National Aeronautics and Space Administration

Space Shuttle Systems Engineering Processes for Liftoff Debris Risk Mitigation

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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.
Examples: Space Shuttle Program Liftoff Debris

- Fastener
- Bolt
- Foreign Object Debris
- Rust
- Gauge Bezel
- Throat Plug
- Bezel

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NASA Systems Engineering Process (NPR 7123.1A)
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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 Management

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
8. Product Validation
   - 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
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
Liftoff Debris Operational Phase of Systems Engineering

**Documentation**
- Requirements:
  - NSTS 07700 Vol X Bk 1
  - NSTS 60559 Vol 1
  - NSTS 08303
  - NSTS 16007
- Analytical Resources:
  - NSTS 60559 Vol 3
  - Analysis Methodology
  - Sub-tier Methodology Docs.
  - Ascent Debris Source Database
  - Liftoff Debris Website
  - Analyses, Assessments, Links
  - Liftoff Debris Database
- Integrated Hazard Reports:
  - IDBR-01 - Integrated Debris Risks:
    - SIRMA Risk # 2846

**Risk Assessments**
- Individual items
- Bounding analyses
- Accepted Risks/Hazards

**Analyses**
- Testing (Materials, Ballistics)
- Modeling/Simulation
- Statistics

**Launch Pad Readiness**
- Procedures/Controls
- Hardware Configuration/Condition

**Change Management**
- Boards [CM, PSE&I CERB/PRB, KSC ERB, SICB, PRCB]
- Debris Integration Group (DIG) [MSFC, JSC, KSC, AMES]
  - [Orbiter, SSME, ET, RSRB, GO, S&MA]
- Imagery Integration Working Group (IIWG) [MSFC, JSC, KSC]
- Shuttle Integrated Risk Management Application (SIRMA)
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

<table>
<thead>
<tr>
<th>Element Hardware Assessments</th>
<th>MSFC</th>
<th>KSC</th>
<th>JSC</th>
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<tbody>
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<td>Debris Transport Analysis</td>
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<tr>
<td>Liftoff Debris</td>
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</table>

* 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

- 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)

Post Launch Pad Walk Down
Records Each Liftoff Debris Case

Imagery Reviews (KSC JSC MSFC)

Instrumentation Data Reviews
Technical Panels (JSC & MSFC)

Debris Database

Imagery Database

Instrumentation Databases

Environmental Change Identification & Analyses

Debris Source Identification

Instrumentation Databases

Technical Panels (JSC & MSFC)
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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
- IIIFA
  - 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)
- IIIFA: 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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</thead>
<tbody>
<tr>
<td>- Hardware removal or repair to acceptable state</td>
<td>KSC ERB</td>
</tr>
<tr>
<td>- New/update debris controls at Launch Pad</td>
<td>KSC ERB, PSE&amp;I CERB/PRB, SICB</td>
</tr>
<tr>
<td>- New/updated analyses</td>
<td>PSE&amp;I CERB/PRB, DIG, SICB, Tech Panels (Aero, Thermal, etc.)</td>
</tr>
<tr>
<td>- New/updated instrumentation</td>
<td>KSC ERB, Tech Panels</td>
</tr>
<tr>
<td>- New/updated imagery</td>
<td>IIWG, SICB</td>
</tr>
<tr>
<td>- New/updated risk assessment</td>
<td>PSE&amp;I CERB/PRB, SICB, MSERP, ISERP</td>
</tr>
<tr>
<td>- New/updated requirements</td>
<td>PSE&amp;I CERB/PRB, SICB, PRCB</td>
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</tbody>
</table>

## 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.)
Elements of Change Management

Directives

- PRCB assigns directive through CM
- CPE works action & Presents to CERB/PRB
- CERB/PRB: Yes
- CPE presents to Governing Board
- Governing Board: Yes
- CM closes directive

Requests

- Project/Office initiates CR
- CM distributes CR to evaluators
- CPE manages evaluators input
- CPE presents to CERB/PRB
- CERB/PRB: Yes
- CPE presents to Governing Board
- Governing Board: Yes
- CM incorporates change

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
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

Physical Properties → Debris Items → debris Code

Temporal Properties
- Analysis Timeframe
- Vehicle Conditions

Geometry Models
- Vehicle Sections
- Structure Models

Speed → Winds → CFD Case → dprox Code

Impact Geometry Models

Debris Flight Path Traces

Debris Impact Tables

Further Post Processing (as desired)
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
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

Refractory

Rust

Inconel

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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<th>Description</th>
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<td>5</td>
<td>Very Likely: (-10^3)</td>
<td>Expected to happen.</td>
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<td>4</td>
<td>Likely: (-10^2)</td>
<td>Could happen. Controls have significant limitations or uncertainties.</td>
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<tr>
<td>3</td>
<td>Possible: (-10^1)</td>
<td>Could happen. Controls exist with some limitations or uncertainties.</td>
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<tr>
<td>2</td>
<td>Unlikely: (-10^0)</td>
<td>Not expected to happen. Controls have minor limitations or uncertainties.</td>
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<tr>
<td>1</td>
<td>Highly Unlikely: (-10^0)</td>
<td>Extremely remote possibility that it will happen. Strong controls in place.</td>
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## Consequence Rating

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<td>Minor or first aid injury</td>
<td>Moderate injury, illness, incapacitation or impairment</td>
<td>Significant or long-term injury, illness, incapacitation or impairment</td>
<td>Permanent or major injury, illness, incapacitation or impairment</td>
<td>Death</td>
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<td>Greater than 7-day delay in an SSP/ISS free flight point or milestone</td>
<td>SSP/ISS milestone slip of more than one month</td>
<td>Two or more flight delays over 30 days</td>
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<td>Cost</td>
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<td>$15\text{M} - 50\text{M}$</td>
<td>$&gt;50\text{M}$</td>
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</table>

**Reference:** NSTS 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 per flight basis