Failure Analysis of Space Shuttle Orbiter Valve Poppet

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Failure of Space Shuttle Orbiter Flow Control Valve (FCV) Poppet

- During the ascent of *Endeavour* (OV-105) on Space Shuttle mission STS-126, the main propulsion system (MPS) engine #2 GH$_2$ flow control valve (FCV) appeared to make an un-commanded transition from the low-flow to high-flow position
  - This anomaly did not impact mission success
  - Post-mission disassembly of the FCV revealed that the poppet was fractured and a crescent-shaped piece was missing
• One FCV per main engine
  - Controls the flow of \( \text{GH}_2 \) pressurant to the external tank (ET)
  - Two positions: low and high flow
  - Operating pressure is approximately 3400 psig
• Poppet is made from CRES 440A
FCV Poppet

"Barrel" or "spool"

FLOW PATH

"Upstream flange", or "shim flange"

Fracture at barrel to flange radius

"Flow flange", a.k.a, "downstream flange", or simply "the flange"
Optical Fractography

- Poppet fracture surface exhibited five (5) distinct zones:
  - Zones 1 & 2: Initial “thumbnails”
  - Zone 3’s (2): Circumferential propagation
  - Zone 4 & 5: Propagation through the flange and final fracture
- Fracture initiation occurred at middle of the body-to-flange radius and primarily propagated circumferentially along the radius, then through the flange thickness
  - The general plane of the fracture was ~45° from the flange face
Zones 1 & 2: Initial thumbnails

- Fracture initiated on two planes along the radius surface, then merged together into one plane

Zone 1: 0.011 x 0.043 inch

Zone 2: 0.026 x 0.133 inch
Zone 1: Initial thumbnail

- Scanning electron fractography revealed:
  - small, semi-planar areas
  - rounded ridges
  - exposed carbide particles,
  - "divots", which presumably resulted from spherical carbides being pulled out (i.e., carbide decohesion).
- No substantial secondary or intergranular cracking
- No striations
In Zone 2, the fracture propagated on a less torturous path, exhibiting larger "semi-planar" regions, consisted with the smooth, shiny optical appearance. Otherwise, the features were fairly consistent with that of Zone 1.
Zones 1 & 2
Zone 3 "Wings"

- From the thumbnails, the fracture propagated circumferentially along the radius, not penetrating further into the flange thickness.
- The topography of the fracture surface in the Zone 3 wings was similar to that of Zone 1.
Zone 4: Propagation through the flange

- The fracture surface increased in general roughness in Zone 4
  - Exhibited some secondary cracking
  - Sharper, more angular features
- Fracture toughness testing of 440A at NASA-MSFC in a 3400 psig GH₂ environment clearly demonstrated that the features of Zone 4 were consistent with a sustained load cracking mechanism
Zone 5: Final fracture

- The Zone 5 “corners” exhibited a fracture surface typical of final, rapid overload
  - Primarily dimpled rupture
Summary of Poppet Analysis

• Investigation concluded that the poppet failed due to fatigue cracking that, most likely, occurred under changing loading conditions, explaining the multiple zones observed
  – Comparison of the various zones with fracture surfaces generated by testing specimens in GH$_2$ at MSFC indicated that the cracks most likely initiated in a hydrogen environment
  – These comparisons also revealed that the crack propagation through the flange wall (Zone 4) was primarily driven by a sustained load (mean stress) cracking mechanism in GH$_2$
• No evidence of a defect was found that would explain the failure, such as corrosion, a raw material flaw, or other anomaly
Fatigue Testing of Old Poppets

- At the time the failure occurred, there was no known cyclic loading of the poppet to explain the fatigue failure
  - Also unknown was whether the fracture surfaces indicated a high cycle fatigue mechanism consistent with flow-induced vibration or a low cycle mechanism consistent with poppet actuation (translation from low to high flow)
- A test program was conducted using obsolete poppets that were no longer in service
  - To acquire results quickly, the testing was performed with mechanical loading of the flange, as opposed to performing a series of flow tests
  - A hook mechanism was used to pull on the poppet flange, loading the radius in tension
Test Setup
Test Results

- The test results were very inconsistent, with lighter test loads resulting in relatively fast failures.
- More importantly, the "quick failures" exhibited the thumbnail zones characteristic of the original failure.
- Conclusion: The thumbnail cracks were pre-existing.

<table>
<thead>
<tr>
<th>S/N / Test</th>
<th>Load (lbs.) @ R = 0.1</th>
<th>Cycles to Failure</th>
<th>Thumbnail</th>
</tr>
</thead>
<tbody>
<tr>
<td>530-01 First</td>
<td>150 lbs</td>
<td>1M cycles</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>250 lbs</td>
<td>12K cycles</td>
<td></td>
</tr>
<tr>
<td>530-06</td>
<td>175 lbs</td>
<td>3600 cycles</td>
<td>Yes (2)</td>
</tr>
<tr>
<td>530-01 Second</td>
<td>175 lbs</td>
<td>1684 cycles</td>
<td>Yes (2)</td>
</tr>
</tbody>
</table>
The thumbnail zones of the test articles exhibited fracture features that were very similar to that of the original failure.
A Fleet-Wide Issue

- The discovery of pre-existing thumbnail cracks in the previous, now "retired" flight hardware used for the fatigue testing indicated that poppet cracking was a generic problem that had existed for the life of the Shuttle program.
- Subsequently, the program developed an eddy current (EC) technique that was capable of reliably detecting these small, very tight cracks.
  - EC detected cracks in 10 of 15 retired flight poppets.
- Before the next mission after STS-126 could be flown, the integrity of the current flight hardware required verification.
  - EC inspections found 4 of 13 cracked.
Ongoing Risk Mitigation

• With so few missions remaining for the Shuttle program, there is insufficient time to implement a permanent corrective action, so the program is mitigating the risk of using the current flight poppets by monitoring their “health” with EC inspections
  – Each poppet is inspected after every mission
  – After GN2 flow balance testing at the valve vendor
  – After GH2 flow calibration and mission duty cycle (MDC) testing at WSTF

• To date, a total of 12 current flight units, including the original failure, have been found cracked by EC inspections
  – All cracks subsequently verified by SEM examination
Of the current flight hardware poppets found cracked, five of them were actually new poppets, pulled from spares, that were to replace poppets that had been found to be cracked.

- In each case, the EC inspections after MDC testing at WSTF detected the cracks.
- EC inspections prior to MDC did not detect the cracks.

Fractography of two zero-flight poppets found that the fractures were quite similar to the original failure and the cracked obsolete (fatigue test) poppets.
Conclusions

- The poppet failed during STS-126 due to fatigue cracking that most likely was initiated during MDC ground-testing.
- This failure ultimately led to the discovery that the cracking problem was a generic issue affecting numerous poppets throughout the Shuttle program's history.
- This presentation has focused on the laboratory analysis of the failed hardware, but this analysis was only one aspect of a comprehensive failure investigation. One critical aspect of the overall investigation was modeling of the fluid flow through this valve to determine the possible sources of cyclic loading.
  - This work has led to the conclusion that the poppets are failing due to flow-induced vibration.