AGENDA

RSRM Accomplishments – Jack Phelps
- SRM/RSRM Evolution
- Insulation J-Leg
- Improved Resiliency O-rings/Gaskets
- ETM-3 – Five Segment Margin Test
- Carbon Fiber Rope
- ATK BSM

RSRM Lessons Learned – Fred Perkins
- Nozzle Pocketing
- Field Joints and Nozzle-to-Case Joint
- Pressure Sensitive Adhesive
- RSRM Evolved Toolbox

RSRM Culture – Dennis Moore
- RSRM Test Program
- RSRM Postflight
- 7 Elements of Good Flight Rationale
- Some Thoughts on Minority Opinions
- Summary
Supplied by ATK
Supplied by USA-Booster Element
RSRM Accomplishments

- SRM/RSRM Evolution
- Insulation J-Leg
- Improved Resiliency O-rings/Gaskets
- ETM-3 – Five Segment Margin Test
- Carbon Fiber Rope
- ATK BSM
**ACCOMPLISHMENTS**

- 1977: Redesigned Case Joints (J-Leg)
- 1978: Nozzle Joints and Ply Angle
- 1979: EPDM Reformulation
- 1980: Rigorous Postfire Evaluation
- 1981: Igniter J-Leg
- 1982: Witness Panels
- 1983: Nozzle Bond Improvements
- 1984: Dedicated Final Assembly (M-397)
- 1985: PPIA/NEQA
- 1986: Electronic Shop Instructions

**SRM/RSRM EVOLUTION**

- 1987: New Nozzle Bond Facility (M-113A)
- 1988: Advanced Static Test Facility (T-97)
- 1989: New X-ray Facility (M-197)
- 1990: Work Centers
- 1991: Ultrasonic Gantry
- 1992: New Propellant Pre-Mix Facility (M-314)
- 1993: High Temp NARC
- 1994: Columbia ETM-3
- 1995: FSM-17

**JACK PHELPS**

- 1996: Insulation Facility Humidity Control
- 1997: Toyota Production System Adopted
- 1998: Propellant Fin Transition Redesign
- 1999: Process System Design
- 2000: 52nd Static Test
- 2001: ATK BSM Qualification
- 2002: 264 Motors Flown
- 2003: 2004: ATK BSM Qualification
- 2005: Process System Design
- 2006: 52nd Static Test
- 2007: ATK BSM Qualification
- 2008: 264 Motors Flown
- 2009: 2010
How it Works

1. Prior to Motor Operation
   - Motor pressure enters J-Leg slot
   - Free volume near J-Leg tip compresses equalizing the pressure so that the tip is not actuated
   - PSA allows J-Leg and Clevis Insulation to track together

2. Ignition
   - Motor pressure enters J-Leg slot
   - Free volume near J-Leg tip compresses equalizing the pressure so that the tip is not actuated
   - PSA allows J-Leg and Clevis Insulation to track together

3. PSA keeps J-Leg adhered to Clevis Insulation
   - PSA keeps J-Leg adhered to Clevis Insulation

Takeaway Success: J-leg performance has been exceptional, not only has it performed its intended thermal barrier function, it has also never allowed gas into the joint (except for RSRM-55 special cause)
Major Findings from Testing

- Case field joint O-ring tracking margin at 41° F for improved resiliency V1288 is the same as V1247 at 81° F
- V1288 erosion rate is 50% less than V1247
- All other physical properties and characteristics meet V1247 requirements
**Conditions more severe than RSRM**

- Thermal environment
- Structural loads
- Erosive burning
- Acoustic activity
- Slag
- Burn time
- Mass flow and mach number
- Pressure and pressure drop
- Buckling and joint loading
- Increased length and fill volume for the igniter

**Benefits**

- ETM-3 demonstrated robust margins for RSRM
- Learning experience and challenge for the NASA/ATK workforce (design, build and test a new motor from scratch)
- ETM-3 success was a great step toward Ares/RSRMV five segment motor development

**ETM-3** was instrumented with 620 gages and 635 total channels
A change in paradigm (pressurized joints) led to significant design improvements that enhanced thermal margins and eliminated a potential failure mode.
**Takeaway Success:** It took an exceptional effort and great teamwork by ATK to certify, build and fly BSM hardware in only 19 months.

**Improvements**

- Interchangeable fwd and aft motors
- Sling lined chamber
- Batch cast vs. continuous flow production
- TIGA adhesive (RSRM baseline)
- Graphite throat redesign to improve margins
- Interchangeable metal hardware—eliminates matched sets
- Increased O-ring squeeze
- V-1288 low temp O-ring material
- Igniter-to-case leak test port added
- Redesigned Igniter

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**Qualification Test Matrix**

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RSRM Lessons Learned

- Nozzle Pocketing
- Field Joints and Nozzle-to-Case Joint
- Pressure Sensitive Adhesive
- RSRM Evolved Toolbox
Background
- Carbon-Cloth Phenolics (CCP) form the nozzle contour and protect underlying structure
- CCP wrapped on a mandrel, cured and machined to a final profile

Observation
- Pocketing occasionally observed in nose and throat
- Seemingly “random” behavior indicated subtle variability
- Behaviors not observed during certification/verification testing
- Work as a result of STS-8 nose pocketing led teams to believe problem understood and rectified via nose ply angle change
- Subsequent, STS-51D exhibited similar behavior in throat region

Resolution
- Root cause determination and corrective action worked in iterative phases – tendency to assume the problem solved until new occurrence
- Design ply angles, processing, material screening, higher carbonization temperature – Changed in separate waves of corrective actions

Lesson Learned – Robust root cause analysis essential to comprehensive understanding. Subtle effects of material/process variability on performance must be understood and verified. Controls sufficient to verify material/process variability within certified range
**Background**
- SRM (pre-RSRM) used putty between the motor segments as a thermal barrier
- Assembly process could leave vent holes through the putty
- Joint movement from ignition sometimes caused “blow-by” of the seals

**Observation**
- Blow-by occurred in the primary seal locations of the SRM field joints and nozzle-to-case joint – erosion of O-ring was not design intent
  - Team accepted performance inconsistent with design intent
  - “Hardware was talking”
  - Weak CoFR process – selling as opposed to risk disclosure
- Team understood that the primary seal could fail but were convinced that the secondary seal would hold
  - Common cause failure (O-ring material low temperature resiliency and dynamic tracking) resulted in joint failure and loss of Challenger crew

**Resolution**
- Robust joint redesign – addressed gas path to O-ring, fill volume, O-ring tracking (geometry, gap opening, and resiliency), thermal protection system
- Robust certification process – subscale and combined loads full-scale test, analysis and fault tolerance
- CoFR process based on risk assessment and communication/sharing

**No gas to primary O-rings since redesign (over 700 total joints flown/tested )

*Lesson Learned* – Robust root cause determination, corrective action, certification process (including off-nominal and fault tolerance) result in robust flight design
**Background**
- RSRM redesigned field joints include J-leg interference fit thermal barrier as first leg of joint seal thermal protection system
- RSRM redesigned field joints performed as designed on first 300 joints flown

**Observation**
- Hot gas penetrated past the tips of all six J-legs on RSRM-55 (STS-78) launch in June 1996
  - Out-of-flight family performance
  - New ODC-free pressure sensitive adhesive used for the first time on RSRM-55
  - Adhesive had worked perfectly in a full-scale static-test motor fired in Utah

**Resolution**
- RSRM-54 (STS-79) utilized same PSA – de-stacked
- Environment at Kennedy Space Center (high humidity) reduced the peel strength of the adhesive; peel strength was key to keeping the J-leg sealed. In addition, the design team believed the J-leg would seal without any adhesive
- The immediate fix was to return to the baseline adhesive
- Long-range actions included extensive subscale and full-scale testing, plus thermal and structural analysis to understand in detail, the J-leg response to processing and operating environments

## Lesson Learned – Test what you fly.
Testing ideally to include all operating environments and parameters. Identify and assess risk (FMEA) of flight attributes/interactions not explicitly tested
Several Key Factors in Achieving and Maintaining Excellent Flight Performance

- Robust Process Control
  - Statistical process control – Identify and disposition within-engineering but out-of-family data
  - Fingerprinting of materials – Allows identification of subtle changes in the supplier chain
  - Extensive use of PPIA audits (stamp warranty) both in-house and at suppliers
  - Process sensitivity testing – Design of experiments, corners of the box testing, etc.
  - Emphasis with suppliers on change identification
- Comprehensive change verification process
  - Fault Tolerant / Failsafe testing and analysis
  - Enhanced analytical models and material databases
  - Models anchored to test
  - Yearly full-scale static testing
- Rigorous anomaly investigation/resolution and root cause analysis (listen to the hardware)
  - Structured postflight teardown and inspection prior to a subsequent flight
- Rigorous certification of flight readiness process (understand and communicate risk)

Conclusion – The RSRM program has learned from past events and evolved an extensive toolbox of techniques, practices, and systems designed to ensure the configuration and integrity of each RSRM flight set before flight
RSRM Culture

- RSRM Test Program
- RSRM Postflight
- 7 Elements of Good Flight Rationale
- Some Thoughts on Minority Opinions
- Summary
The RSRM is the highly reliable rocket motor it is today due to constant vigilance and focus on the necessary elements of RSRM flight safety. These elements are key to the successful culmination of the Space Shuttle Program.
Subscale Solid Rocket Test Motor (SRTM)

5 Inch Propellant Center Perforated Subscale Testing

Flight Support Motor

Insulation Witness Panel Subscale Testing

Igniter Testing

Propellant Dog Bone Testing
Test Summary

- **Material/Process Change Categories**
  - Obsolescence
  - Improvements – Implementing better materials/methods or reacting to postflight observations

- **Typical Process for Evaluating Significant Changes**
  - Multiple candidates screened by least expensive testing (dog-bone type)
  - Down-selected candidates to sub-scale hot-fire
  - Best Candidate selected for FSM demonstration/qualification

- **FSMs tested were tested about 1 per 12-month cycle**
  - Highly instrumented – can detect subtle drifts
  - Many changes typically on any one FSM
  - Changes had to be evaluated for conflicting objectives

- **FSM tests evolved from original intent of testing production line motor to being the Change Precursor**
  - Combined with our level of Postflight makes up for inability to “Green Run”
Postflight Team
- ATK DEs, MEs & QEs (responsible for hardware)
- MSFC Project/Engineering/S&MA

Postflight Task
- Thoroughly evaluate and document hardware condition
- Identify, assess, and document reportable conditions and items of interest

**Disciplined approach to evaluating hardware, dispositioning findings, and identifying IFAs**

**Approach is unique in SRM Industry**
Solid technical understanding
- Physics based or root cause understanding of issue, based on engineering data (perhaps using a fault tree)

Condition relative to experience base
- Experience base includes full-scale flight, ground test, or qualification level tests

Bounding case established
- Using physics based understanding, determine the bounding case (e.g., lower A-basis allowables, upper three sigma loads and environments, anchored with test data)

Self limiting aspects
- Physical reasons why it can’t get any worse than the bounding case or show the part is fail-safe

Margins understood
- Adequate margins, ideally not substantially reduced from baseline

Assessment based on data, testing and analysis
- Final risk assessment based on test data and analysis, not gut feel or expert opinion

Interactions with other elements/conditions addressed
- Address interactions with other conditions (MRB, changes, technical issues), and vehicle elements

**Implemented 2001**
## Worksheet Example

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<th>Current State</th>
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<th>Mod</th>
<th>Weak</th>
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<td>- Complete statistical analysis of measured void distribution</td>
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<td>- Complete stress analysis</td>
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<tr>
<td>Impact of stress risers due large non-bond regions not quantified</td>
<td></td>
<td></td>
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<tr>
<td><strong>Margins</strong></td>
<td></td>
<td></td>
<td>X</td>
<td>- Complete statistical analysis of measured void distribution</td>
</tr>
<tr>
<td>Current margins unknown</td>
<td></td>
<td></td>
<td></td>
<td>- Complete high rate capability button testing</td>
</tr>
<tr>
<td><strong>Assessment based on Testing, Data, Analysis</strong></td>
<td></td>
<td></td>
<td>X</td>
<td>- Complete loads survey</td>
</tr>
<tr>
<td>Based on analyses and test data</td>
<td></td>
<td></td>
<td></td>
<td>- Complete stress analysis</td>
</tr>
<tr>
<td>Extensive capability database</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>New analysis methodologies</td>
<td></td>
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<tr>
<td>Reduced conservatism</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Interactions with other Conditions/Components</strong></td>
<td></td>
<td></td>
<td>X</td>
<td>- None</td>
</tr>
<tr>
<td>No known interactions except age – no age effects identified</td>
<td></td>
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</tbody>
</table>
Benefits from 7 Elements Approach

- Can be used to assess multiple types of issues
  - Technical Issues
  - Design Changes
  - MRB Items
  - Postflight Anomalies

- Clearly identifies Flight Rationale Strengths and Weaknesses

- Focuses on the facts
  - Removes emotion from characterizing risk

- Provides a “roadmap” when implemented early
Seek out minority opinions
- Silence doesn’t always mean agreement – a lot of thinkers support us
- Don’t allow any fence sitters

Have a team of folks listen carefully – Hear Them Out
- Pull in some help from expert(s)
- Avoid arguing or making counterpoints until they’ve been heard out
- Keep in mind they could be right

Make a decision and tell them how you got there

Be an advocate for the minority opinion
- Encourage and offer to take it forward
- Use the management chain

Allow folks to change their minds
- New data or new way of thinking
RSRM is a highly reliable human-rated Solid Rocket Motor
  - Largest diameter SRM to achieve flight status
  - Only human-rated SRM

RSRM reliability achieved by:
  - Applying special attention to Process Control, Testing, and Postflight
  - Communicating often
  - Identifying and addressing issues in a disciplined approach
  - Identifying and fully dispositioning “out-of-family” conditions
  - Addressing minority opinions
  - Learning our lessons

We look for weaknesses and figure out how to improve as a RSRM NASA/ATK team