Laboratory Reproduction and Failure Analysis of Cracked Orbiter Reaction Control System Niobium Thruster Injectors

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Presentation Outline

• Description of RCS Thruster
  • Thruster/Injector Photos & Cross Sections
  • Injector Crack Descriptions
• History of Injector Cracking
• Reproduction of Injector Cracking
  • Brownfield Specimen
  • Hydrofluoric Acid Tests
    • Specimen Loading Arrangement
    • Specimen #3 Results
    • Specimen #5 Results
  • Test Matrix
• Krytox/Brayco Tests
  • Specimen Loading Arrangement
  • Specimen #13 Results
  • Test Matrix
• Conclusions/Recommendations
RCS Thruster

Flange containing the 16 counterbored holes

Electron beam weld joining the nozzle to the injector
Thruster Cross-Section
RCS Injector

Injector Cross Section

Sectioned S/N 120
RCS Thruster, S/N 120

Thruster was sectioned through the EB weld using EDM

Acoustic Cavities

Hole O

Hole N

Hole M

Hole L

Hole K

Hole H

Counterbored Holes

Hole I

Hole J
Counterbore Cracks

Counterbore locations
Relief Radius Cracks

Crack extending from relief radius towards acoustic cavity

Penetrant indication
RCS Thruster Cracking History

- Three groupings of cracked thrusters

- **1979 - SN 128, 130, 132**
  - No Direct cause of cracking found
  - Corrective actions
    - Developed ultrasonic inspection technique
    - Accomplished one time ultrasonic inspection of fleet
    - Added ultrasonic inspection to manufacturing flow (pre bake-out)
    - Completed 100 mission Qual test with SN 130 & 132

- **1982 - SN 322, 415, 416, 433**
  - Cracking attributed to HF etchant and 600 F insulation bake-out
  - Corrective actions
    - Eliminate etchants from manufacturing process
    - Added ultrasonic inspection immediately after bake-out cycle

- **2004 - SN 120**
  - Counter bore cracks found near new nozzle EB weld
  - First time such cracks found, discovered incidentally (penetrant inspection)
  - Relief radius cracks similar to 1979/1982 subsequently found
## Thruster Manufacturing Timelines

<table>
<thead>
<tr>
<th>Thruster SN</th>
<th>1979</th>
<th>1982</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>128</td>
<td>130</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>Qual test</td>
<td>Qual test</td>
<td></td>
</tr>
<tr>
<td>Prebake ultrasonic</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Leak Test</td>
<td>2/12/79</td>
<td>3/1/79</td>
<td>11/15/78</td>
</tr>
<tr>
<td>Torque Bolts</td>
<td>2/13/79</td>
<td>3/2/79</td>
<td>11/16/78</td>
</tr>
<tr>
<td>Insulation Bake</td>
<td>2/28/79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post bake Ultrasonic (One time fleet insp. after 128 found)</td>
<td>n/a</td>
<td>4/14/79 Cracked @ MAC</td>
<td>4/12/79 Cracked @ MAC</td>
</tr>
<tr>
<td>Post bake Ultrasonic (Mfg. Insp. Initiated after 322 found)</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Post bake Leak test</td>
<td>3/14/79 Cracked</td>
<td>o.k.</td>
<td>o.k.</td>
</tr>
<tr>
<td>Penetrant Inspection @ WSTF</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Laboratory Reproduction of Injector Cracking

• Test Purpose
  • Identify Offending Species
  • Identify Conditions for Cracking
  • Establish Conditional Thresholds
    • Temperature
    • Stress Level
    • Time, etc.

• Test Protocol
  • Followed Guidance in 1982 CAR
    • Apply HF Etchant to C103
    • Cover with Titanium
    • Stress to 30 KSI
    • Heat to 600F for 48 hrs

• Laboratory Reproduction of Cracking Was Enhanced
  • When 1982 Cracked “Brownfield” Specimen Was Found
  • When Brownfield Fracture Surface Was Same As Thruster’s
The “Brownfield” Specimen...
HF Etchant Tests/Specimen Loading

Generic Test Protocol:
1. Cut & Prep C103 Test Sample
2. Place Hardness Indentations at Max Tensile Stress Location
3. Cover With Titanium, Clamp, & Apply Constant Load (Yield Strength / 40 KSI)
4. Apply HF Etchant to Crevice
5. Heating Profile, 400F-600F for 48 Hours
6. Remove from Test, Clean, Examine Under Microscope / SEM
7. Bend to Open Cracks
8. Examine Fracture Surface Morphology to Establish Failure Mode

Cantilever Test Configuration

- Load = Constant (Equivalent to 40 KSI)
- Ti 6-4
- HF Etchant
- S.S. Clamp
- σ_{Max Tension}
- 0.75”
- Variables = T, t, HF Concentration

Specimen Dimensions
- ≈ 1” X 0.2” X 0.040”

DMA Test Equipment
- Trend Load, Deflection, Temp, Time
- Dry Air Purge
Specimen #3 – HF + 600F

After Cleaning

Opened
Specimen #3 – IG Fracture
Specimen #5 – HF + 600F

- 3 IG Crack Initiation Sites (Correspond to Hardness Indents)
Specimen #5 – “Popcorn”

Near Origin

Near Termination
Specimen #5 – Cleaned and Bent

As-Tested

As-Cleaned

As-Bent
<table>
<thead>
<tr>
<th>Specimen #</th>
<th>C103 Cantilever Beam Tests (Constant Load)</th>
<th>X = Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Vise + Nb etch + Ti cover + dry + 40KSI + 600°F + 48hrs</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Vise + Nb etch + dry + Ti cover + 40KSI + 600°F + 48hrs</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Vise + Ti cover + 40KSI + Nb etch + dry + 600°F + 48hrs</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Vise + Nb cover + 40KSI + Ti etch + dry + 600°F + 48hrs</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Vise/Hard + Ti cover + 40KSI + Nb etch + dry + 600°F + 48hrs</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>Vise/Hard + Ti cover + 40KSI + Nb etch + dry + 400°F + 48hrs</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Vise/Hard + Ti cover + 40KSI + Nb etch + dry + 500°F + 48hrs</td>
<td>X (minor)</td>
</tr>
<tr>
<td>9</td>
<td>Vise/Hard + Ti cover + 40KSI + Nb etch + dry + 600°F + 3hrs</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>Vise/Hard + Ti cover + 40KSI + Nb etch + dry + 70°F + H2O (3X/day) + 260hrs + 600°F + 48hrs</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>Vise/Hard + Ti cover + 40KSI + Nb etch + dry + 600°F + 168hrs</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>Vise/Hard + Nb cover + 40KSI + Nb etch + dry + 600°F + 48hrs</td>
<td>X</td>
</tr>
<tr>
<td>13</td>
<td>See Table 2</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Hard + Ti cover + 40KSI + air + + + 600°F + 48hrs</td>
<td></td>
</tr>
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</table>
Krytox 143AC Tests

• What is Krytox?
  • Perfluoropolyether (PFPE) Polymer
  • Also Referred to as a Synthetic Oil
  • Composed of Carbon, Oxygen and Fluorine

• Why Test Krytox?
  • Used in Thruster Manufacturing
  • Contained Fluorine
  • Original Compatibility Tests at 1100F not 600F
  • XPS Analysis Showed PFPE on Fracture Surface
Krytox Tests/Specimen Loading

3-Point Bend (Constant Deflection)

Hardness Indents
(Top & Bottom Surfaces)

10-38 Screw

C103
≈ 1.0 x 0.15 x 0.043

Deflection

PFPE Oil
(Tension Surface)

Stainless Steel

2.0"
Specimen #13 – Krytox + 600F

Missing Grains at Crack Origin

“Popcorn” on Free Surface + IG Crack
# Krytox Exposure Test Matrix

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>C-103 Cantilever Beam Tests (Constant Load)</th>
<th>X = Cracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Hardness + Ti cover + 40KSI + Krytox + 600°F + 48hrs</td>
<td>X</td>
</tr>
<tr>
<td>14</td>
<td>See Table I</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Hardness + Ti cover + 40KSI + Krytox + 400°F + 48hrs</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Hardness + Ti cover + 40KSI + Krytox + 500°F + 48hrs</td>
<td>X (minor)</td>
</tr>
<tr>
<td>17</td>
<td>Hardness + Ti cover + 40KSI + Krytox + 600°F + 96hrs</td>
<td>X</td>
</tr>
<tr>
<td>18</td>
<td>Hardness + Ti cover + 40KSI + Krytox + 600°F + 3hrs</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>C-103 Three-Point-Bend Tests (Constant Deflection)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>Hardness + no Ti + &gt;45KSI + Krytox + 600°F + 1hrs</td>
</tr>
<tr>
<td>30</td>
<td>No indent + no Ti + &gt;45KSI + Krytox + 600°F + 1hrs</td>
</tr>
<tr>
<td>31</td>
<td>Hardness + no Ti + &gt;45KSI + Brayco + 600°F + 1hrs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specimen #</th>
<th>Cb752 Three-Point-Bend Tests (Constant Deflection)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>Hardness + no Ti + &gt;45KSI + Brayco + 600°F + 23 hrs</td>
</tr>
</tbody>
</table>
Conclusions / Recommendations

- Cracks Successfully Reproduced in Laboratory
- Simultaneous Conditions Necessary for Cracking
  - Mechanically Disturbed/Cold Worked Surface
  - Externally Applied Sustained Stress near Yield
  - Fluorine Containing Fluid
  - Sustained Temperature above 400F
- Cracking Occurred During Manufacturing
  - Only Time all Four Conditions act Simultaneously
  - Eliminate use of Fluorine with Niobium
- Same Cracking Mechanism Operating in HF and PFPE Fluids
- Specific Cracking Mechanism not Identified
Back-Up
Location Of Cracks

SSRCS-PRIMARY INJECTOR

- Mounting Flange
- Injector Flange
- Spacer
- Injector Bolt
- Boundary Layer Cooling Hole Passage
- Chamber
- Acoustic Cavity

- Fuel Tube (P/N 234121)
- Oxidizer Tube (P/N 234122)
- Fuel Closure (P/N 234124)
- Flow Splitter (P/N 234126)
- Standoff (P/N 234118)

- Titanium
- Relief Radius Cracks
- Counter bore Cracks

Injector-chamber EB Weld
Fracture Face of Relief Radius Crack

Overview of fracture face

Cold worked surface layer and intergranular facets in failure origin area
Cleavage Fracture on S/N 120

Opened Relief Radius (Between Holes J & K)
<table>
<thead>
<tr>
<th></th>
<th>1979</th>
<th>1982</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thruster SN</strong></td>
<td>128</td>
<td>132</td>
<td>322</td>
</tr>
<tr>
<td><strong>Crack Initiated in Mfg.</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Cracked 100% Intergranular</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Fracture Discolored</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Surface Chemistry</strong></td>
<td>F,O,C</td>
<td>F</td>
<td>F,O,C</td>
</tr>
<tr>
<td><strong>Crack Extension Beyond Discoloration</strong></td>
<td>No</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td><strong>Crack Extension In service/Qual Test</strong></td>
<td>No service history</td>
<td>Qual, No</td>
<td>Qual, No</td>
</tr>
</tbody>
</table>
Discussion

• Chemical breakdown of the PFPE polymer chain is a well known phenomena to the lubrication community.

• The mechanism tends to follow three steps:
  1. The metal/oxide surface reacts with fluorine from the PFPE to form a Lewis acid (i.e. NbF3 / NbF5).
  2. The Lewis acid catalyzes the cleavage of the polymer chain.
  3. The broken polymer chain can react with water to form a carboxylic acid terminated group releasing hydrofluoric acid.
Injector Crack Flight Rationale Road-Map

- Conditions for cracking no longer exist
- M&P "popcorn" oxidization theory
- All thrusters stability screened
- WSTF OMDP helium mass spec external leak test requirement

- All thrusters passed a 525 psig external leak test during original ATP.
- S/N 130 & 132 qual test history
- Risk of on-orbit instability is low
- Thrusters routinely screened for leakage
- Minimal risk to flight safety

- Injectors are leak free
- Existing cracks do not propagate due to service conditions
- Instabilities could possibly induce external leakage (S/N 132 history)
- Thrusters routinely screened for leakage

- WSTF OMDP helium mass spec external leak test requirement (50 psig)
- S/N 120 flight history
- 20+ years of service for etchant exposed thrusters with no external leakage
- Effect of external leakage is not catastrophic
- Possible to add KSC turnaround external leak test requirement if absolutely necessary

- Consistency across all F/A's despite usage
- Pc tube burn through test history indicates small flow paths would likely plug with combustion residue
- Impingement areas understood and risks are minimal