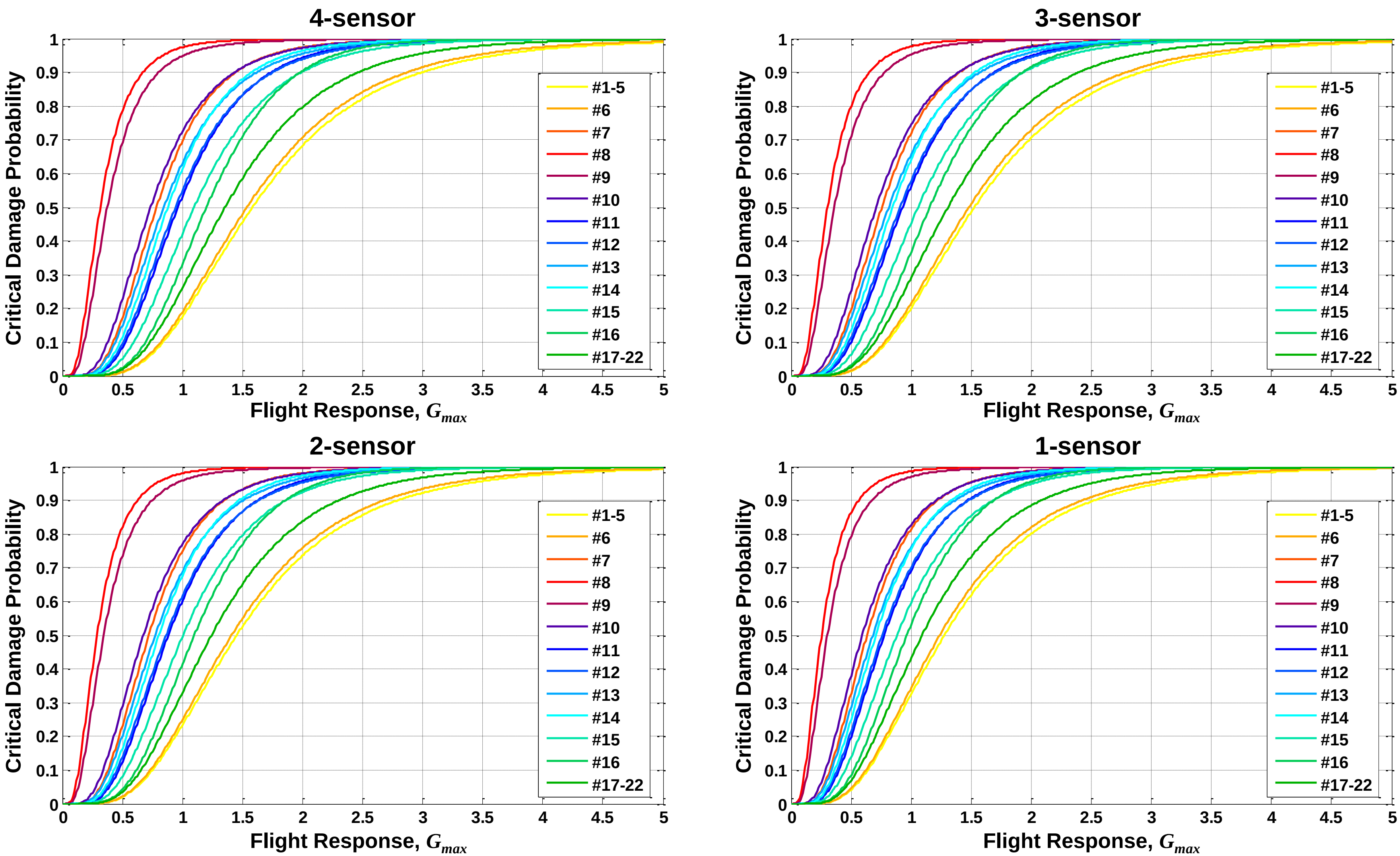
Foam Impact on Apex, P=1/500



Foam Impact on Apex, P=1/1000



MM/OD PRA Results



Summary

Key Success Drivers	Significance
Common Analysis Tool	Provided a unified analysis software for the mission support team
Auto-detection	Saved valuable analysis time & resources while improving the quality of results
Impact Criteria	Allowed rigorous quantitative & qualitative evaluation of impact indications
Analysis Procedure	Guaranteed consistent results by formalizing the analysis steps
Knowledge Integration	Developed strong knowledge base from testing, modeling, & flight experience
Aeroheating Correlation	Demonstrated high sensitivity, built confidence in detecting damaging impacts
Reporting Threshold	Enhanced operational feasibility & sustainability by setting a minimum threshold
Computational PRA	Extended the analysis capability to severity determination

Project Elements	Lessons Learned
System Development	SHM helps manage risk of operating structures under a hazardous environment
	A deployed system can continue to evolve through on-going operation & analysis
Instrumentation	Wireless instrumentation provides a practical solution for a retrofit design
	Power source affects utilization of wireless transmission and monitoring duration
Testing & Modeling	Extensive testing provides valuable data for model development
	Test & model development is most meaningful when driven by analysis goals
SHM Analysis	Complete SHM analysis involves identification, localization, & severity assessment
	Probabilistic analysis is useful for handling many issues involving uncertainty

Conclusions

- **System Role**
  - Debris Risk Management
    - Debris hazard environment experienced by the Orbiter presented a challenging risk management problem
    - SHM reconditioned this problem, as hazard monitoring made the pertinent flight risk more manageable
  - Mission Highlight
    - During STS-132 early inspection, OBSS could not properly position the LDRI due to a snagged cable
    - EVA was planned to fix the snag, but RCC could not be cleared for re-entry per flight rule
    - WLEIDS analysis helped determine that RCC was unlikely to have sustained unacceptable damage
- **Future Development**
  - Wireless Instrumentation
    - Overcame many difficulties associated with incorporating the system into an entrenched structure
    - Provided a practical platform for an integrated impact sensing, signal processing, and analysis operation
  - Future SHM
    - Enhance the safety of human space transportation, exploration, and habitation
    - Focus on MM/OD monitoring instead of ascent due to in-line design of future launch vehicles
    - Medium size particles large enough to cause damage despite shielding and yet too small to be tracked
    - Advanced impact criteria developed for MM/OD monitoring will contribute to a more reliable SHM system
    - Build on previous technology concept (instrumentation, interface firmware, impact analysis tools)
    - Perform cost-benefit study by assessing risk mitigation options within a certain lead-time
    - Pursue severity assessment to help realize the risk buy-down from SHM
    - Simultaneously monitor for multiple hazards and conditions to get the most bang for your buck

Acknowledgements

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  - George Studor (Principal Investigator), Eli Rayos (led development of modeling and mission operations), Chip McCann (led development of impact criteria and operations), Josh Johnson (analysis procedures), Tammy Gafka (project/engineering lead) (*NASA-JSC*)
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  - Structures, Loads & Dynamics (SLD), Leading Edge Subsystem (LESS)
  - Micro-wireless Instrumentation (MWIS), Debris Integration Group (DIG), Safety & Mission Assurance (S&MA)

WLEIDS Publications

- Yap, K. C., Macias, J., Kaouk, M., Gafka, T., Kerr, J.
  "Probabilistic Structural Health Monitoring of the Orbiter Wing Leading Edge"
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  The 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit, Tucson, AZ, 2005
- Prosser, W. H. et al., "Structural Health Management for Future Aerospace Vehicles"
  The 2nd Australasian Workshop on Structural Health Monitoring, Melbourne, Australia, 2004