Development Testing and Subsequent Failure of a Spring Strut Mechanism

Jared Dervan (NASA MSFC)
Brandan Robertson (NASA JSC)
Lucas Staab (NASA GRC)
Michael Culberson (LMSSC)
Joseph Pellicciotti (NASA GSFC)

Agenda

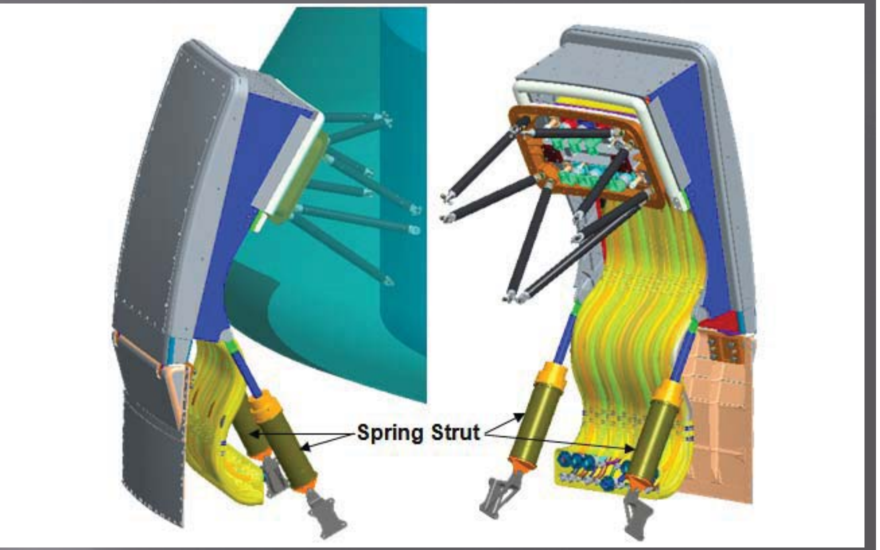
Presenter
Jared Dervan
Date
May 15, 2014

- Background & Approach
- Hardware Description
- Development Testing
- Root Cause Investigation
- Failure Scenario Summary and Supporting Rationale
- Follow-on Development Testing
- Lessons Learned
- Conclusion

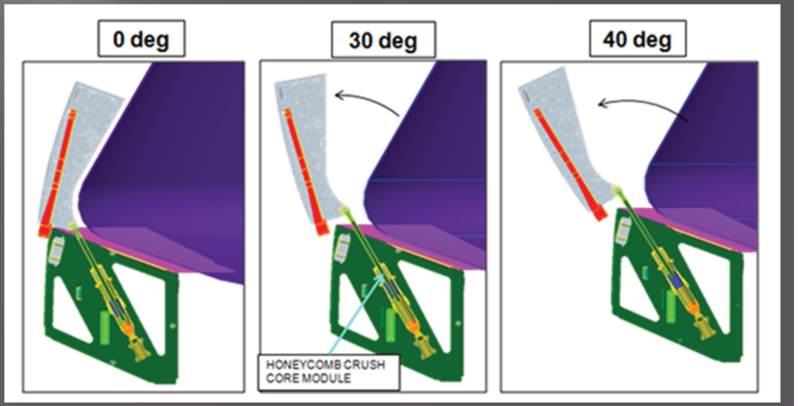
Background & Approach

Presenter
Jared Dervan
Date
May 15, 2014

- **Background**
  - Commodities transferred between CM-SM via external umbilical
  - Dual spring-loaded struts drive umbilical away during separation
  - No vibration testing on strut development units scoped in Orion Multi Purpose Crew Vehicle (MPCV) program plan



Spring Strut in Stowed Configuration



Umbilical Separation

Background & Approach

Presenter
Jared Dervan
Date
May 15, 2014

- **Background (contd.)**
  - Problems discovered on other Orion spring assemblies during vibration testing (e.g. Spacecraft Adapter Fairing Jettison Spring (SAFJS) Assembly)

SAFJS Assembly

SAFJS Assembly Wear Post Vibration Testing

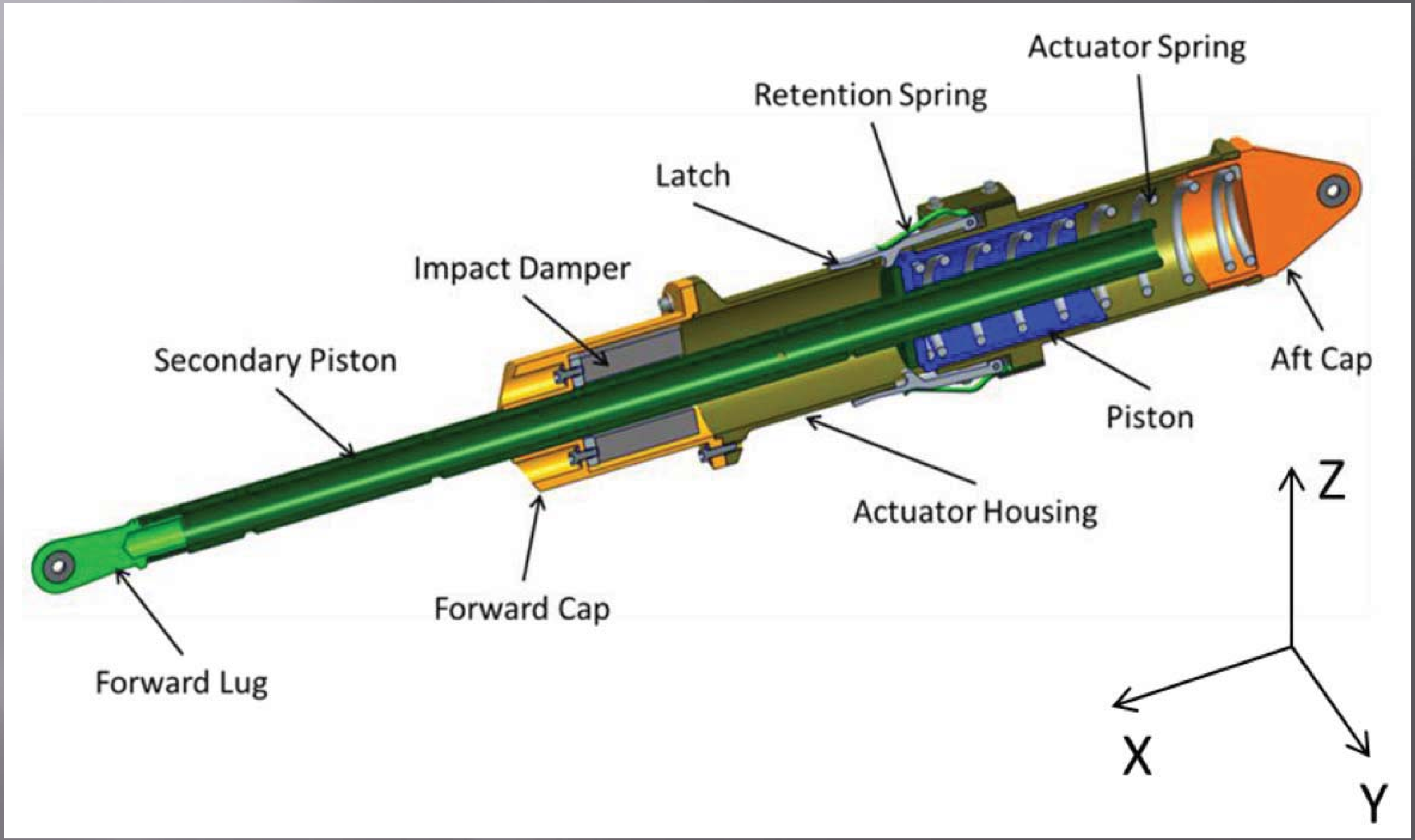
Background & Approach

Presenter
Jared Dervan
Date
May 15, 2014

- **Approach**
  - Joint NASA Engineering and Safety Center (NESC) and Lockheed Martin (LM) team
    - Assessment No. 11-00747
  - Perform development testing on a single Exploration Flight Test 1 (EFT-1) spring strut development unit
  - Testing included functional and random vibration testing
  - Preliminary results inform qualification unit development and follow-on testing

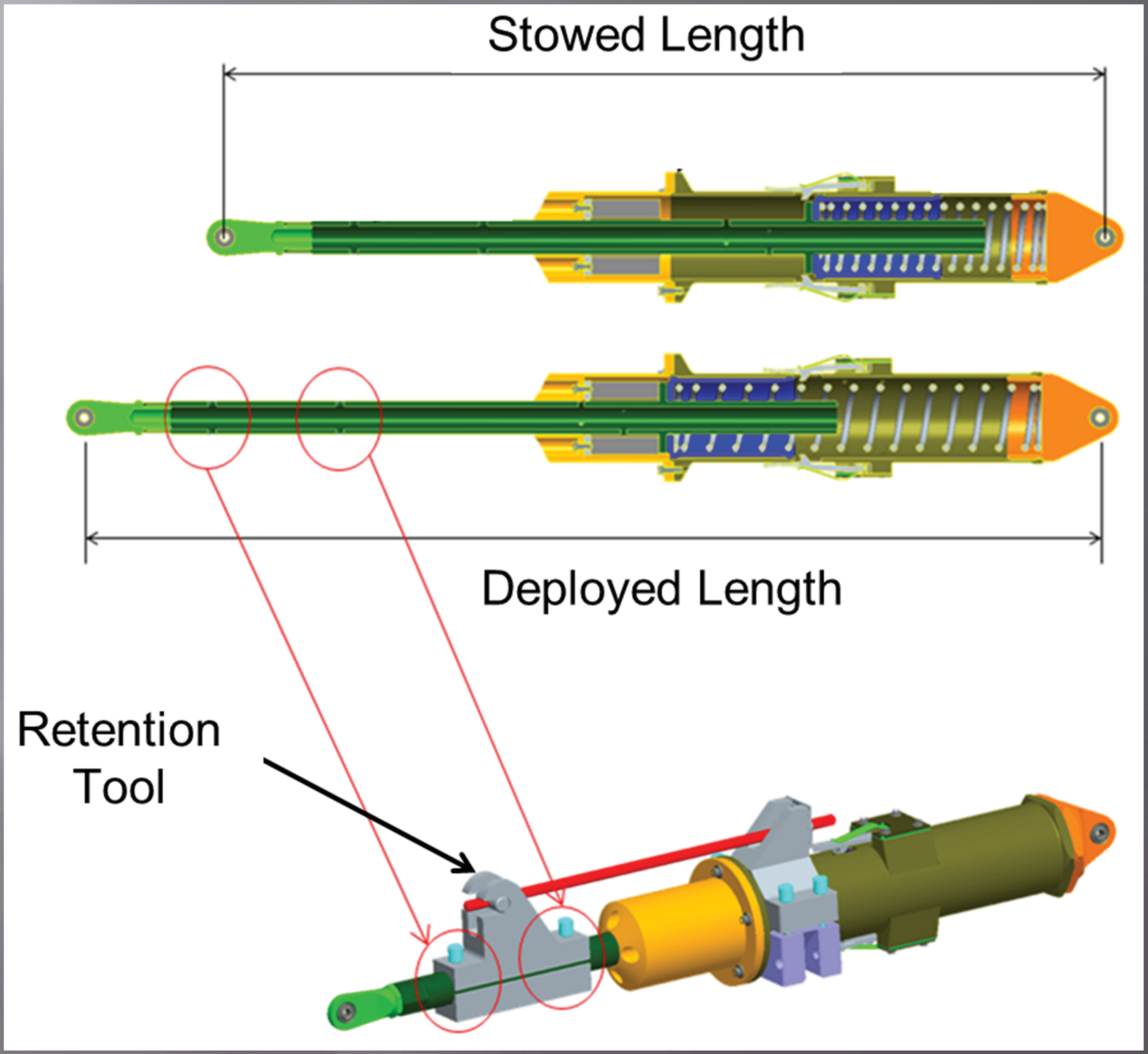
CM-SM Umbilical Spring Strut Detail

Presenter	Jared Dervan
Date	May 15, 2014



Retention Tool

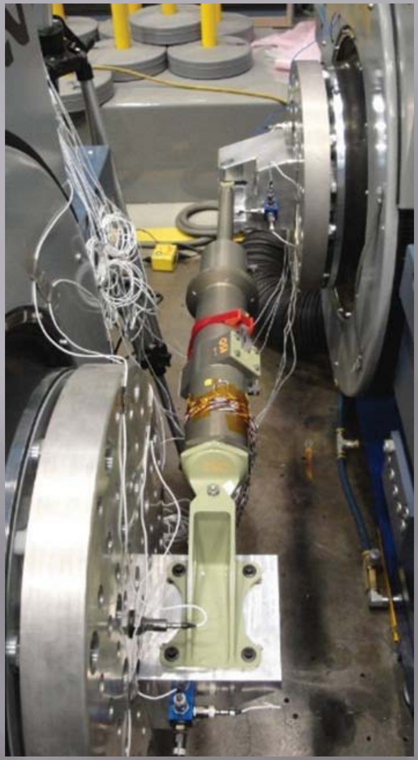
Presenter
Jared Dervan
Date
May 15, 2014



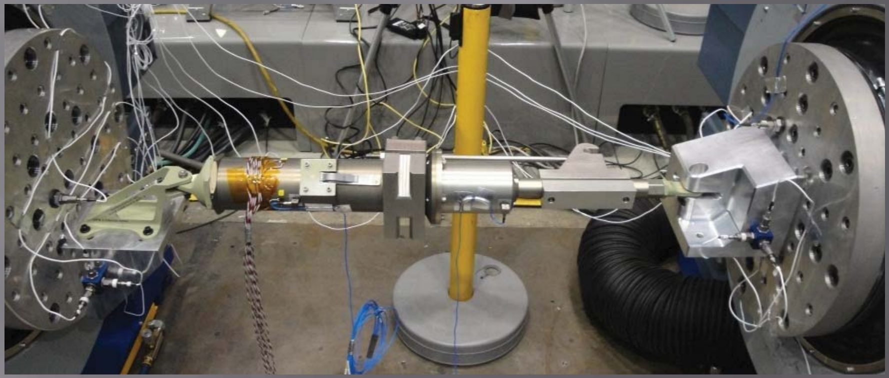
Random Vibration Testing

Presenter
Jared Dervan
Date
May 15, 2014

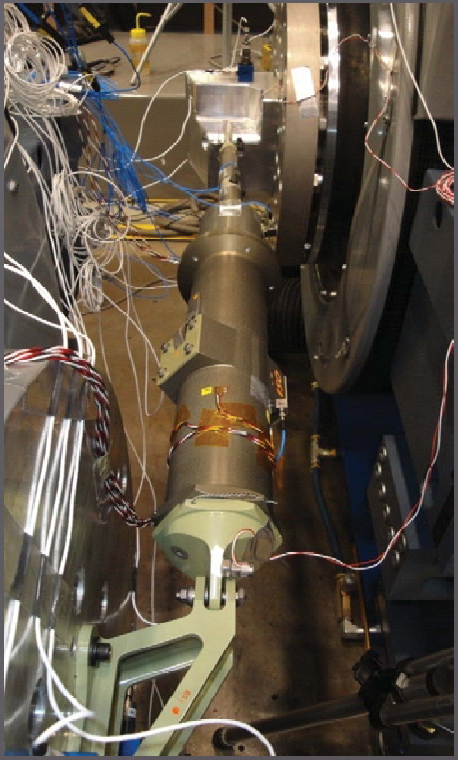
- *Two shaker tables utilized (uncorrelated)*
- *Other configurations traded (single shaker (correlated); grounding one end)*



Z-Axis
Successful



X-Axis
Successful



Y-Axis
Failure

Test Failure Observations

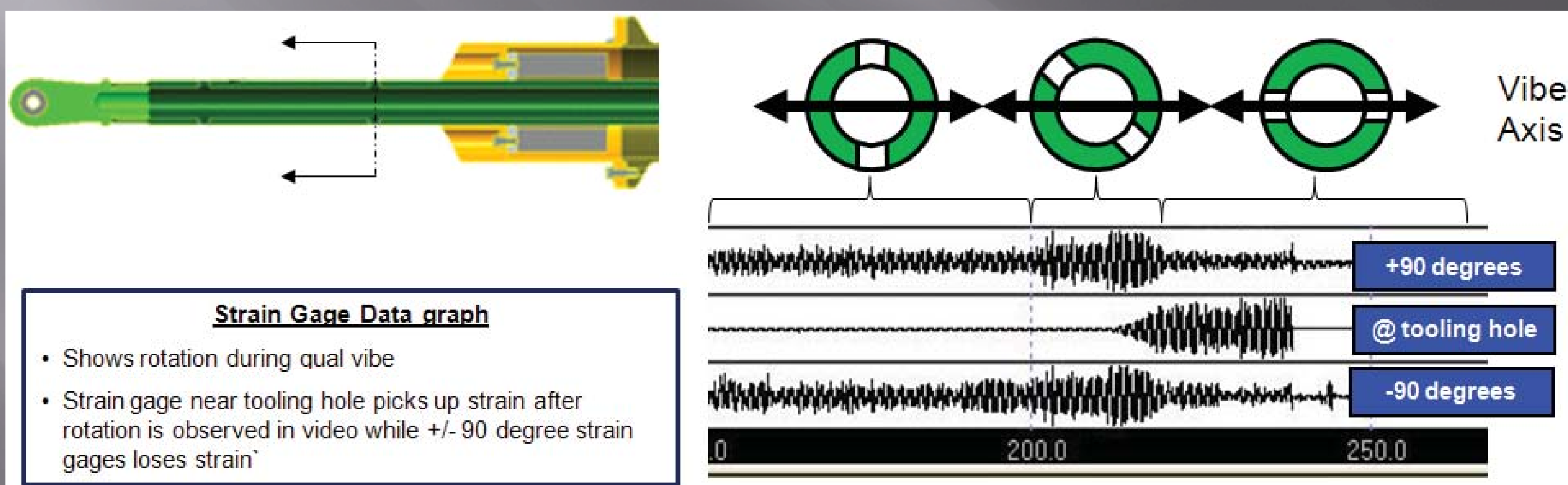
Presenter
Jared Dervan
Date
May 15, 2014

[redacted]

Test Failure Observations

Presenter	Jared Dervan
Date	May 15, 2014

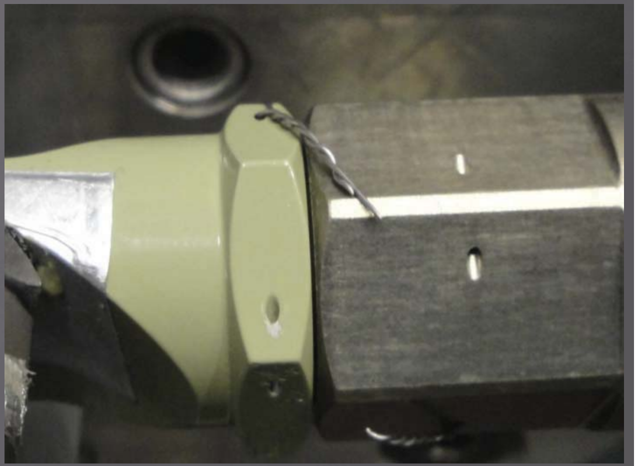
- Rotation of strut forward and aft subassemblies
  - Actuator Housing rotates clockwise
  - Failure of forward subassembly lockwire
  - Counterclockwise rotation of secondary piston ~90 degrees
- Noticeable decrease in noise ~30 seconds after qualification levels applied
- Less dynamic response in strut assembly



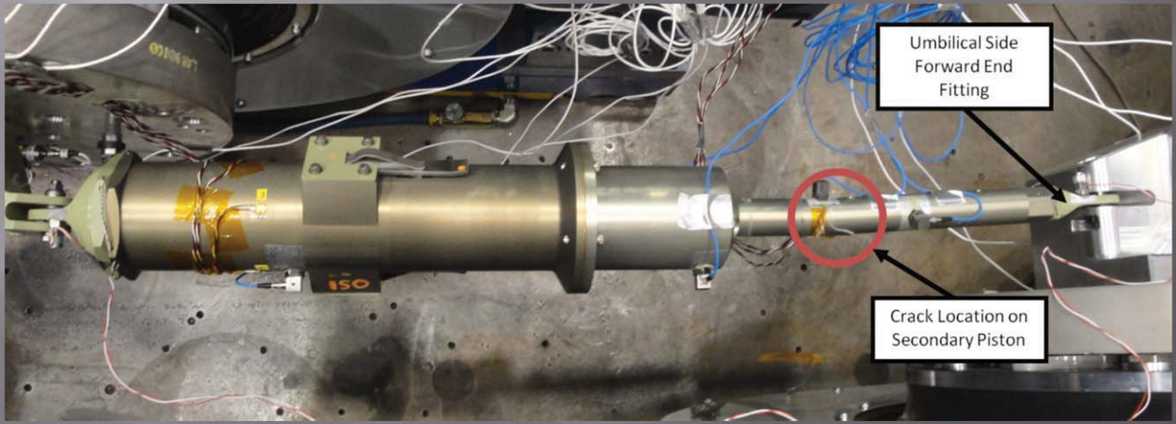
Post-Test Inspection

Presenter
Jared Dervan
Date
May 15, 2014

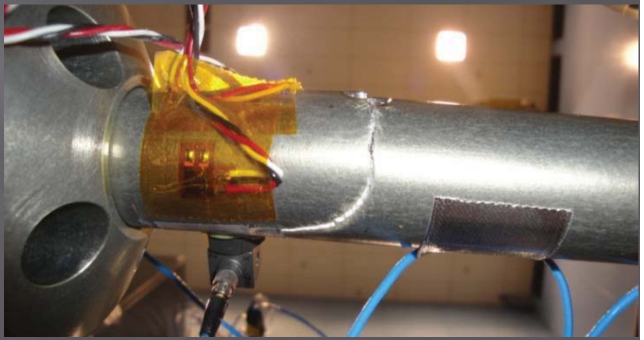
- Failure of forward lockwire and loosening of Forward Lug
- Structural failure of Secondary Piston through tooling hole
- Indications of fatigue on opposite tooling hole
- Crack identified as fatigue failure at tooling hole



Forward Lug Lockwire Failure



Y-axis Post-RV

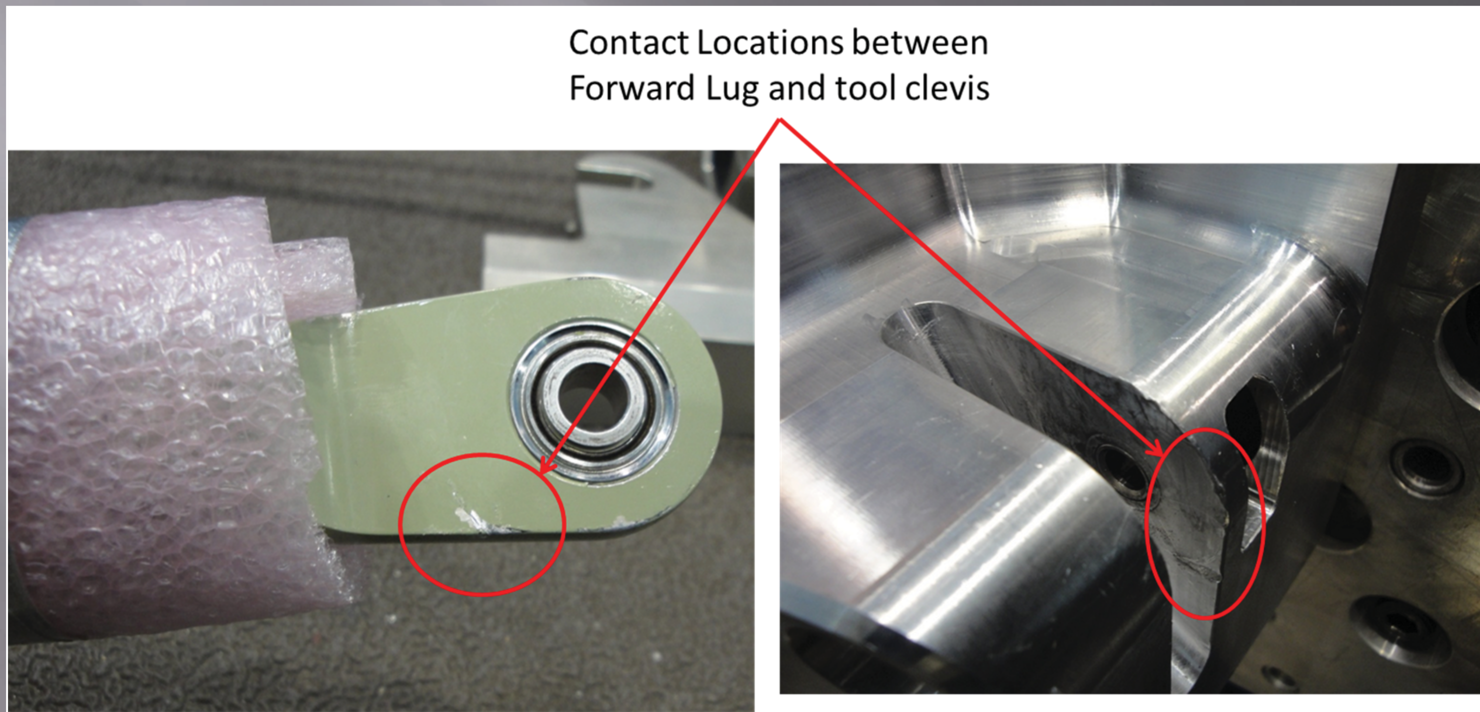


Secondary Piston Failure

Post-Test Inspection

Presenter	Date
Jared Dervan	May 15, 2014

- **External Wear**
  - Indications of contact at the end fittings and interfacing clevis
  - Contact (rotational offset) observed during testing

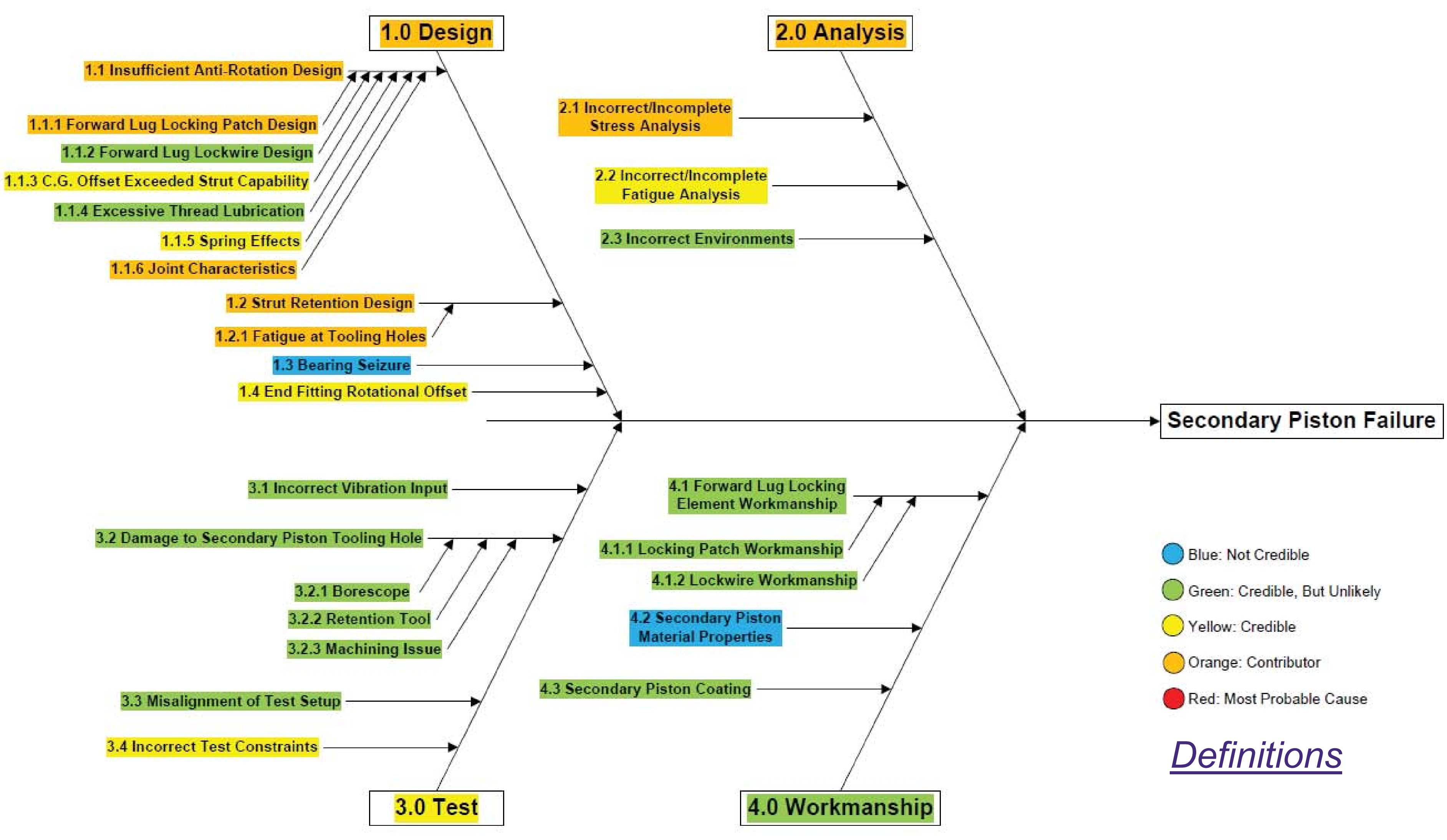


Forward Lug Wear (Post-RV)

Umbilical Side Tool Wear (Post-RV)

Fishbone

Presenter
Jared Dervan
Date
May 15, 2014



Definitions

Failure Scenario Summary

Presenter	Date
Jared Dervan	May 15, 2014

1. Rotational misalignment cause contact at end fittings
2. Inertial forces due to strut C.G. offset result in off-axis contact force
3. Induced force results in loosening torque
4. Torque exceeds resistive capability of joint
5. Lockwire breaks; rotation until C.G. offset aligns with applied force vector
6. Secondary piston tooling holes placed in maximum bending
7. Fatigue failure at secondary piston tooling hole

Rotational Misalignment (Aft Cap)

Contributors:	**Credible:**
1.1.1 Forward Lug locking patch design	1.1.3 C.G. offset exceeded strut capability
1.1.6 Joint characteristics	1.1.5 Spring effects
1.2.1 Fatigue at tooling holes	1.4 End fitting rotational offset
2.1 Incorrect/incomplete stress analysis	2.2 Incorrect/Incomplete fatigue analysis
	3.4 Incorrect test constraints

LM-led Development Testing

Presenter
Jared Dervan
Date
May 15, 2014

- Due to resource constraints, LM implemented corrective actions addressing proximate cause
- NESC continued root cause investigation
- LM 2nd Development Test
  - Corrective Actions: larger locking patches; larger diameter lockwire and quantity; increase in joint preload
  - Select parts reused from previous test
  - Fatigue failure due to life exceedance on Forward Lug
- LM 3rd Development Test
  - Corrective Actions: integral forward end fitting; aft assembly locking patch removed and joint adhesively bonded
  - Select parts reused from previous test with supporting fatigue life analysis
  - Y-axis qualification test completed successfully

2nd Development Test: Forward Lug Fatigue Failure

Lessons Learned

Presenter
Jared Dervan
Date
May 15, 2014

1 Care must be taken in adapting heritage designs to new applications.

- *Actuator design adapted from another mission*
- *Obsolete features were retained (forward interface)*

2 Threaded aluminum parts should only be used in lightly loaded applications.

- *Lower permissible preloads and severe cyclic loads promote self loosening*
- *Galling potential drives uncertainty in locking torque*

Lessons Learned

Presenter
Jared Dervan
Date
May 15, 2014

3 Avoid designs that have the potential to utilize fastener thread locking features to react applied or induced torque in the higher level assembly.

- *Thread locking features resist self loosening*
- *Applied loads significant relative to capability*

4 Ensure sufficient preloads are obtained to reduce the potential for joint loosening.

- *Preload much lower than best practice (25% vs. ~70% of tensile yield strength)*
- *Preload primary means to prevent self loosening*

Lessons Learned

Presenter	Jared Dervan
Date	May 15, 2014

5 Conduct machining operations prior to surface treatments to reduce the potential for crack initiation.

- *Machining after anodic coating application promotes crack initiation*
- *Reduction in fatigue life and bending endurance limits*

6 Utilize dedicated tooling for locking patch process development.

- *Reduces unnecessary cycling of threads (aluminum particularly sensitive)*

Lessons Learned

Presenter
Jared Dervan
Date
May 15, 2014

7 Utilize visual movement indicators for threaded joints.

- *Torque stripping flags relative motion at joints*

8 Conduct testing to determine the required limits on running torque for joint designs not conforming to available standards and specifications.

- *Running torque and preload recommendations dependent on joint material and geometry*
- *Steel fastener recommendations not applicable*
- *Compliance in joint due to hollow geometry*

Lessons Learned

Presenter
Jared Dervan
Date
May 15, 2014

9 Perform a bounding fatigue analysis in all possible orientations on mechanism components that are subject to rotation.

- *Off-nominal contact conditions*
- *Joint susceptible to rotation*
- *Tooling hole fatigue analyzed without worst-case considerations*

10 Review requirements, references, and methodologies used in the analyses for design applicability.

- *Bending not considered in joint separation*
- *Standards applicable to bolted joints and fasteners*

Lessons Learned

Presenter
Jared Dervan
Date
May 15, 2014

11 Assess the contribution of assumed secondary effects to analysis results, and perform an analysis and correlation study that reflects the major contributors.

- *C.G offset found to induce substantial loads relative to joint capability*
- *Sliding fits, spring buckling, and assembly tolerances driver for C.G. offset*
- *Off-axis contact condition at clevises induced loosening torque*

Summary

Presenter
Jared Dervan
Date
May 15, 2014

- NESC/LM spring strut development testing resulted in failure, highlighting design deficiencies
- Root cause investigation conducted and failure scenario identified
  - Evidence to support failure scenario not definitive
  - Demonstration of successful development test by LM reduces risk
  - Strengthening rationale would require more resources with limited benefit to current Orion flight opportunity
- Lessons Learned identified and communicated

Special Thanks

Presenter	Jared Dervan
Date	May 15, 2014

- NASA Engineering and Safety Center (NESC)
- Lockheed Martin Space Systems Company

Assessment Team Members and Support

Arthur Brown (NASA MSFC)
Damon Delap (NASA GRC)
Alison Dinsel (NASA JSC)
Michael Dube (NESC/LaRC)
Tina Dunn-Pittman (NESC/LaRC)
Steven Gentz (NESC/MSFC)
Ryan Gordon (LMSSC)

Tom Irvine (Dynamic Concepts, Inc.)
Brent Knight (NASA MSFC)
Ryan Pfeiffer (LMSSC)
Ivatury Raju (NESC/LaRC)
Kyong Song (NASA LaRC)
Philip White (NASA MSFC)
Christina Williams (NESC/LaRC)

Development Testing and Subsequent Failure of a Spring Strut Mechanism

Jared Dervan (NASA MSFC)
Brandan Robertson (NASA JSC)
Lucas Staab (NASA GRC)
Michael Culberson (LMSSC)
Joseph Pellicciotti (NASA GSFC)

BACKUP

Fishbone Element Classification

Presenter	Jared Dervan
Date	May 15, 2014

- **Definitions**
  - Most Probable Cause: single event or element that resulted in failure; supported by conclusive evidence with allowance for minimal reinterpretation
  - Contributor: event or element that, when combined with other elements, resulted in the failure; evidence, quantitative or qualitative, must be conclusive with allowance for minimum reinterpretation
  - Credible: event or element that may have contributed to the failure; conclusive evidence is not available or multiple interpretations exist such that event or element cannot be considered to satisfy the definition of ‘Contributor’
  - Credible, But Unlikely: event or element that has a potential to contribute to the failure; available evidence, while not conclusive, suggests event or element’s potential for contribution is unlikely
  - Not Credible: event or element, supported by conclusive evidence, that did not contribute to failure

Findings Technical Limitations

Presenter
Jared Dervan
Date
May 15, 2014

- Unable to prove exceedance of torque resistive capability with linear FEM (only spreadsheet calculations)
- No photographic evidence available showing misalignment of Forward Lug prior to Y-axis test
- Forward Lug wear to indicate loosening less evident
- Insufficient information on as-built assembly process
- Unverified lockwire torque capability
- C.G. offset of assembly unavailable
- Unverified spring static torque contribution

Activities to Address Technical Limitations

Presenter	Jared Dervan
Date	May 15, 2014

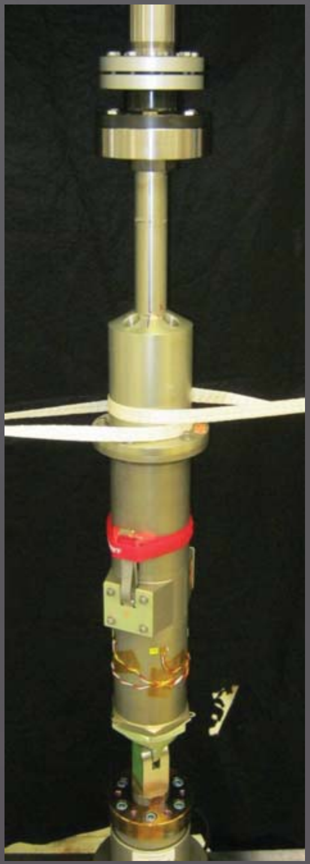
- Incorporate non-linear effects (e.g., contact conditions) and C.G. offset into FEM to measure induced torque at joint interfaces
- C.G. measurement of assembly and additional piece parts (Secondary Piston, Spring)
- Lockwire torque test
- Use empirical methods to sanity check environments
- Static compression spring torsion induced torque test

Performance Testing

Presenter
Jared Dervan
Date
May 15, 2014

- Ensures adequate force margin exists after being subjected to qualification levels
- Pre-random vibration
  - Both ends of strut attached to Instron through clevis
  - 'Slow' performance test measuring force vs. displacement; data compared to analytical prediction
  - Wear-in testing performed at deployment velocity; 15 cycles
- Post-random vibration
  - Secondary piston truncated aft of 1st development test failure location
  - Cupping interface to Instron at secondary piston
  - Performance test conducted at two speeds (slow and deployment)
  - Pre- and post-vibration data compared

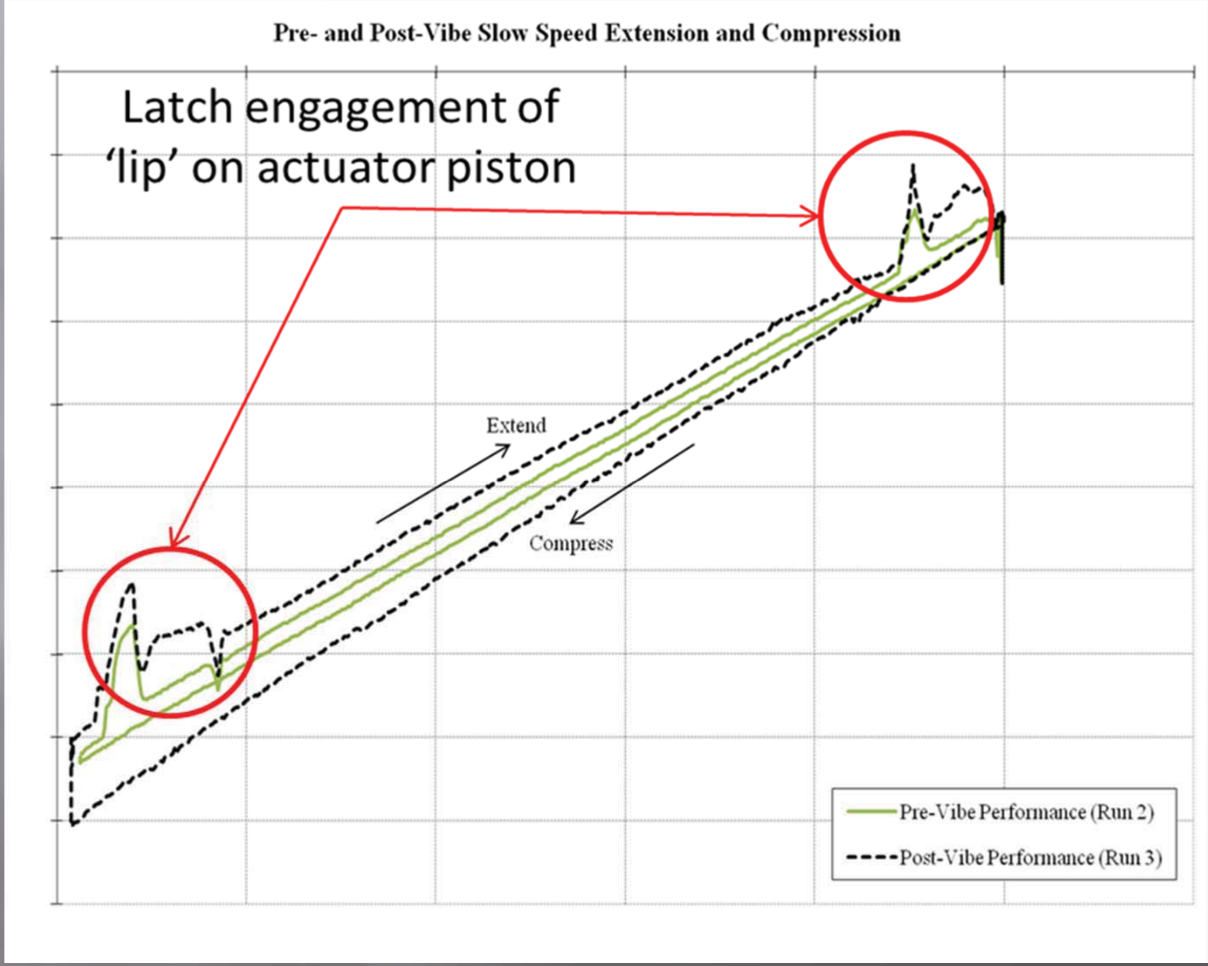
Pre-RV



Post-RV

Performance Testing

Presenter
Jared Dervan
Date
May 15, 2014



Nominal engagement of anti-back travel latches

Results yielded acceptable force margin

Assessment Timeline

Presenter
Jared Dervan
Date
May 15, 2014

- NESC funded the fabrication at MSFC of flight-like spring strut parts using Lockheed Martin (LM) drawings
- LM assembled the spring strut and configured to flight length with help of LM Retention Tool
- Pre- and post-random vibration performance testing performed at LM Materials Technology Laboratory (MTL) (Pre-RV: 07/25/2012; Post-RV: 08/24/2012)
- Random vibration testing performed at LM Acoustics Vibration Laboratory (AVL) (08/15-16/2012, 08/20-21/2012)
  - Fatigue failure of Secondary Piston at Y-axis qualification levels
- Root cause investigation initiated (08/21/2012)
- LM assumed ownership of development test program implementing corrective actions
  - 2nd Development Test (fatigue failure, unrelated to first test) – (11/28/12)
  - 3rd Development Test (success) – (02/14/13)
- NESC root cause investigation completed (~02/26/13)
- Final report completed (11/07/13)

Post-Test Inspection

Presenter
Jared Dervan
Date
May 15, 2014

- **Internal Wear & Particulate Formation**
  - Borescope inspection between random vibration test axes (insertion through tooling hole)
  - Larger particulate accumulated at Aft Cap; powder observed throughout
    - Observed existing tooling holes, latch holes, and Forward Cap-to-Secondary Piston interface during testing
    - Powder most noticeable internal to Secondary Piston