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.
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Examples: Space Shuttle Program Liftoff Debris

Fastener

Rust

Rust

Bolt

Gauge Bezel

Throat Plug

Foreign Object Debris
National Aeronautics and Space Administration

NASA Systems Engineering Process  (NPR 7123.1A)
National Aeronautics and Space Administration
Liftoff Debris Systems Engineering Process

System Design

Requirements Definitions Processes
1. Stakeholder Expectations Definition
   - Columbia Accident Investigation Board (CAIB) Report
   - KSC, JSC, MSFC
   - Shuttle Element Projects (e.g. Orbiter, External Tank, etc)
2. Technical Requirements Definition
   - NSTS 07700
   - NSTS 60559
   - NSTS 16007

Technical Solution Definition Processes
3. Logical Decomposition
   - Liberation
   - Transport
   - Damage Tolerance
4. Design Solution Definition
   - Mitigation processes (disposition categories)
   - Tests, Maps, Models, Simulations, & Databases

Technical Planning Process
10. Technical Planning
   - Testing
   - Analyses

Technical Control Processes
11. Requirements Management
   - Technical Boards
12. Interface Management
   - Launch Pad Controls
   - Walkdowns
13. Technical Risk Management
   - LOD Risk Management
   - IDBR-01
14. Configuration Management
   - CRs & Process
15. Technical Data Management
   - Models & Analyses
   - Database
   - Mapping Tool

Technical Assessment Process
16. Technical Assessment
   - Walkdowns
   - IIFA Process
   - Statistical trending
   - Imagery Review

Technical Decision Analysis Process
17. Decision Analysis
   - DOL Analyses
   - What needs to be improved

Product Realization

Product Transition Process
9. Product Transition
   - Resource/Asset Transaction
   - Improvements
   - Lessons learned
   - Closeout

Evaluation Processes
7. Product Verification
   - Imagery Review
   - Models
   - Statistics
   - Testing (Material, Ballistic, Wind Tunnel)
   - Debris Sims

Design Realization Processes
5. Product Implementation
   - Pad Repair Process
   - Inspection Process
6. Product Integration
   - KSC ERB
   - PSE&I CERB/PRB
   - DIG
   - FRR Process

1. Stakeholder Expectations Definition
2. Technical Requirements Definition
3. Logical Decomposition
4. Design Solution Definition

5. Product Implementation
6. Product Integration
7. Product Verification
8. Product Validation

9. Product Transition
10. Technical Planning Process
11. Requirements Management
12. Interface Management
13. Technical Risk Management
14. Configuration Management
15. Technical Data Management

16. Technical Assessment
17. Decision Analysis

Requirements Definitions Processes
- Stakeholder Expectations Definition
- Technical Requirements Definition
- Logical Decomposition
- Design Solution Definition

Technical Planning Process
- Testing
- Analyses

Technical Control Processes
- Requirements Management
- Interface Management
- Technical Risk Management
- Configuration Management
- Technical Data Management

Technical Assessment Process
- Technical Assessment
- Decision Analysis

Technical Decision Analysis Process
- What needs to be improved

Resource/Asset Transaction
- Improvements
- Lessons learned
- Closeout
STS-119 revealed a bolt liberation trend on the Fixed Service Structure (FSS) 275’ level elevator room.


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
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
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

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<tr>
<th>Element Hardware Assessments</th>
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<th>KSC</th>
<th>JSC</th>
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* 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)

- Environmental Change
  Identification & Analyses

**Debris Database**

- 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
Change Management – Example Changes

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

1. **PRCB assign directive thru CM**
2. **CPE works action & Presents to CERB/PRB**
3. **CERB/PRB Approved?**
   - Yes: **CPE presents to Gov. Board**
   - No: **No**
4. **Governing Board Approved?**
   - Yes: **CM closes directive**
   - No: **No**

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

### Requests

1. **Project / Office initiates CR**
2. **CM distributes CR to evaluators**
3. **CPE manages evaluators input**
4. **CPE presents to CERB/PRB**
5. **CERB/PRB submits evaluation**
6. **CPE presents to Gov. Board**
7. **Governing Board Approved?**
   - Yes: **CM incorporates change**
   - No: **No**

**Definitions:**
- CERB - Chief Engineer Review Board
- CM - Configuration Management
- CR - Change Request
- CPE - Change Package Engineer
- PRB - Project Review Board
- PRCB - Program Requirements Control Board
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
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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:
- Safety & Mission Assurance:
  - Statistical & Probabilistic Analysis, Hazard Analysis
Debris Transport Analysis Process

1. Physical Properties → Debris Items
2. Initial Conditions
3. Temporal Properties
   - Analysis Timeframe
   - Vehicle Conditions
   - Geometry Models
4. Speed → Winds
5. Direction
6. CFD Case
7. Debris Flight Path Traces
8. dprox Code
9. Debris Impact Tables
10. Further Post Processing (as desired)
11. Impact Geometry Models
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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
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

7 ft/s
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
## Shuttle Integrated Risk Management

### Likelihood Rating

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<td>Highly Unlikely: $10^{-5}$</td>
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### Consequence Rating

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### Reference

Reference NTS 07700, Volume XIX

9/18/2006
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
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 a per flight basis