ROOT CAUSE ANALYSIS
EXPANDER INTAKE FLANGE STUD FAILURE

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Started in March 2001. Five studs were found broken during a scheduled shutdown in September 2003.
Assembly Drawing

**STUD**

1¼-12 UNF, 2A, IN718 PER AMS 5663
UTS: AT ROOM TEMP 185 ksi,
AT 1,200°F 145 ksi

**BELLEVILLE WASHER**

IN X-750, Rated For 45,000 lbs.
UTS: AT ROOM TEMP 160 ksi
AT 1,200°F 135 ksi
## Minimum Required Mechanical Properties

Tensile Test Results for Stud Samples (ksi):

<table>
<thead>
<tr>
<th>Order/PO #</th>
<th>Room Temperature</th>
<th>AT 1,200°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UTS</td>
<td>YS</td>
</tr>
<tr>
<td>Batch 1</td>
<td>203.0</td>
<td>173.0</td>
</tr>
<tr>
<td></td>
<td>202.0</td>
<td>170.0</td>
</tr>
<tr>
<td>Batch 2</td>
<td>206.8</td>
<td>172.9</td>
</tr>
<tr>
<td>Batch 3</td>
<td>203.8</td>
<td>164.8</td>
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<tr>
<td></td>
<td>206.8</td>
<td>176.7</td>
</tr>
<tr>
<td>Batch 4</td>
<td>205.6</td>
<td>172.1</td>
</tr>
<tr>
<td></td>
<td>201.5</td>
<td>165.0</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Average Value</td>
<td>204.2</td>
<td>170.6</td>
</tr>
<tr>
<td>Minimum Required</td>
<td>185</td>
<td>150</td>
</tr>
</tbody>
</table>
Fishbone Diagram

Environment
- High Temp 1300F
- Sulphur & Chlorides
- Flange Leak

People
- Experience
- Technical Knowledge
- Technical Training

Machine
- Thread Fabrication
- Flange Design
- Bolt Sequence

Methods
- Torque Measurement
- Operation, Heating Rate
- Torque Application

Measurements
- Flange Condition
- Thread Inspection
- Flange & Piping Alignment

Washer Assembly
- Thermal Growth

Materials
- Coated Bolts
- Different Bolt Material
- Diff Thread Lubricant
- Diff Gasket Material

Impact

Implementation

<table>
<thead>
<tr>
<th>Easy</th>
<th>High</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Hard</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Root Cause Analysis
Stud Failure
### Chemical Properties

### Chemical Composition Comparison

<table>
<thead>
<tr>
<th>Elements</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CHEMICAL COMPOSITION WITHIN SPECIFICATION LIMIT
Mechanical Properties

Notch Tensile Strength For Broken Stud

- Room Temp NTS 314 KSI (AVE NTS 274 KSI)
- Broken Stud Hardness 389 Brinell (42°C), Min Required 331 Brinell (36°C)
## Initial Load Condition

**Stress Developed on Stud for 535 ft.lb Initial Torque:** 43,228 psi  
**Load on Belleville Washer:** 46,400 Lbs for 535 ft.lb Initial Torque

**Stress Developed on Belleville Washer for 0.008” Compression**  
At Different Locations (UTS 160 ksi, YS 105 ksi)

<table>
<thead>
<tr>
<th>Stress Developed</th>
<th>Elastic Stress</th>
<th>Neuberized Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_0 ), Spring Stress at Point 0 (ksi) =</td>
<td>-281</td>
<td>-127</td>
</tr>
<tr>
<td>( F_I ), Spring Stress at Point I (ksi) =</td>
<td>-398</td>
<td>-149</td>
</tr>
<tr>
<td>( F_{II} ), Spring Stress at Point II (ksi) =</td>
<td>372</td>
<td>144</td>
</tr>
<tr>
<td>( F_{III} ), Spring Force at Point III (ksi) =</td>
<td>220</td>
<td>117</td>
</tr>
<tr>
<td>( F_{IV} ), Spring Stress at Point IV (ksi) =</td>
<td>-203</td>
<td>114</td>
</tr>
</tbody>
</table>

Stress Developed:  
\[ > \text{YS} \]  
\[ < \text{UTS} \]
Normal Operating (At 1,200°F)

ASME Code Calculation

ASME, SEC VIII, APPENDIX-2

Minimum Stress Required for Joint Seal on Stud (52) = 5,098 (PSI)

FLANGE STRESS FOR THE GIVEN PARAMETERS:

<table>
<thead>
<tr>
<th>TYPE</th>
<th>t</th>
<th>g0</th>
<th>g1</th>
<th>h</th>
<th>SH</th>
<th>SR</th>
<th>ST</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.5</td>
<td>0.906</td>
<td>1.632</td>
<td>4.167</td>
<td>3,266</td>
<td>1,082</td>
<td>797</td>
<td>OK</td>
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</table>

MAX PERMITTED VALUE FOR:  
- SH = LONGITUDINAL STRESS IN HUB, PSI
- SR = RADIAL STRESS IN FLANGE, PSI

MAX PERMITTED VALUE FOR:  
- SR & ST = 4,400(PSI)
- (SH+SR)/2 OR (SH+ST)/2 = 4,400(PSI)

SH = LONGITUDINAL STRESS IN HUB, PSI
ST = TANGENTIAL STRESS IN FLANGE, PSI
g0 = THICKNESS OF HUB AT SMALL END, IN
h = HUB LENGTH, IN

t = FLANGE THICKNESS, IN.
g1 = THICKNESS OF HUB AT BACK OF FLANGE, IN

Meets ASME Requirements
Normal Operating (At 1,200°F)
Initial Torque And Thermal Loads

Stress Developed on Stud for 535 ft.lb Initial Torque: 43,230 psi
Stress Developed on Stud Due To Thermal Loading: 56,890 psi
Net Stress Developed on Stud (Int. Torq. + Thermal): 100,120 psi

Net Bolt Stress < 125,000 psi (YS), Acceptable

Net Bolt Stress > Min Required For Joint Seal, Acceptable

Load on Belleville Washers 107,470 Lbs, Failure will Occur
Startup Stress, Torque 535 Ft.lb

Net Stress on Stud During Start-up

- Minimum UTS 145,000 (psi)
- Flange at 1425F
- Flange at 1200F
- Flange at 1000F
- Flange at 800F

Temperature Difference Between Flange and Stud (F)
### Bolt Thermal Load For Different Temperature Lags, Flange at 1,200°F

<table>
<thead>
<tr>
<th>Temperature Difference Flange/Stud (°F)</th>
<th>Bolt Material</th>
<th>Flange Material</th>
<th>Thermal Strain (in/in)</th>
<th>Bolt Thermal Stress (psi)</th>
<th>Net Bolt Extension (in)</th>
<th>Bolt Force Due To Thermal Load (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bolt Exp Coeff. (in/in/DegF)</td>
<td>Elasticity Modulus (psi)</td>
<td>Bolt Exp Coeff. (in/in/DegF)</td>
<td>Elasticity Modulus (psi)</td>
<td></td>
<td></td>
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<tr>
<td>0</td>
<td>8.400E-06</td>
<td>2.480E+07</td>
<td>1.043E-05</td>
<td>2.070E+07</td>
<td>0.00229</td>
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<tr>
<td>50</td>
<td>8.350E-06</td>
<td>2.500E+07</td>
<td>1.043E-05</td>
<td>2.070E+07</td>
<td>0.00277</td>
<td>69198</td>
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<tr>
<td>100</td>
<td>8.300E-06</td>
<td>2.520E+07</td>
<td>1.043E-05</td>
<td>2.070E+07</td>
<td>0.00324</td>
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<tr>
<td>150</td>
<td>8.200E-06</td>
<td>2.565E+07</td>
<td>1.043E-05</td>
<td>2.070E+07</td>
<td>0.00375</td>
<td>96185</td>
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<tr>
<td>200</td>
<td>8.100E-06</td>
<td>2.610E+07</td>
<td>1.043E-05</td>
<td>2.070E+07</td>
<td>0.00425</td>
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<tr>
<td>235</td>
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<td>2.638E+07</td>
<td>1.043E-05</td>
<td>2.070E+07</td>
<td>0.00460</td>
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</table>
Start-up Probability of Failure, Torque 535 Ft.Lb

Stud Temperature Lags 235°F For Flange Temperature 1,425°F
Stud Temperature Lags 190°F For Flange Temperature 1,290°F

Max Stress Value at Flange Temp 1425°F
(Stud Temp 1190°F) = 170.817 ksi

Min Value Stress at Flange Temp 1290°F
(Stud Temp 1100°F) = 141.314 ksi

99.7% Population

UTS Test Data at 1200F
Max 178.4 ksi,
Min 156.7 ksi
(+/- 4 Sigma)

Net probability of Failure ~7% (4 out of 52)
Conclusion

**Initial Condition:**
- Failure Will Not Occur For Studs or Washers
- Stress Values Are Well Within Permissible Limits

**Normal Operating Condition:**
- Studs Will Not Fail, However, Washers Will Fail
- Stress Values Are Within Permissible Limits For Studs

**Start-up Condition:**
- Probabilistic Analysis Result:
- 7% Failure For Initial Torque of 535 (Ft.Lbs)
Corrective Action

Corrective Actions Taken:

1. Belleville Washers Replaced by Regular Flat Washes
   (Belleville Washer For Load Capacity over 45,000 lbs. Not Available)

2. Initial Bolt Torque Reduced From 535 (Ft.Lbs) To 400 (Ft.Lbs)

3. Evaluated the Bolt Stress For Above loading
Corrective Action Normal Operating (At 1,200°F)

Stress Developed on Stud for 400 ft.lb Initial Torque: 32,330 psi
Stress Developed on Stud Due To Thermal Loading: 56,890 psi
Net Stress Developed on Stud (Int. Torq. + Thermal): 89,220 psi

Net Bolt Stress < 125,000 psi (YS), Acceptable

Net Bolt Stress > Min Required For Joint Seal, Acceptable

Load on Belleville Washers 95,770 Lbs. (Failure will Occur)
Corrective Action, Startup Stress

Reduced Initial Bolt Torque 400 FT.LB

Net Stress on Stud During Start-up

Net Stress (psi)

Temperature Difference Between Flange and Stud (F)

Minimum UTS 145,000 (psi)

Flange at 1425F

Flange at 1200F

Flange at 1000F

Flange at 800F
Corrective Action, Probability of Failure

Reduced Initial Bolt Torque 400 FT.LB

Normal Distribution Chart
400 Ft.lbs. Initial Torque

Max Stress Value at Flange Temp 1425F (Stud Temp 1190F) = 159.8 ksi
Min Value Stress at Flange Temp 1290F(Stud Temp 1100F) = 130.8 ksi

UTS Test Data at 1200F
Max 178.4
Min 156.7
(+/- 4 Sigma)

UTS Test Data, Stress Developed, Z = 3.6 (0.015% Failure)
Stress Developed, Z = 3.7 (0.001% Failure)

Net probability of Failure ~ 0.016% (16 out of 100,000)
Recommendations and Results

**Recommendations:**

1. Use Regular Flat Washes
   (Belleville Washer For Load Capacity over 45,000 lbs. Not Available)

2. Reduce Initial Torque
   From 535 (Ft.Lbs) To 400 (Ft.Lbs)
   (Exceeds Min Required Bolt Load For Joint Seal)

**Results:**

No Failure for the Studs Has Been Reported Since Last 4 Years.