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Space Shuttle Systems Engineering Processes for Liftoff Debris Risk Mitigation

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Systems Engineering processes integrate skills with resources to define and methodically service the Space Shuttle Program (SSP) need to limit debris risk

- Debris risk mitigations were implemented since the inception of the SSP
- Debris struck the Space Shuttle Columbia (STS-107) during ascent causing the tragic loss
- SSP elevated the need to understand and limit debris hazards associated with launch phase
- Debris hazards remain top risks for the Space Shuttle Vehicle (SSV) due to analytical uncertainties and limited controls

Top Debris Risk Types

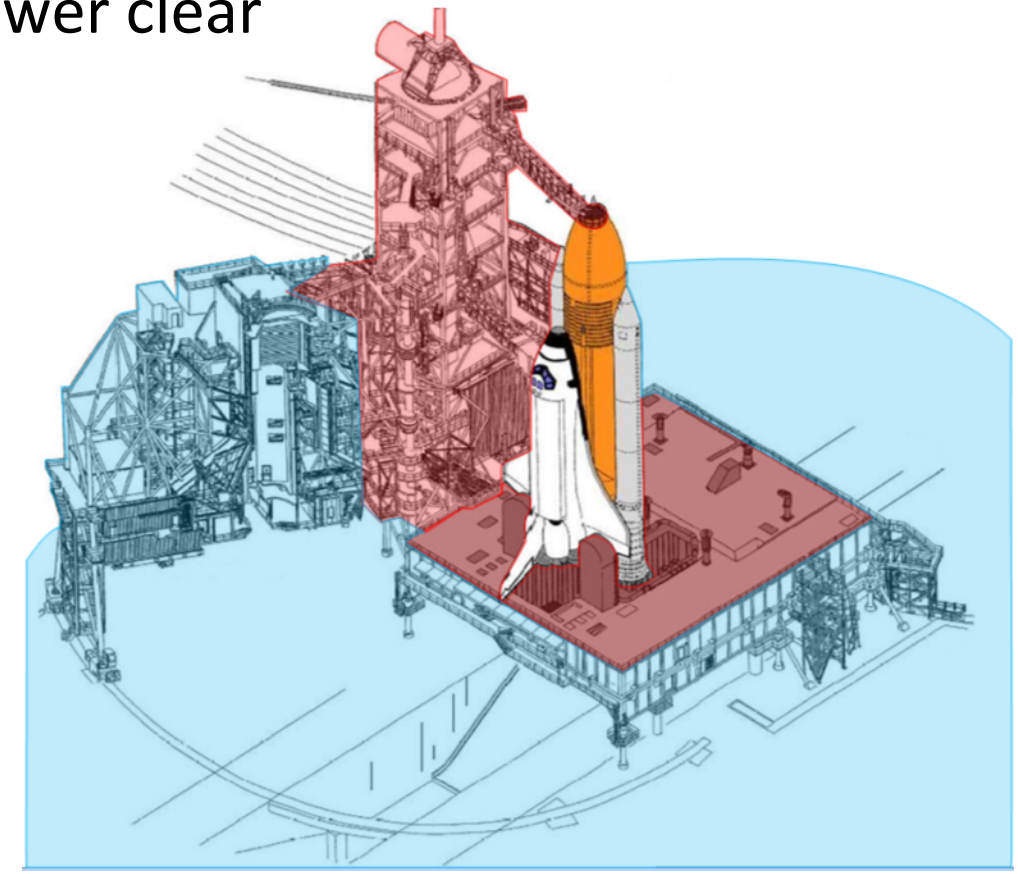
- **Liftoff Debris**
  - Begins Day of Launch (DOL) from tanking through vehicle tower clear
  - *Subject of this presentation*

- **Ascent Debris**
  - Begins DOL after vehicle tower clear until External Tank separation

- **Micrometeoroid Orbital Debris**
  - Begins DOL after External Tank Separation until Re-entry

Space Shuttle Liftoff Debris Definition

- Liftoff debris is any hazardous mass transporting inside the Critical Debris Zone on DOL from tanking through vehicle tower clear



Critical Debris Zone in Red

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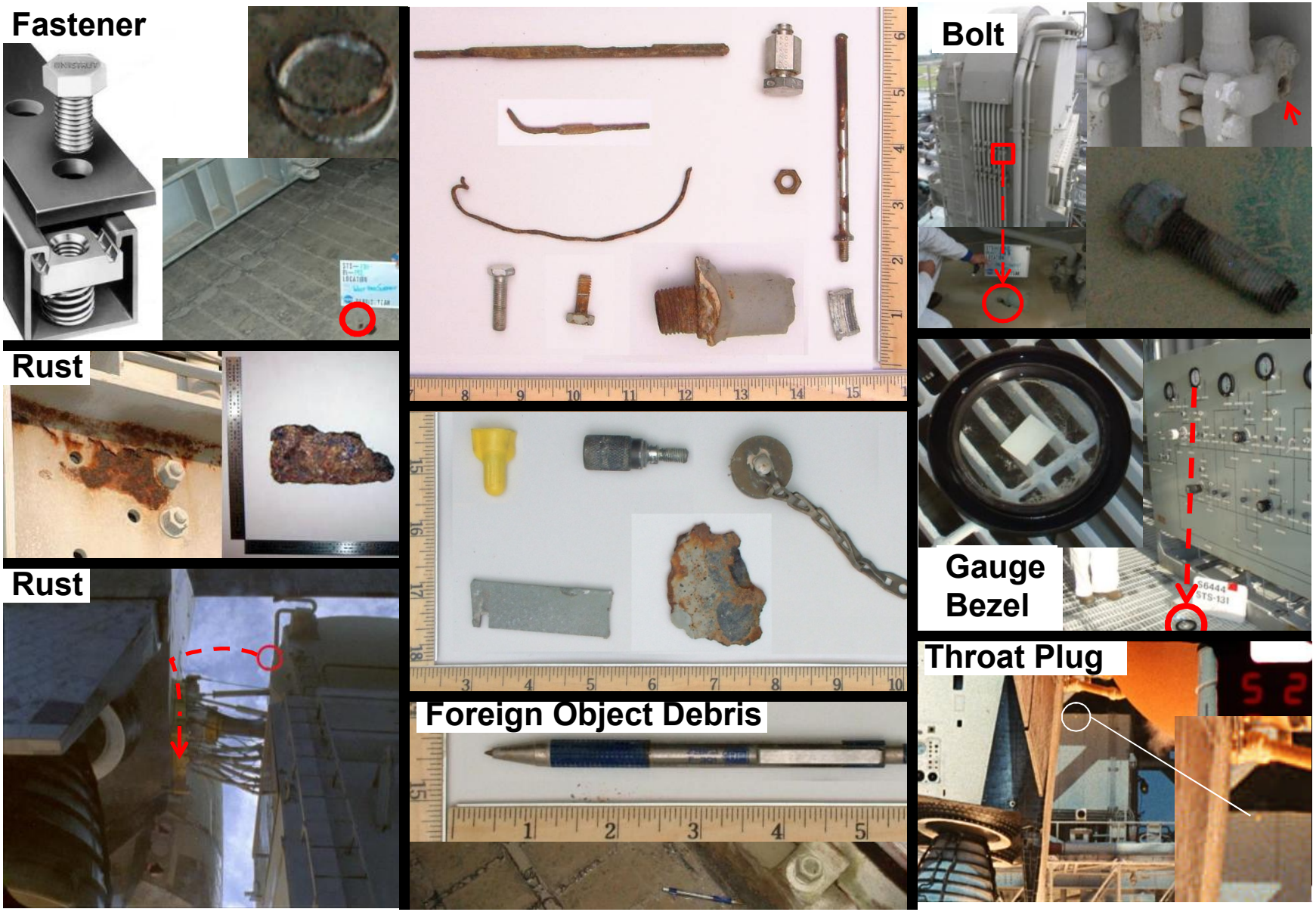
Examples: Space Shuttle Program Liftoff Debris



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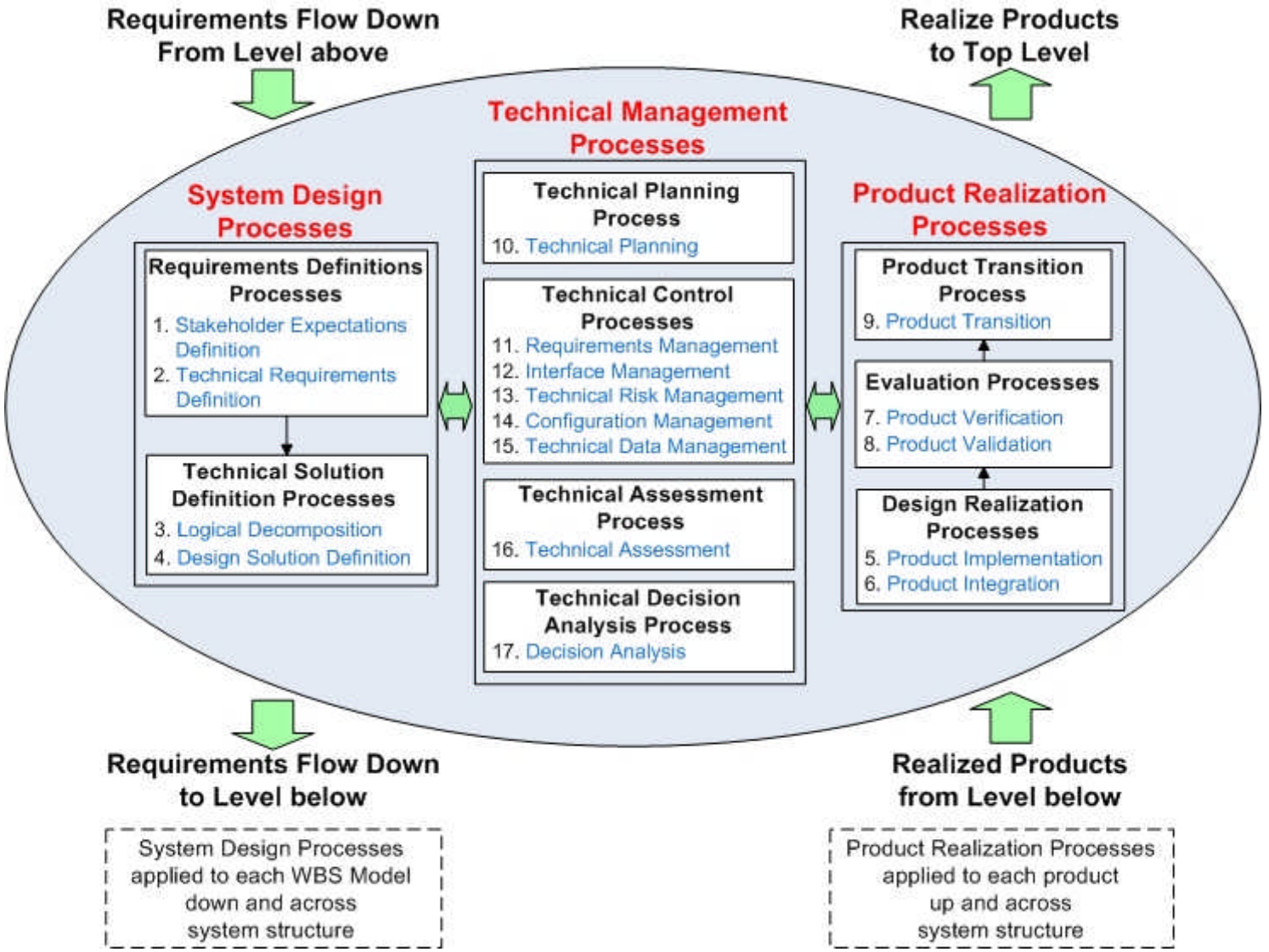
NASA Systems Engineering Process (NPR 7123.1A)



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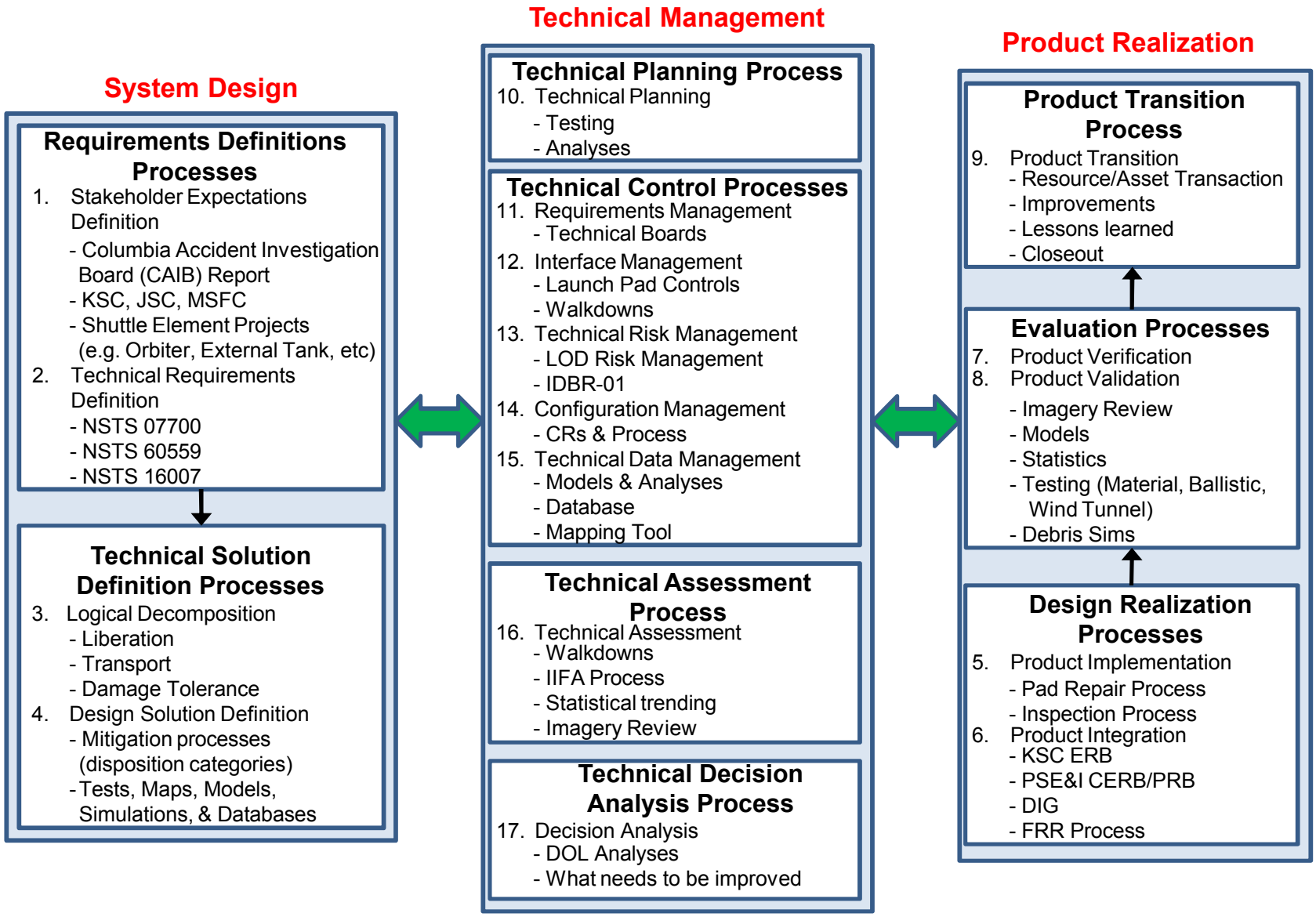
Liftoff Debris Systems Engineering Process



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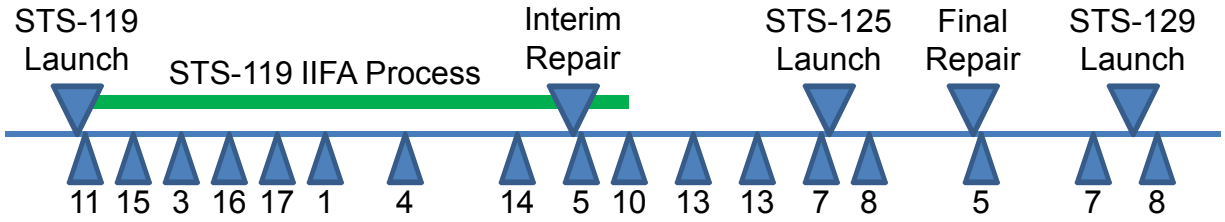
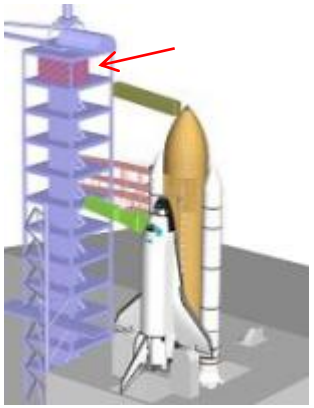
Example of Liftoff Debris Systems Engineering Process

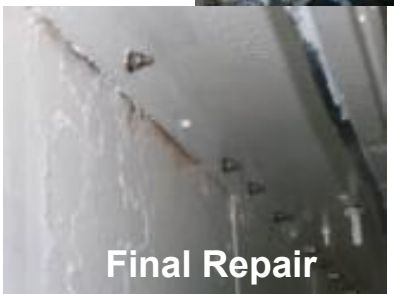
STS-119 revealed a bolt liberation trend on the Fixed Service Structure (FSS) 275' level elevator room





System Design Processes (1–4) **Product Realization Processes (5–9)** **Technical Management Processes (10–17)**

11) Bolts violated accepted risk (STS-120, STS-126, and STS-119)
15) LOD Team adds new debris finding to database, compares to existing entries, and identifies trend
3) LOD Team characterized analysis parameters (mass range, drag model, release timing, starting location, etc.)
16) MSFC analysts provided transport analysis showing criticality of this region and why this condition was unacceptable
17) LOD decided to elevate issue to management & KSC engineers through IFA process
1) LOD Team conveyed hazard to stakeholders [KSC, JSC, MSFC]
4) LOD Team coordinated with KSC engineers to ensure repair adequately mitigated the liberation of bolts
14) KSC updated configuration to reflect planned repair procedures
5) Interim repair verified each bolt was tight and applied RTV over bolt heads
10) Coordinated IIFA closure process
13) Due to repairs, no change in overall risk posture or requirements
13) Issue (as part of IIFA) documented in backup section of hazard report
7) Pad walkdown to check that repair was implemented per plan
8) Pad walkdown to check that the interim repair survived launch
5) Final repair replaced old bolts with new stainless steel fasteners
7) Pad walkdown to check that repair was implemented per plan
8) Pad walkdown to check that the final repair survived launch



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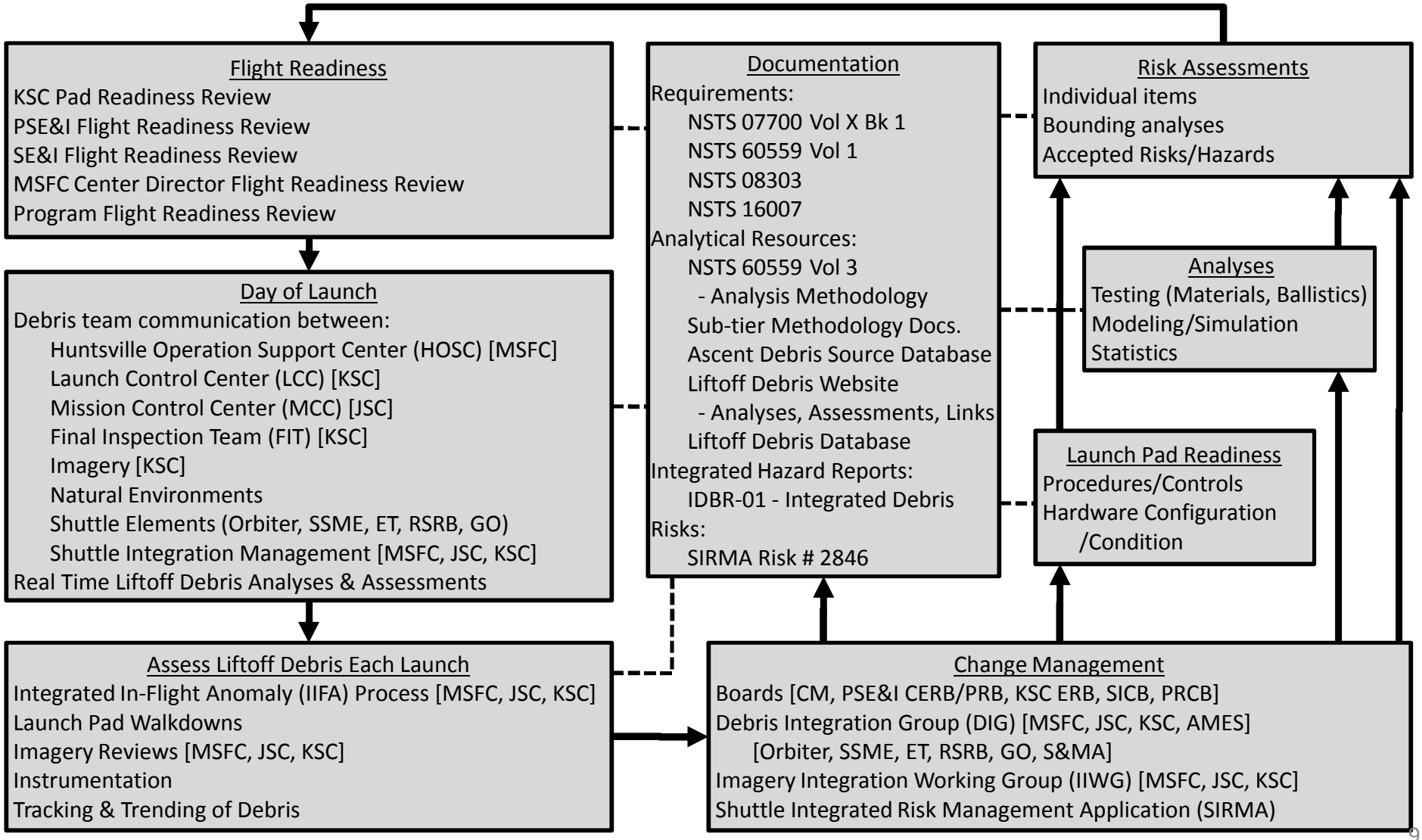
Liftoff Debris Operational Phase of Systems Engineering



Flight Readiness

- Certification of Flight Readiness (CoFR) for Liftoff debris includes
  - Lift-off debris from previous mission dispositioned
  - Flight acceptance rationale has been provided for Lift-off debris sources/causes
  - Lift-off debris mission support documentation, processes and tools are in place for the up-coming mission

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Day of Launch & Liftoff Debris Team Systems Engineering

MSFC Huntsville Operations Support Center (HOSC)

- Facilitates Space Shuttle Vehicle monitoring
- Provides capability to analyze launch data, and assist in day of launch problem resolution.
- Enables integrated connections among element prime contractors and the KSC Launch Control Center.

Liftoff Debris Team

- Assembles proper skills and resources
- Provides coordinated analytical transactions to characterize potential liftoff debris hazards
- Communicates among stakeholders via voice loops and emails
- Enables element hardware owners to assess risk posed by potential liftoff debris hazards

Day of Launch Communications

		MSFC	KSC	JSC
Oversight	Management	X	X	X
	Engineering	X	X	X
	Integration	X	X	X
	Safety	X	X	X
Element Hardware Assessments	Orbiter (Boeing)		X	X
	SSME (Pratt & Whitney)	X	X	
	ET (Lockheed Martin)	X	X	
	RSRB/RSRM (ATK/USA)	X	X	
	Ground Operations (USA)		X	
	Damage Assessment Team			X
Debris ID	Final Inspection Team		X	
	Imagery	X	X	
	Radar		X	
Debris Transport Analysis	Debris Integration Group	X	X	X
	Ascent Debris		X	X
	Liftoff Debris	X		

* Other support sites exist & are communicated with across the country

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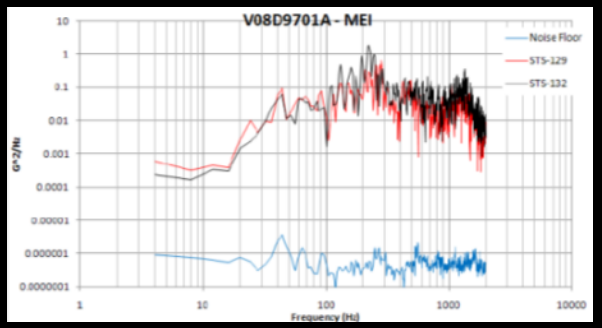
Liftoff Debris Data Collection After Each Launch

Compile & Synthesize Launch Data

Post Launch Pad Walk Down
Records Each Liftoff Debris Case

Imagery Reviews
(KSC JSC MSFC)



Instrumentation Data Reviews
Technical Panels (JSC & MSFC)

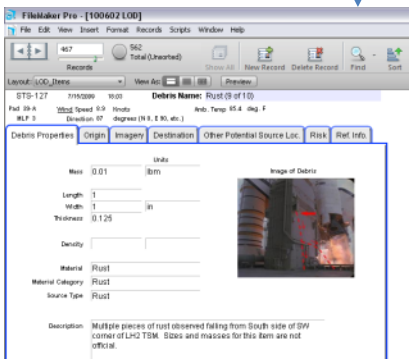
\+ Debris Source Identification

\+ Environmental Change
Identification & Analyses

Debris Database

Imagery Database

Instrumentation Databases



- Characterizes each debris item
- All Post Columbia Launches
- Database content:
  - -- Mission data (#, wind data, time, hardware)
  - -- Debris properties (mass, size, material, etc.)
  - -- Locations (pre- & post-launch)
  - -- Imagery info (camera observations, timing)
  - -- Resolution (mitigation or risk assessment)

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Assess Liftoff Debris Post Launch

In Flight Anomaly Resolution

Kennedy In Flight Anomaly (KIFA)

- Launch and Landing Debris
- Launch Support GSE and Facilities Abnormalities

Integrated In Flight Anomaly (IIFA) for LOD

- Debris Violations Prior To Pad Clearance

IFA Responsibilities

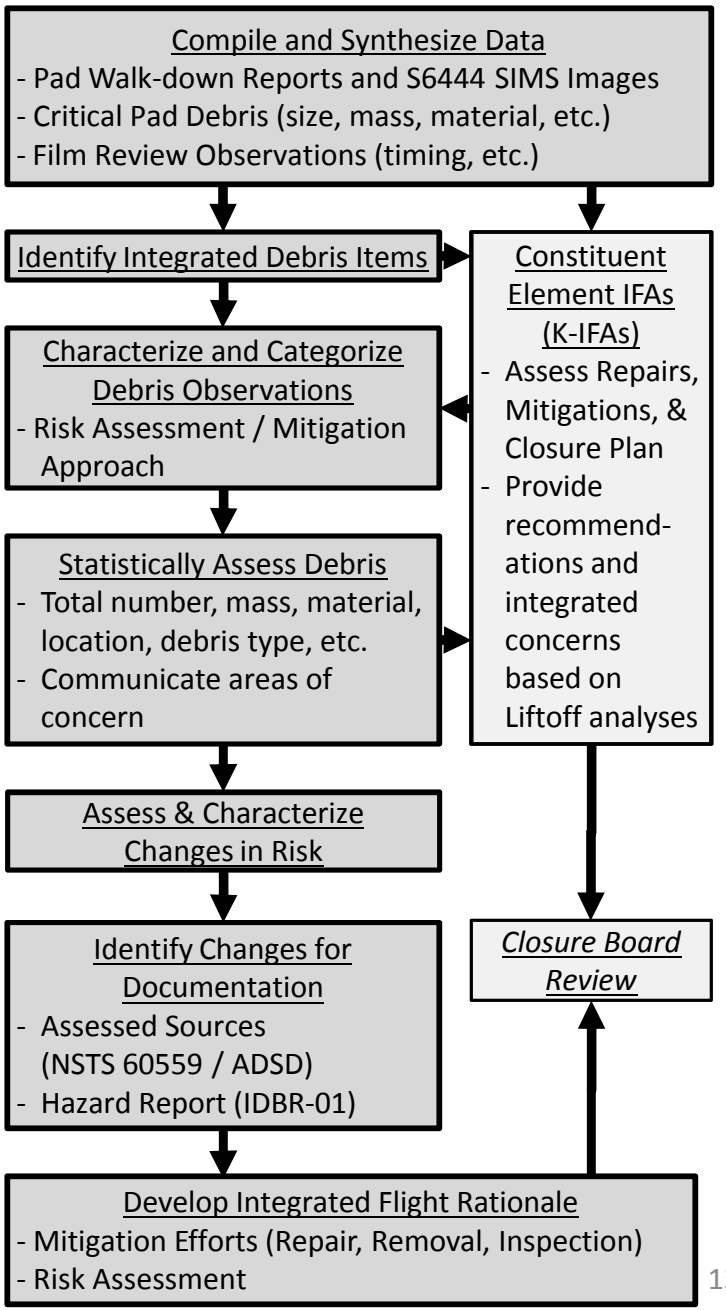
- KIFA
  - Assess anomalies
  - Coordinate expertise to evaluate potential issues for; launch support systems and facilities/or hazards
  - Promote corrective action
  - Document rationale
- IIFA
  - Assess anomalies
  - Coordinate expertise to evaluate potential cross element issues and/or impacts to integrated hazards.
  - Promote corrective action
  - Document rationale

IFA Adjudication Authorities related to LOD

- KIFA: KSC Engineering Review Board (ERB)
- IIFA: Systems Integration Control Board (SICB)

Reference: NSTS 08126 Problem Reporting and Corrective Action System Requirements

Integrated In-Flight Anomaly (IIFA) Resolution Process



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Change Management – Example Changes

Change Type	Associated Board, Panel, or Working Group
- Hardware removal or repair to acceptable state .	KSC ERB
- New/update debris controls at Launch Pad ……	KSC ERB, PSE&I CERB/PRB, SICB
- New/updated analyses ……	PSE&I CERB/PRB, DIG, SICB, Tech Panels (Aero, Thermal, etc.)
- New/updated instrumentation ……	KSC ERB, Tech Panels
- New/updated imagery ……..	IIWG, SICB
- New/updated risk assessment ……..	PSE&I CERB/PRB, SICB, MSERP, ISERP
- New/updated requirements ……	PSE&I CERB/PRB, SICB, PRCB

Legend of Acronyms

PSE&I	- Propulsion Systems Engineering & Integration
PSE&I PRB	- PSE&I Project Review Board
PSE&I CERB	- PSE&I Chief Engineer Review Board
KSC ERB	- Kennedy Space Center Engineering Review Board
SICB	- Systems Integration Control Board
PRCB	- Program Requirements Control Board
DIG	- Debris Integration Group
IIWG	- Imagery Integration Working Group
SIRMA	- Shuttle Integrated Risk Management Application
ISERP/MSERP	- Integrated/MSFC Safety Engineering Review Panel
Tech Panels	- Technical Panels (e.g. Aerodynamics, Loads & Dynamics, Thermal, Instrumentation, etc.)

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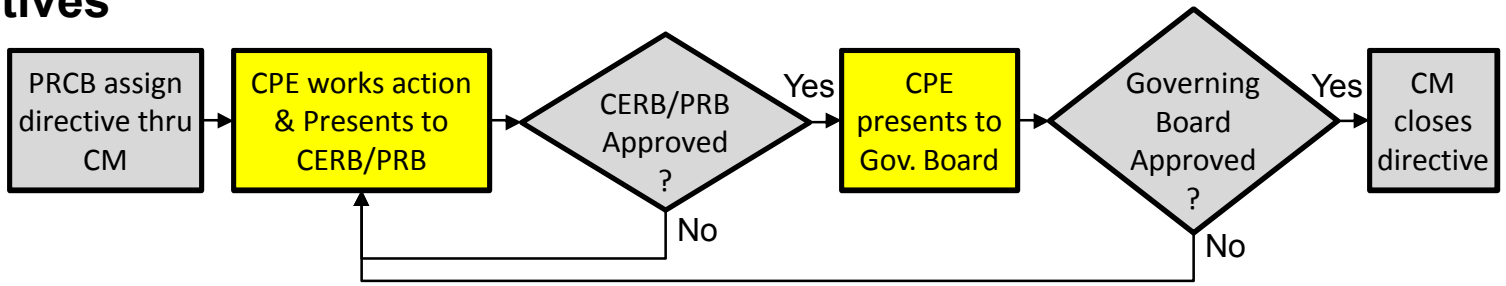
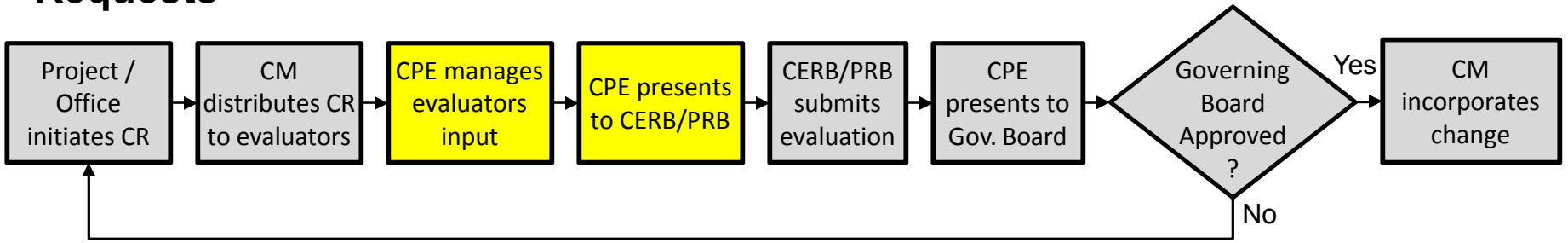
Elements of Change Management

Directives



Requests



CERB	-	Chief Engineer Review Board
CM	-	Configuration Management
CR	-	Change Request
CPE	-	Change Package Engineer
PRB	-	Project Review Board
PRCB	-	Program Requirements Control Board

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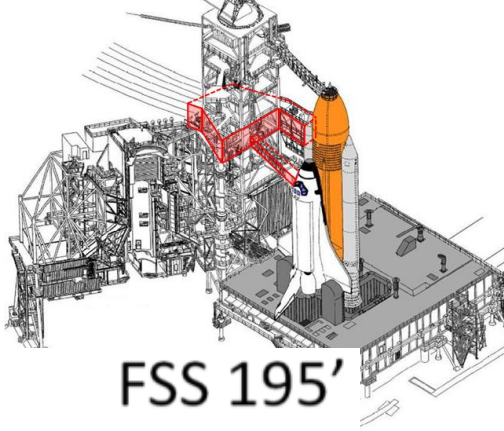
Launch Pad Readiness



Continuous Foreign Object Debris (FOD) Walk Down Inspections

- Multiple daily FOD inspections occur to limit FOD proximate to all SSV systems
- FOD database recorded metrics & findings

LOD Team Post Launch Pad Walk Down Inspections

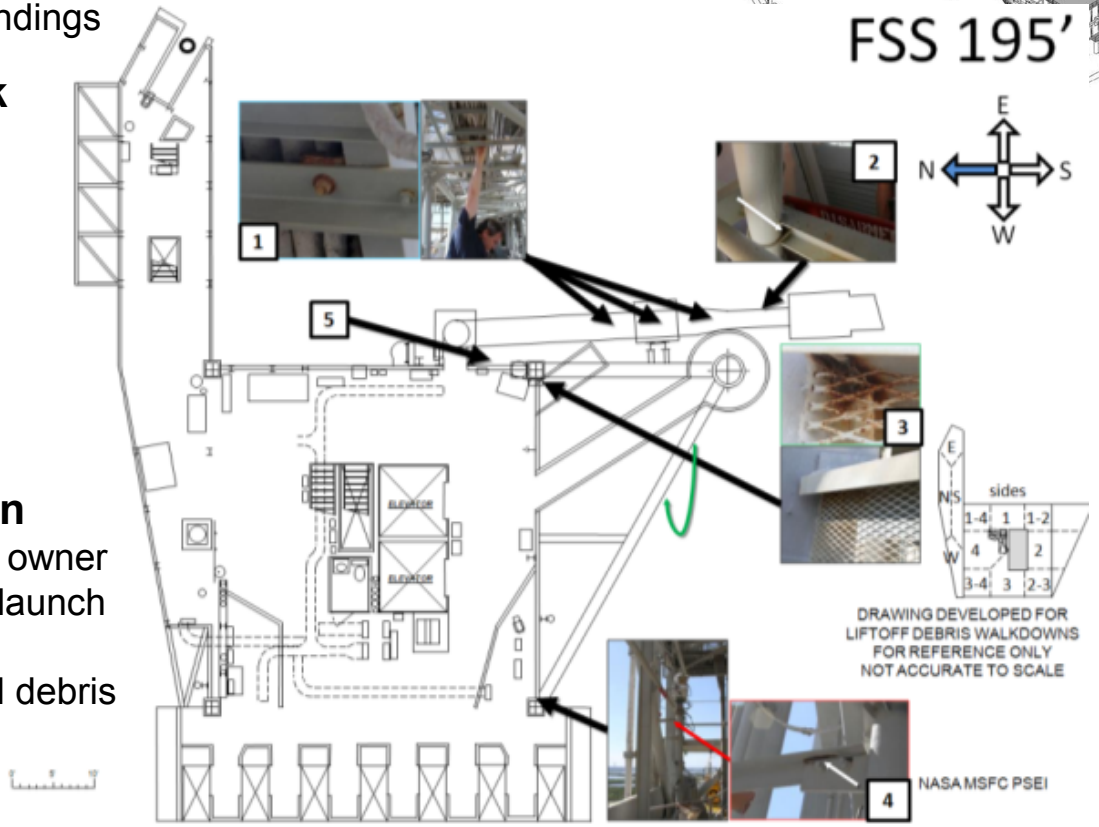
- Inspections occur ≤ T +7 days
- Assesses pad conditions
- Reports map liftoff debris concerns, with descriptions, and pictures
- Prioritizes KSC concerns for work prior to next launch

In Flight Anomaly (IFA) Resolution

- Closure rationale is produced by IFA owner
- Closure typically occurs before next launch
- Records corrective action
- Identifies statistical trends in nominal debris attributes

Pad Readiness Standings

- Launch pad repair & construction occurs pre-rollout
- KSC Pad Readiness Review certifies area for SSV rollout
  - Enhanced control requirements commence
- KSC Final inspection (T-4 hours)
- Perform DOL debris assessments as required



Example Launch Pad Walk Down Map

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Liftoff Debris Analyses

Objectives

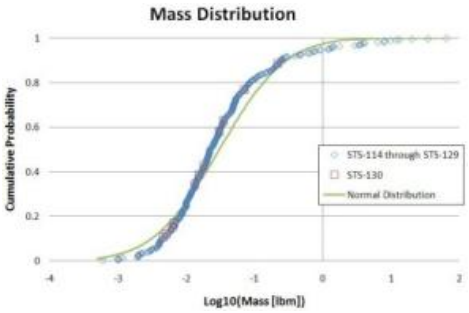
- Recognize liftoff debris hazards that put Space Shuttle systems at risk
- Reveal effective methods to control liftoff debris
- Understand the nature and surrounding conditions of liftoff debris

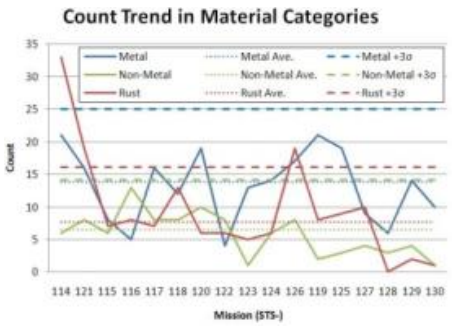
Subjects of Analysis

- Liberation
- Transport
- Damage Tolerance

Expertise & Resources

- Shuttle Projects:
  - SE&I, OV, ET, SSME, RSRB, RSRM , Prime Contractors
- Engineering:
  - Propulsion Systems, Materials & Processes, Impact Tests, Ballistics, Models, Simulations
- Safety & Mission Assurance:
  - Statistical & Probabilistic Analysis, Hazard Analysis





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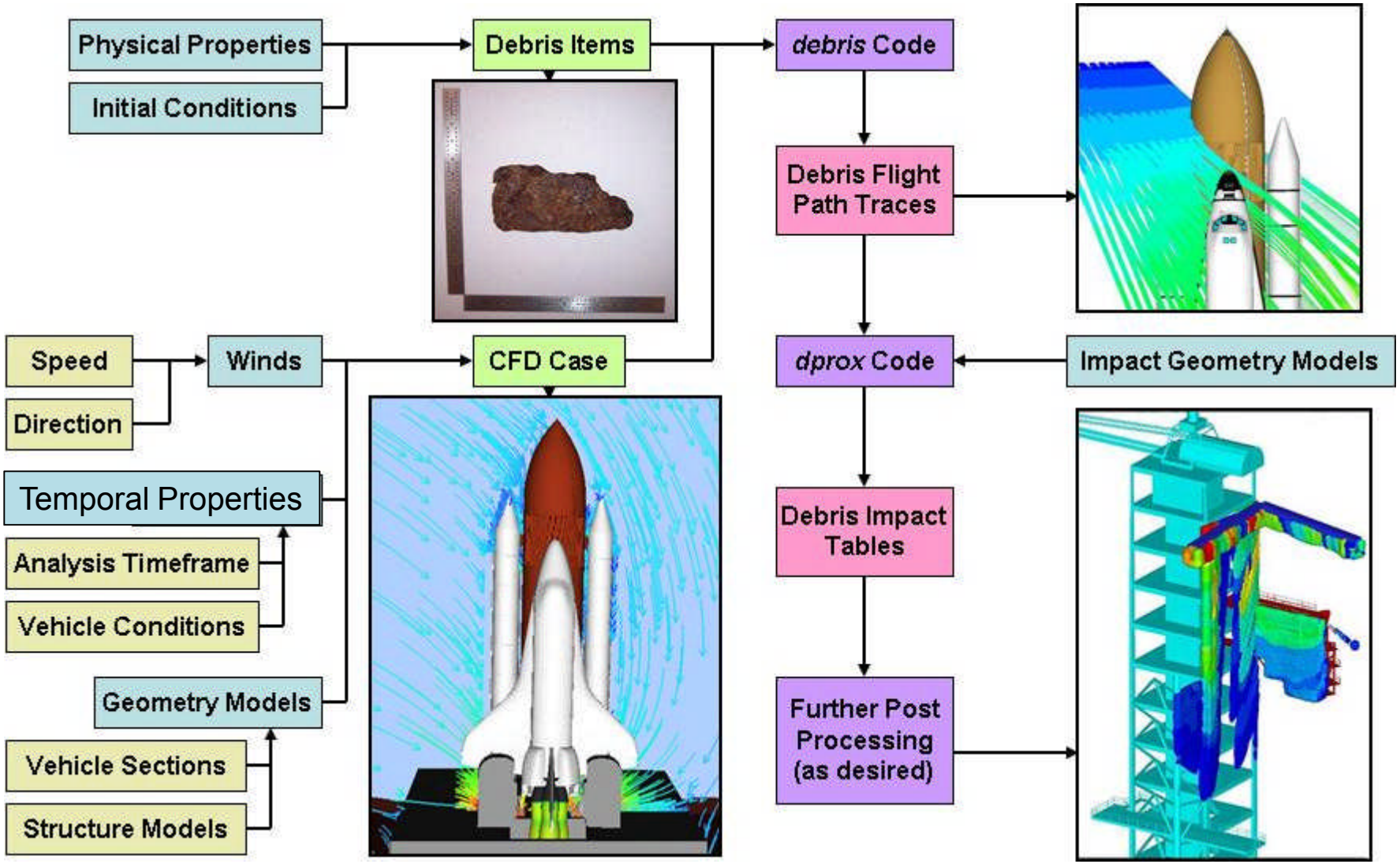
Debris Transport Analysis Process



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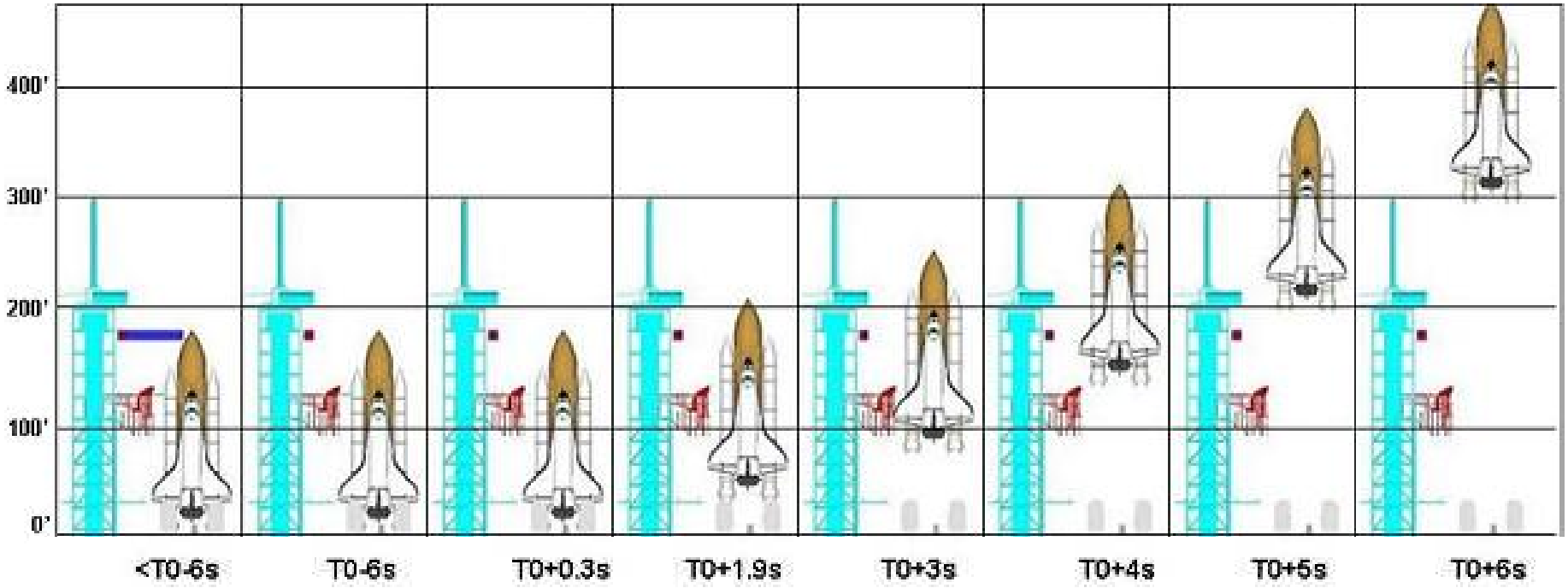
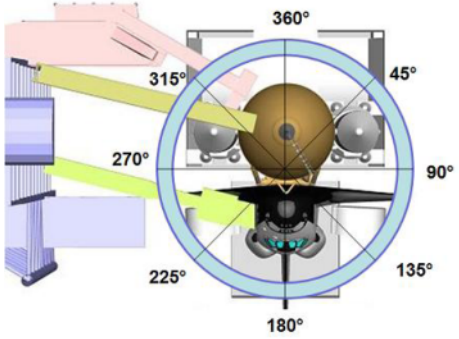
Temporal and Spatial Framework of Analyses

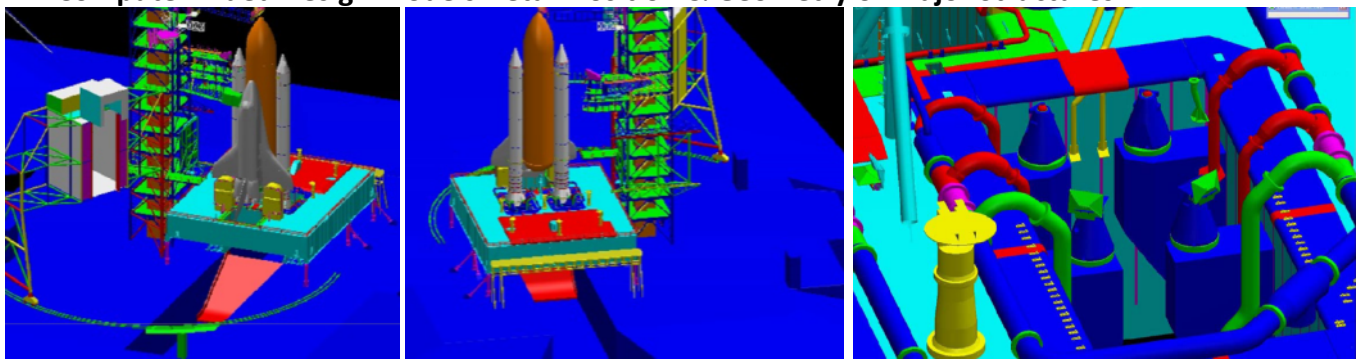
Typical Vehicle Position with Time During Liftoff



Wind Directions With Respect to Shuttle & Pad Structures



Computer Aided Design Models Detail Position & Geometry of Major Structures



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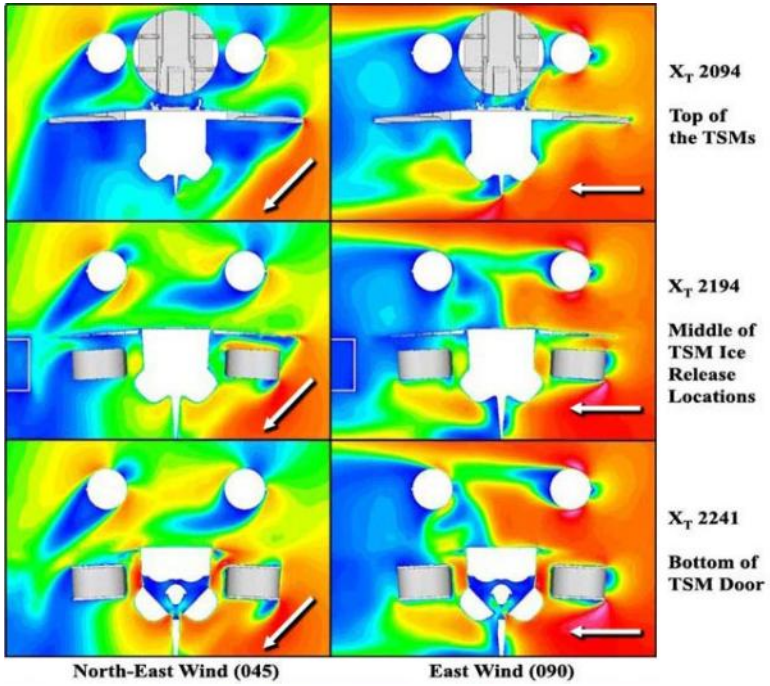
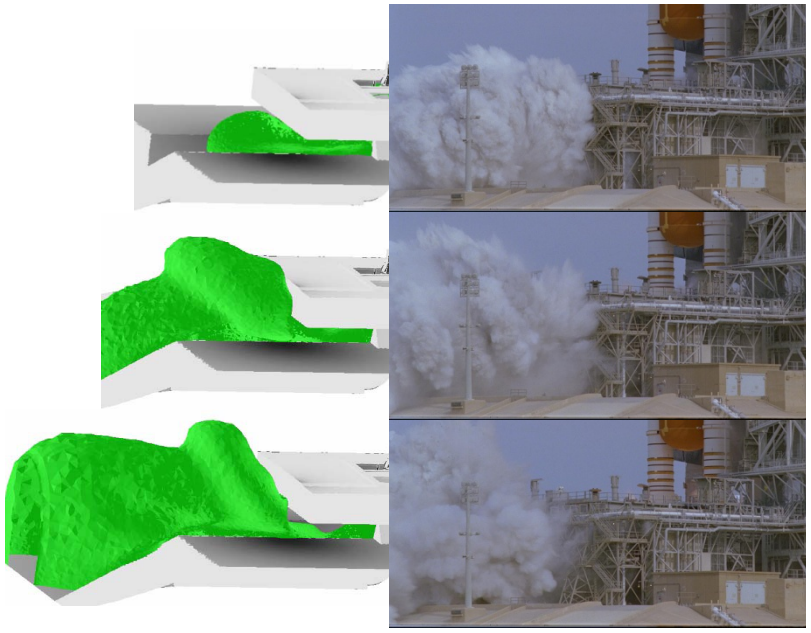
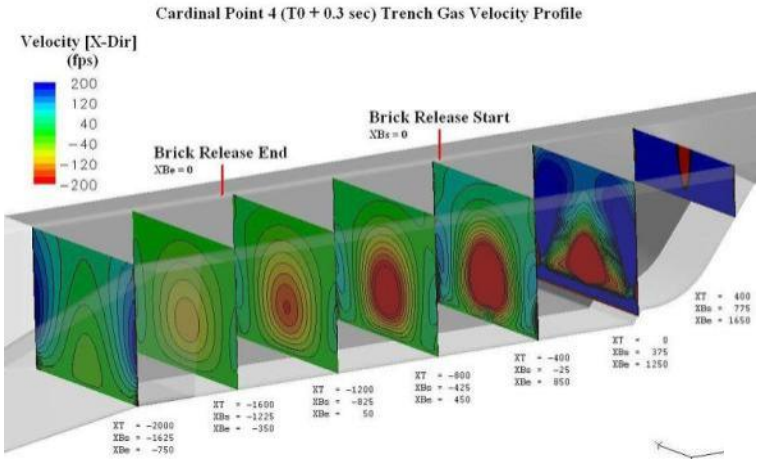
Computational Fluid Dynamics (CFD) Analyses

- Simulate Interaction of Wind and Plumes with the Vehicle and Launch Pad Structure
  - Transient Models
  - Steady State Models
- Quantify parameters to enable debris transport analyses
  - Wind & Gravity Features
  - Plume Entrainment & Plume Driven Features
- Complete model validations via comparison with actual launch data imagery and instrumentation records







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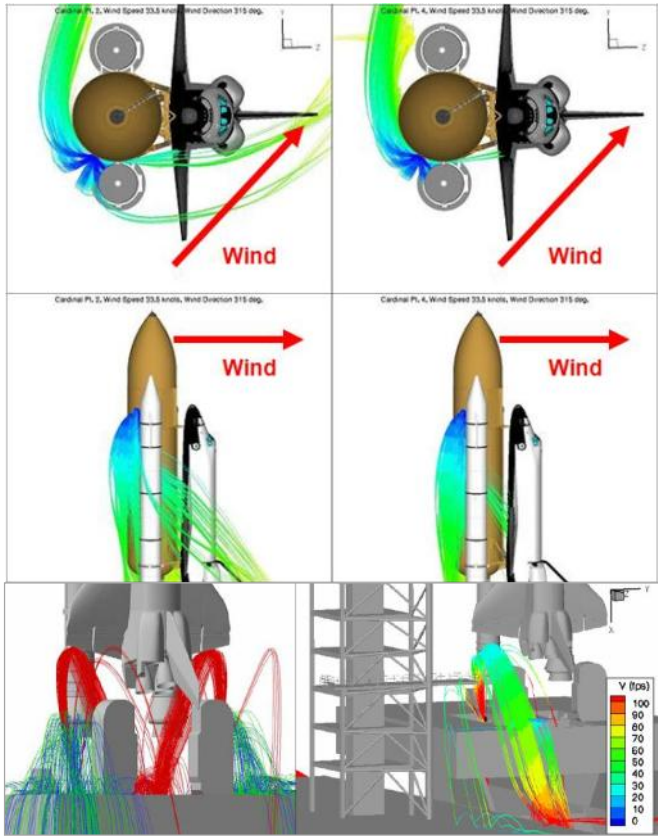
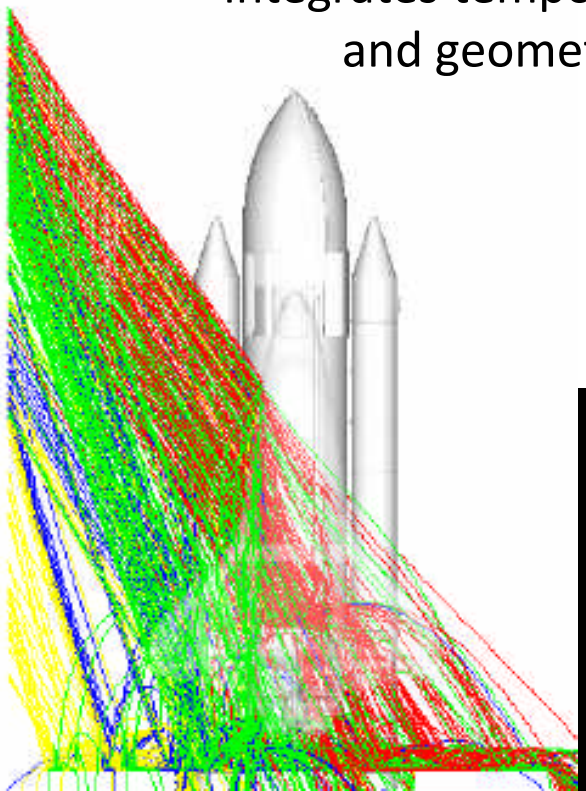
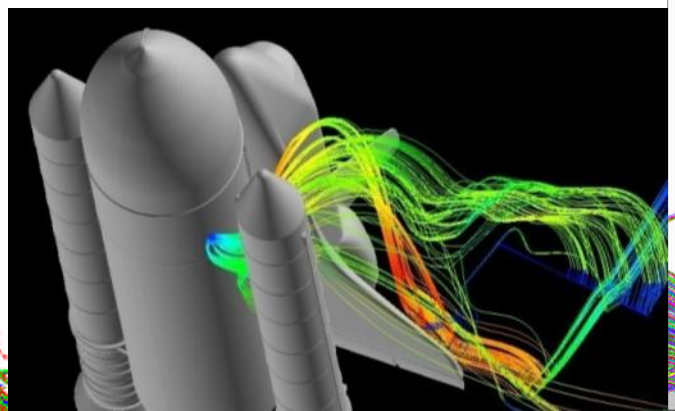
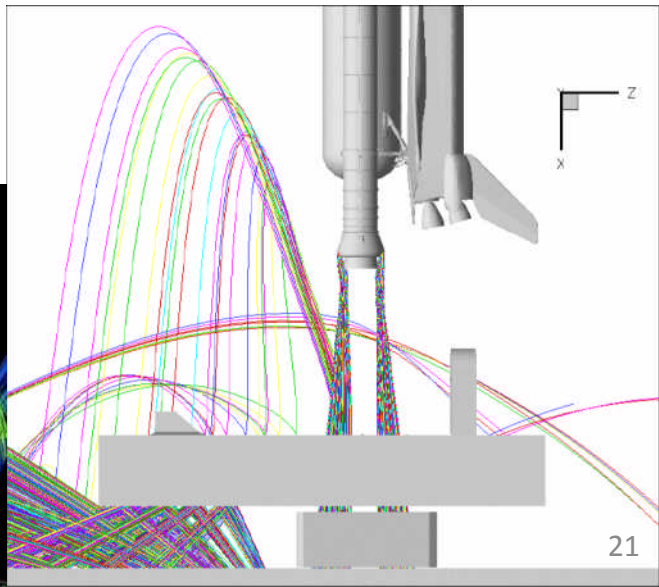
Debris Transport Analyses (DTA)

- DTA reveals time, position, velocity, and impact energy for specific debris shapes and densities
  - Uses CFD generated flow field environments
  - Integrates temporal, atmospheric, physical and geometric properties into analysis









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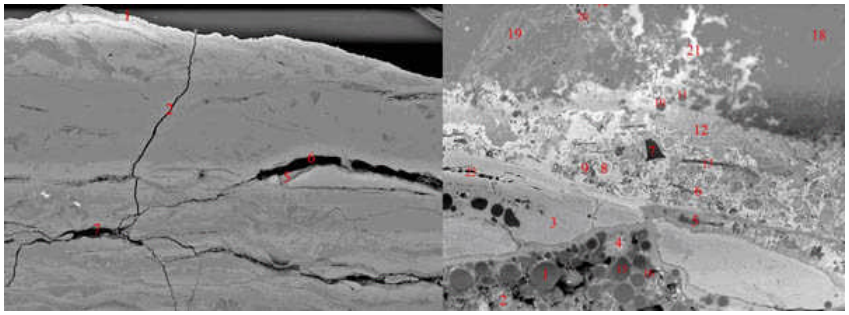
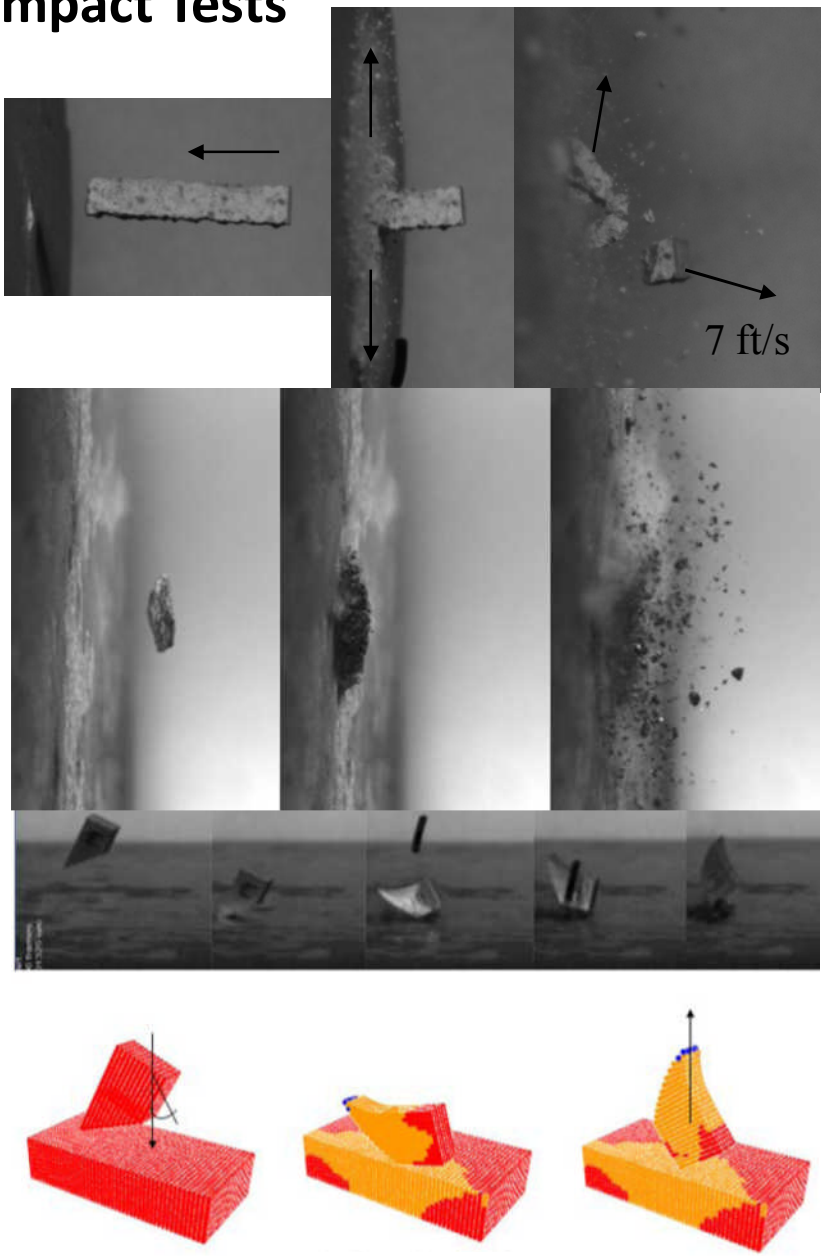
Analyzing Debris Materials & Impact Tests

- Materials tests & analyses
  - Reveals compositions & densities
  - Verifies specifications & processes
  - Provides key aspects in failure diagnostics
- Impact tests & analyses
  - Provides basis to establish debris transport boundaries
  - Reveals features of impactor break-up and rebound
  - Demonstrates impact vulnerability of flight hardware to specific impactor
  - Validates impact models



SEM Imagery of Rust

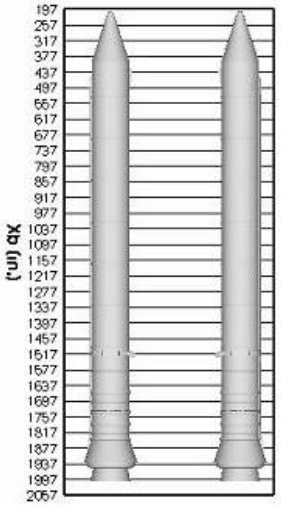


Impact Analyses

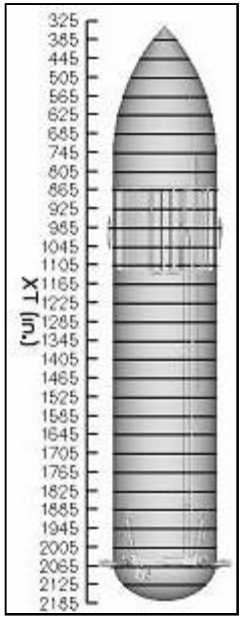
- Damage threshold specifications are element project office responsibility
- DTA results are sorted into position bins according to element
  - SRB, ET, SSME and Orbiter
- Orbiter DTA results are sorted into bins according to surface material
  - FRSI, LRSI, AFRSI, RCC, HRSI Upper, HRSI Lower, and Windows

SSME Surfaces

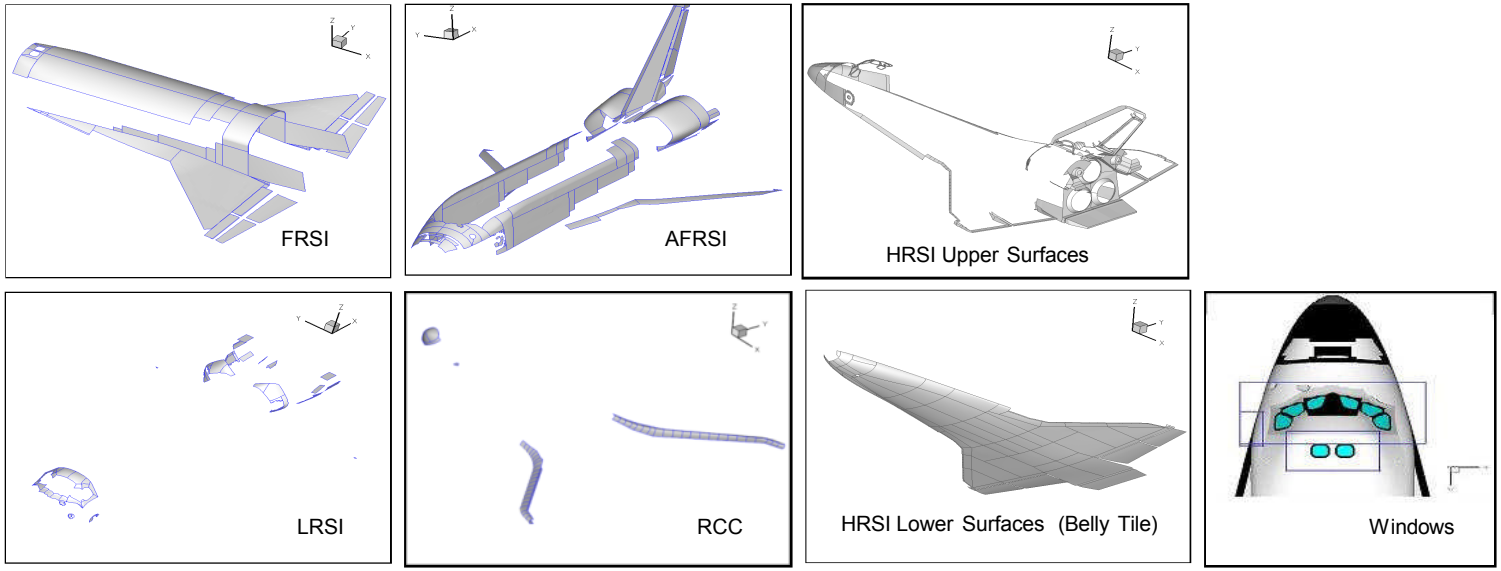
RSRM/SRB Surfaces



ET Surfaces



Orbiter Surfaces



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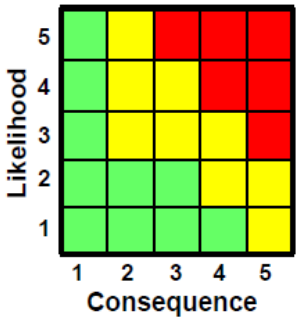
Shuttle Integrated Risk Management

Likelihood Rating	
5	**Very Likely:** ~10^{-1} Expected to happen.
4	**Likely:** ~10^{-2} Could happen. Controls have significant limitations or uncertainties.
3	**Possible:** ~10^{-3} Could happen. Controls exist with some limitations or uncertainties.
2	**Unlikely:** ~10^{-4} Not expected to happen. Controls have minor limitations or uncertainties.
1	**Highly Unlikely:** ~10^{-5} Extremely remote possibility that it will happen. Strong controls in place.



Identify and Assess Risk

1. **Start with a Concern.** Is this a program risk?
   - What information is available? Gather information: requirements status, problem data, trends, hazards, critical item history, etc.
2. **Define Risk Statement.**
   - Given the condition _(A)_ , there is a possibility that _(B)_ will occur.
     - (A) - Single phrase briefly describing current key circumstances or situations that are causing concern, doubt, anxiety, or uncertainty
     - (B) - Consequences or impacts of the current conditions that could be realized due to (A)
3. **Define the Consequences (B).** Locate the most accurate description(s) among the Safety, Mission Success, Supportability, Cost, and Schedule consequence descriptions.
4. **How likely is this risk scenario?** Likelihood is the chance of a risk occurring.
   - Evaluating the likelihood rating requires subjective judgment. Select the most accurate rating based on the quantitative values or the qualitative descriptions.
   - Only one rating is selected per risk statement. It is evaluated for the period being assessed.
5. **Plot the Risk.** Select the highest consequence score. Plot this against the ONE Likelihood Score on the RED/YELLOW/GREEN risk matrix.

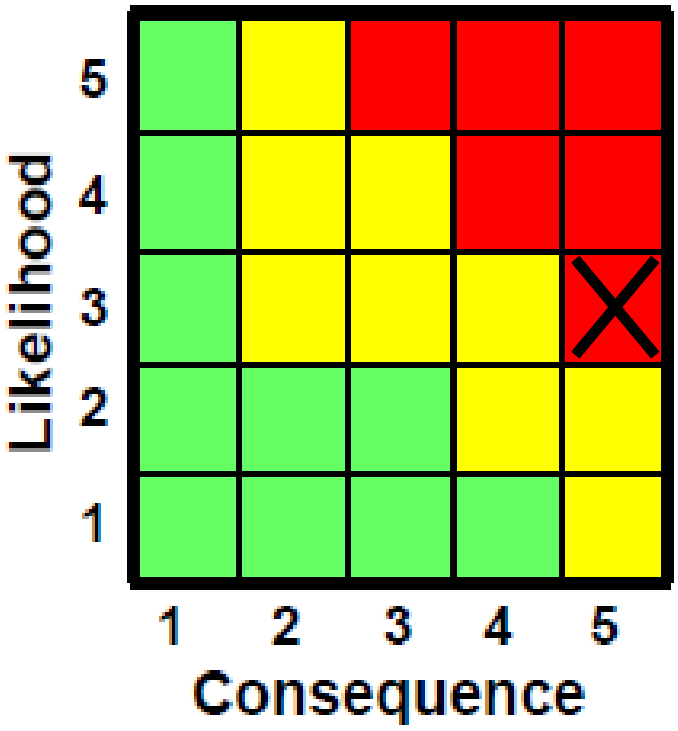
Consequence Rating			1	2	3	4	5
TECHNICAL	Safety	*Human Health*	- Minor or first aid injury	- Moderate injury, illness, incapacitation or impairment	- Significant or long-term injury, illness, incapacitation or impairment	- Permanent or major injury, illness, incapacitation or impairment	- Death
		System Safety	- Damage to non-flight Critical assets	- Loss of non-flight critical assets	- Damage to major element(s) of flight vehicle or ground facility	- Loss of major element(s) of flight vehicle or ground facility	- Loss of program
		Environmental Safety	- Minor environmental impact	- Moderate environmental impact	- Significant environmental impact	- Major environmental impact	- Catastrophic environmental impact
		HSE Compliance	- Minor non-compliance	- Moderate non-compliance	- Significant non-compliance	- Major non-compliance	- None defined
	Mission Success	*Shuttle Operations*	- Minor increase in flight operations timelines or complexity	- Failure to achieve any planned SSP mission objective	- Minimum duration flight (MDF) - Significant increase in flight operations timelines or complexity	- Failure to achieve all Shuttle major mission objectives (MMO) - Early mission termination - Pad abort or intact abort	- Contingency abort - Shuttle crew evacuation
		ISS Operations	- None defined	- Failure to achieve any planned ISS mission objective	- None defined	- Failure to support assembly critical ISS requirements	- ISS evacuation
		SSP Developmental Activities	- Failure to meet developmental requirements, minor workarounds or temporary waivers required for flight	- None defined	- Inability to complete commit to flight test, analysis or certification - Failure to meet developmental requirements. Significant or permanent waivers required for flight	- Failure to meet key development requirements (e.g. performance)	- None defined
	Supportability	*Capability to Maintain SSP Assets*	- Temporary usage loss or LOCM of non-flight critical asset	- Permanent usage loss or LOCM of non-flight critical asset	- Temporary usage loss or LOCM of major element(s) of flight vehicle or ground facility	- Permanent usage loss or LOCM of major element(s) of flight vehicle or ground facility	- Inability to support further Shuttle flight operations
		Flight Processing	- Collateral damage to non-flight critical assets during processing	- Moderate increase timeline or complexity	- Collateral damage to major element(s) of flight vehicle or ground facility during processing - Significant increase timeline or complexity	- Loss of major element(s) of flight vehicle or ground facility due to direct or collateral damage during processing	- None defined
PROGRAMMATIC	Schedule	*SSP / ISS Schedule*	- Minor operational slips	- Less than 7-day slip in an SSP/ISS freeze point or milestone	- Greater than 7-day slip in an SSP/ISS freeze point or milestone - ISS hardware/software delivery date not met for on-orbit needs	- One flight decrease from baselined manifest - One mission increase in ISS assembly plan - Flight delay occurring pre-FRR - SSP/ISS milestone slip of more than one month	- Two or more flight decrease from baselined manifest - Two or more mission increase in ISS assembly plan - Flight delay after L-2 - Cannot achieve major SSP/ISSP milestone
	Cost	*Risk Recovery Cost*	< $1 M	$1 M - $5 M	$5 M - $15 M	$15 M - $25 M	> $ 25 M

9/18/2006

Reference NSTS 07700, Volume XIX

Risk Assessments

- Baseline liftoff debris assessment methodology
  - Identify and characterize key types of persistent debris
  - Characterize key debris types
    - Source locations
    - Material
    - Risk assessment mass
  - DTA to prioritize hazardous source locations of debris
  - Record statistics of debris attributes
- Assign mitigation for each debris items
  - Limit debris occurrence through mitigation
  - Establish mitigation categories
  - Identify limitations in analyses and mitigation controls
- Assess effectiveness and trends
  - Quantify debris: instances, types, masses, locations, mitigations, etc.
  - Ascertain changes in debris attributes
  - Develop statistical trends
    - Establish normal boundaries
    - Detect outliers to investigate further
  - Qualify debris hazards based on bounding assumptions
- Compare changes to previous risk assessment
- Communicate risk to Space Shuttle Program for disposition



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Lessons Learned to Mitigate Liftoff Debris Risk

- Systems Engineering process can be effectively applied to mitigate liftoff debris for future space launch systems

- Require launch pad design metrics to minimize liftoff debris generation
  - Design structures without places for debris to hide
  - Avoid designing areas difficult to access for repair of rust/corrosion
  - Establish pad cleanliness standards
  - Minimize hardware closest to vehicle

- Plume driven debris is a significant hazard due to high energy content
  - Avoid protrusions in plume flow that can direct flow upward toward the vehicle
  - Multi-plume interaction on launch pad deck produces transient fountain effect with upward flow
  - If upward flows exist, mitigate them (e.g. intense water flow)

- Integrate appropriate liftoff debris and system owner expertise into launch facility walkdown inspections

- Integrate imagery surveillance into liftoff debris analyses

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Shuttle Integrated Risk from Liftoff Debris

- Catastrophic damage is possible given history of debris releases during liftoff
- All elements are vulnerable to some debris sources
- Liftoff debris hazard is documented in Integrated Hazard Report IDBR-01
- Significant uncertainties exist in characterizing the liftoff debris environment through observation and analysis

Space Shuttle Program accepted risk to vehicle due to liftoff debris

- NSTS 60559 Vol III - Liftoff Debris Assessment Methodology
- Liftoff debris mitigation steps and handling processes are documented
- Emergent liftoff debris mitigations are resolved on per flight basis