ABSTRACT:
This presentation provides an overview of the work done at ATK Launch Systems with a demonstration of how engineering knowledge can be applied to several real-world problems. All material in the presentation has been screened to meet ITAR restrictions. The information provided is a compilation of general engineering knowledge and material available in the public domain. The presentation provides an overview of ATK Launch Systems and NASA programs. Some discussion is provided about the types of engineering conducted at the Promontory plant with added detail about RSRM nozzle engineering. Some brief examples of nozzle technical issues with regard to adhesives and phenolics are shared. These technical issue discussions are based on material available in the public domain.
ATK Launch Systems Engineering
NASA Programs
Engineering Examples

David Richardson
April 16, 2007
Objective: Provide an overview of the work done at ATK Launch Systems with an indication of how engineering knowledge can be applied to several real-world problems.

Restriction – material in presentation has been screened to meet ITAR restrictions.

Specifics of rocket motor design, processing, etc. have been left out.

Information will be a compilation of general engineering knowledge and material available in the public domain.

Outline:

- Provide an overview of ATK Launch Systems
- Review NASA programs in general
- Discuss engineering at Promontory plant
- Provide overview of nozzle engineering
- Examples of nozzle technical issues
  - Adhesives
  - Composites

Discussions will range from broad to specific.
ATK Corporate Profile

• $3.4 billion aerospace and defense company
• ~15,000 employees
• Headquarters in Edina, MN
• Ranked 13th largest U.S. defense contractor by Defense News
• Ranked 9th largest world space company by Space News
Lauch Systems
The world leader in the design, development, and production of launch systems for space, strategic, and missile defense applications.

Mission Systems
Pioneering advanced solutions for access to space and delivering greater power, precision, and performance to America’s fighting forces.

Ammunition Systems
The nation’s largest producer of conventional munitions, serving both the military and commercial markets.
Launch Systems

• The **WORLD LEADER** in solid propulsion systems and unequaled expertise in...
  - Engineering design and system analysis
  - Systems engineering and integration
  - Energetic materials and pyrotechnic systems
  - Composite materials and structures
  - High-strength metals
  - High-temperature materials
    - Adhesives
    - Insulators
    - Ablatives
    - Thermal protection systems
  - Integrated vehicle health management
Promontory Facilities

- 3,250 employees
- 535 buildings
- 19,900 acres
- 2.5 million ft² of manufacturing facilities
- 300,000 ft² of R&D laboratories

Promontory Rocket Display

Design
Nozzle
Mix/Cast
Test Operations
NASA Programs - Today

Reusable Solid Rocket Motor (RSRM)

Booster Separation Motor (BSM)
Ares V
Science and Engineering Capabilities

- Over 900 scientists, engineers, and technicians
- Automated preliminary design and analysis tools
- System analysis capability
- Computer-aided design and data management
- Sophisticated materials, aero, thermal, and structural analysis tools
- Complete laboratory and testing facilities and capabilities
• Industry leader in solid rocket motors and related technologies
  • World leader in solid rocket propellant development
  • Highest performing composite case technologies
  • Innovative nozzle/ablative materials technologies
  • Metallurgical, corrosion, and metal restoration expertise
  • World-class bonding and adhesive development capabilities
  • Extensive experience developing high-temperature materials and insulation
  • Industry leader in new energetic materials development
  • High-temperature thermal protection system materials technology
Nozzle Design

- Task
  - Design nozzle
    - Designing next ARES nozzles
  - Control materials
    - Numerous materials
  - Evaluate discrepancies
    - Process is complex
  - Address obsolescence
  - Develop processes
    - Large parts, complex procedures
  - Define inspections
    - Visual, NDE, destructive
Nozzle - Structural Analyses

Manufacturing
- Residual Stress
- Handling Loads

Transportation
- Thermal Loads
- Fixture Loads
- G-loads

Flight
- Thermal Loads
- Pressure Loads
- Vectoring Loads

Post Separation
- Re-Entry
- Splashdown

Material Properties

Structural Analysis of Nozzle

Margins of Safety
- Stress Based
- Fracture Based
- Bolted Joints

O-ring Gap Predictions

Analysis Tools
- Finite Element
- Fracture
- Hand Calcs
- Constitutive model - phenolics
  - Ablative liners -20°F to 4,500°F
    - Material changes
    - Pyrolysis
  - Nonlinear models
    - Yielding
    - Tension/compression

- Failure model - phenolics
  - Failure criterion: accounts for multi-axial loading (3D Tsai-Wu)

- Fracture model - phenolics
  - Evaluate cracks, discontinuities, etc.
  - Mode I assumed to be conservative
- Constitutive model - adhesives
  - Time and temperature dependent
    - Linear models (approximations)
    - Nonlinear viscoelastic models
- Failure models - adhesives
  - Multi-axial temperature and time (MATT) dependent failure criterion
  - Radial bondlines not considered structural
- Fracture model - adhesives
  - Evaluate cracks, discontinuities, etc.
  - Mode I assumed to be conservative
• Statistical inputs
  • A-basis input properties
    • 99% probability with 95% confidence
    • Used where conservatism can be ensured
  • Material capabilities
Residual Stress

- Residual stresses induced during manufacturing
- Massive parts deflected prior to bonding
- Upon release, residual stresses are induced
- Complex material models
- Loading conditions
  - Many sources of stresses
  - 3-D effects confound analyses
  - Boundary conditions not simple
  - Worst on worst superposition
- Bonding induces residual stresses
- Deflected components spring back
- Complex process
  - 3-D
  - Nonlinear
  - Multiple step
Residual Stress Verification

- Extensive verification has been conducted to evaluate accuracy of residual stress analyses
- Full-scale testing
- Subscale testing

Full-Scale Nozzle Bond Residual Stress Simulation Test
Flight

- Analysis
  - Extreme temperatures
  - High pressures
  - Nonlinear material
  - Nonlinear boundary conditions
- Typical thermal input
Bolted Joints

- Model
- 3-D
- Joint skip
- Contact (heads, shanks, threads, and flanges)
- Joint opening
- Analyses show joints are fail-safe
Metal Part Fracture

- Fracture calculations made for metal components
- Critical flaw sizes
- Fatigue crack growth

Joint 3 Flange Bolt Hole
NPT Port
Membrane
Joint 2 Flange Bolt Hole
Leak Check Port
Phenolic and Bondline Fracture

- Phenolic and bondline fracture analyses
- Composite fracture evaluated
- Bi-material interface fracture evaluated
- Effects of proximity of discontinuities are mathematically modeled
• Failure criterion required to address all conditions that influence failure
  • Multi-axial loading
  • Temperature changes
  • Loading times
• Required development of new generalized failure model
MATT failure criterion

\[ A P^2 J_2 + B P I_1 = 1 \]

\( J_2 \) = Second deviatoric stress invariant

\( I_1 \) = First stress invariant

\( A, B \) = Shape parameters (from normal and shear test data)

\( P \) = Size parameter or scale factor (function of temperature and time)

\[ I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33} \]

\[ J_2 = \frac{1}{3} \left[ \sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - \sigma_{11}\sigma_{22} - \sigma_{11}\sigma_{33} - \sigma_{22}\sigma_{33} + 3\sigma_{12}^2 + 3\sigma_{13}^2 + 3\sigma_{23}^2 \right] \]
\( A \rho_1^2 J_2 + B P_{11} = 1 \)

- Linear cumulative damage (to characterize \( P \))

- Equation
  \[
  N_{\sigma} = \left[ \int_0^{t_f} \sigma_i \beta \, dt \right]^{1/\beta}
  \]

- Constant Rate
  \[
  t_f = (1 + \beta) \left[ \frac{N_{\sigma}}{\sigma_f} \right]^\beta
  \sigma_f = N_{\sigma} \left[ \frac{t_f}{1 + \beta} \right]^{-1/\beta}
  \]

- Constant Load
  \[
  t_f = \left( \frac{N_{\sigma}}{\sigma_f} \right)^\beta
  \sigma_f = N_{\sigma} t_f^{-1/\beta}
  \]

Adhesives - Failure Model: Shear Adhesion

# Adhesives - Failure Model Statistics


## Coefficients of Variation for the Tensile Adhesion and Shear Adhesion Tests

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Tensile COV</th>
<th>Shear COV</th>
<th>Tensile Count</th>
<th>Shear Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adh. #1</td>
<td>9%</td>
<td>11%</td>
<td>206</td>
<td>178</td>
</tr>
<tr>
<td>Adh. #2</td>
<td>7%</td>
<td>7%</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Adh. #3</td>
<td>10%</td>
<td>22%</td>
<td>79</td>
<td>41</td>
</tr>
</tbody>
</table>
Adhesives - Verification: Multi-Axial

Adh. #1

- 20 °C Data
- 20 °C Pred.
- 30 °C Data
- 30 °C Pred.
- 45 °C Data
- 45 °C Pred.

Adh. #2

- 20 °C Data
- 20 °C Pred.
- 30 °C Data
- 30 °C Pred.
- 45 °C Data
- 45 °C Pred.

Adh. #3

- 20 °C Data
- 20 °C Pred.
- 30 °C Data
- 30 °C Pred.
- 45 °C Data
- 45 °C Pred.

Adhesives - Verification: Creep

Adh. #1
- 20°C Data
- 20°C Pred.
- 30°C Data
- 30°C Pred.
- 40°C Data
- 40°C Pred.
- 45°C Data
- 45°C Pred.

Adh. #2
- 30°C Data
- 30°C Pred.
- 45°C Data
- 45°C Pred.

Adh. #3
- 20°C Data
- 20°C Pred.
- 30°C Data
- 30°C Pred.
- 40°C Data
- 40°C Pred.
- 45°C Data
- 45°C Pred.

### Coefficients of Variation for the Multi-Axial and Creep Tests

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Multi-Axial COV</th>
<th>Creep COV</th>
<th>Multi-Axial Count</th>
<th>Creep Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adh. #1</td>
<td>13%</td>
<td>15%</td>
<td>56</td>
<td>104</td>
</tr>
<tr>
<td>Adh. #2</td>
<td>11%</td>
<td>21%</td>
<td>57</td>
<td>8</td>
</tr>
<tr>
<td>Adh. #3</td>
<td>23%</td>
<td>20%</td>
<td>50</td>
<td>34</td>
</tr>
</tbody>
</table>

**Adhesives - Overall Statistics**

Coefficients of Variation for All Tests

<table>
<thead>
<tr>
<th>Adh. #1 Count</th>
<th>Adh. #2 Count</th>
<th>Adh. #3 Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>544</td>
<td>130</td>
<td>204</td>
</tr>
</tbody>
</table>

*MATT failure criterion approved by NASA for public release and documented in AIAA Journal, Journal of Adhesion, and proceedings for AIAA JPC and Adhesion Society Meetings*
• Ablative composite liners
  • Surface temperatures approximately 4,000 deg. F
  • Material “ablates” during motor operation
  • Ablative required to insulate metallic structure of nozzle
  • Anomalous performance not acceptable for man rated system

Ply lifting in heated ablative liners is a well known phenomenon documented in many technical journals (e.g. AIAA, JANNAF, etc).
Ply lifting in heated ablative liners is a well known phenomenon documented in many technical journals (e.g. AIAA, JANNAF, etc).
• Analytical modeling of heated phenolics
  • Need material properties as a function of
    • Temperature
    • Time
    • Degree of char
    • Material changes
  • Need to include effects of
    • Pyrolysis gasses (smoke)
  • Coupled analyses
    • Thermal (affected by pyrolysis gas flow)
    • Flow (affected by structural deformations)
    • Structural (affected by thermal and flow predictions)

Testing Conducted by Landers and Singer

Ply lifting in heated ablative liners is a well known phenomenon documented in many technical journals (e.g. AIAA, JANNAF, etc).
• Analytical modeling of heated phenolics
• Need to account for the presence of porosity
• Need to model effects of pressure loading in pores
• Pores can be many shapes
  • Most likely elongated along direction of fibers

Ply lifting in heated ablative liners is a well known phenomenon documented in many technical journals (e.g. AIAA, JANNAF, etc).
• Analytical modeling of heated phenolics
• Need for coordination with Universities
• Need for programs such as VAMUCH

VAMUCH

A General-Purpose Micromechanics Code

http://www.mae.usu.edu/faculty/wenbin/ht_docs/vamuch.html

VAMUCH is coordinated by Dr. Wenbin Yu of Utah State University
Conclusions

- ATK Launch Systems has a wide variety of engineering opportunities
- NASA programs involve new and developing technologies
- Promontory plant at ATK is heavily involved in supporting science and engineering
- Nozzle engineering has unique challenges to address
  - Design of new launch systems
  - Adhesive modeling is complex and state-of-the-art
  - Composite ablative liner studies allow for advancing science in the rocket motor industry