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Failure Analysis of Fractured Poppet from Space Shuttle Orbiter Flow Control Valve

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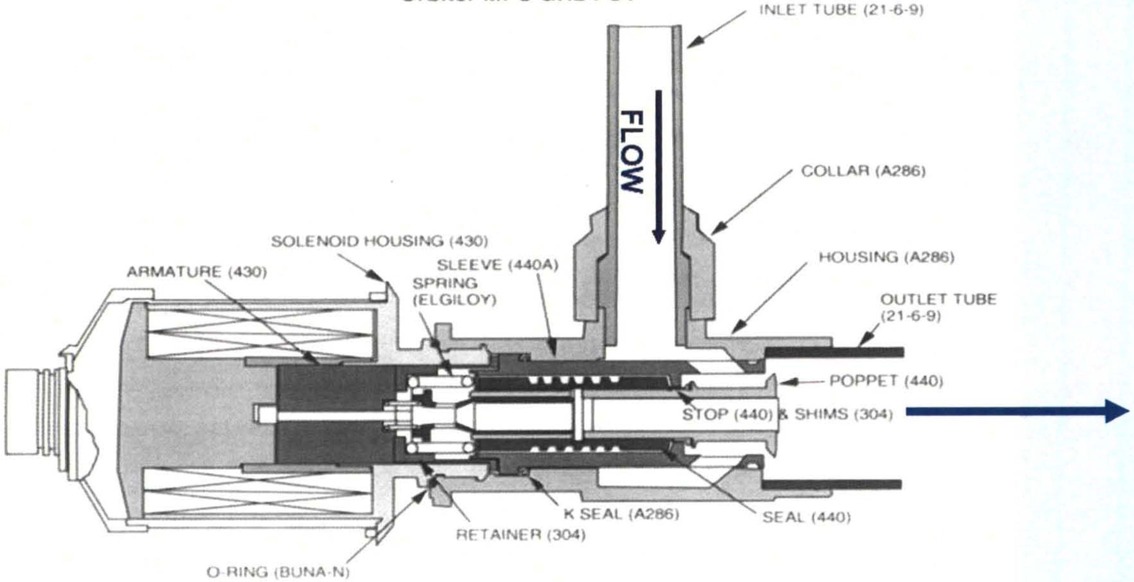
Failure of Space Shuttle Orbiter Flow Control Valve (FCV) Poppet

- 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

GH_2 Flow Control Valve (FCV)

- One FCV per main engine
  - Controls the flow of 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

Orbiter MPS GH2 FCV



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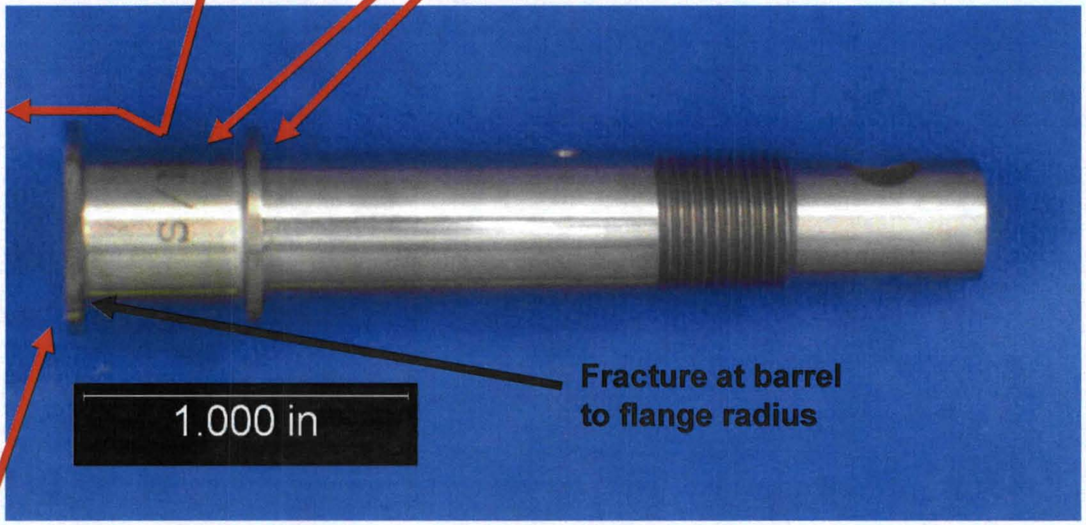
FCV Poppet

"Barrel" or "spool"

FLOW PATH

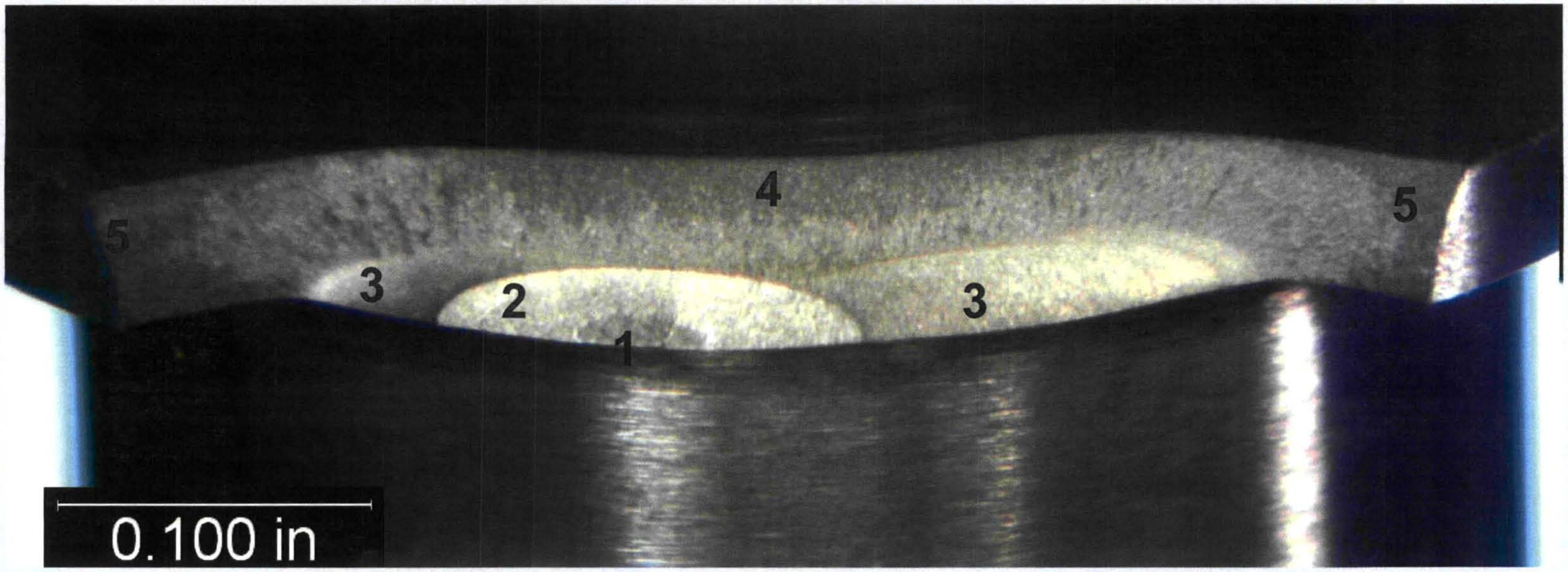
"Upstream flange", or "shim flange"



"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



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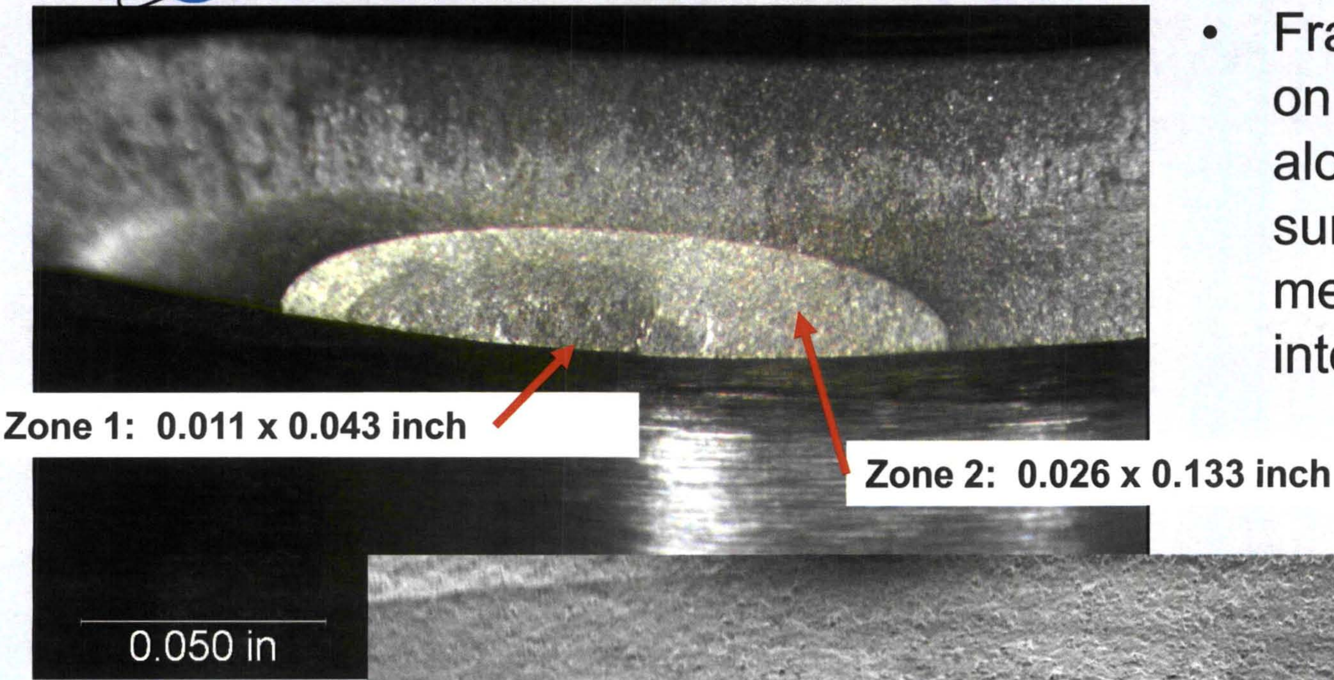
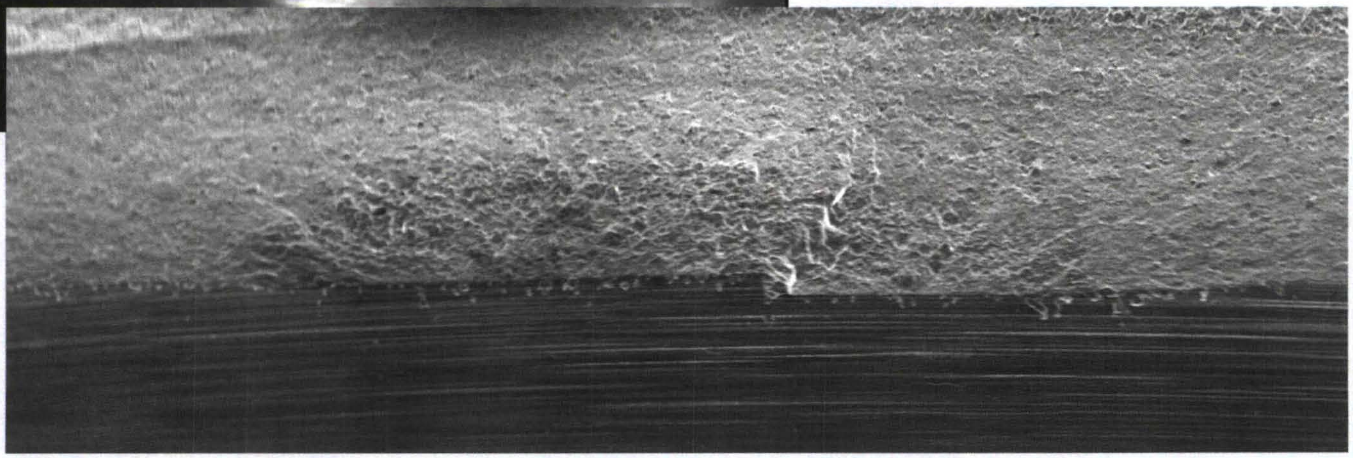
Zones 1 & 2: Initial thumbnails

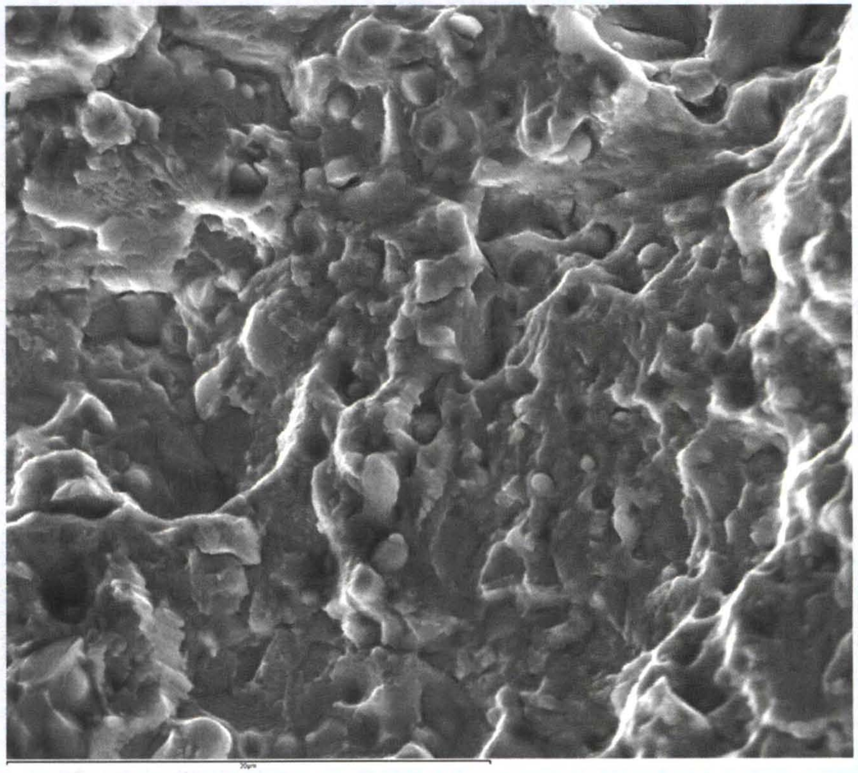
- Fracture initiated on two planes along the radius surface, then merged together into one plane





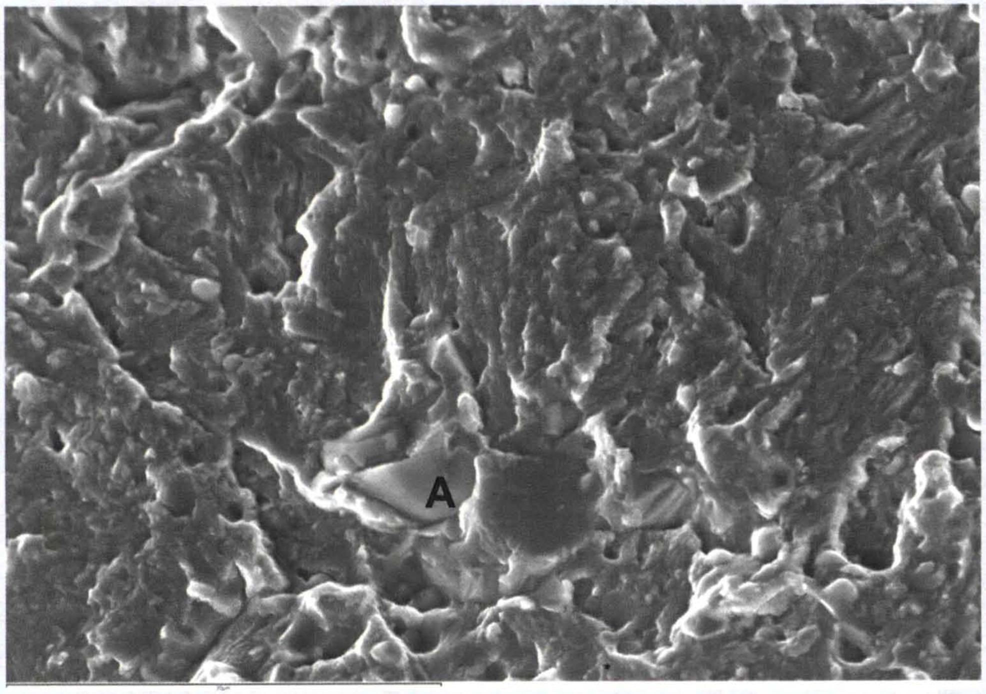
Zone 1: Initial thumbnail

- 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



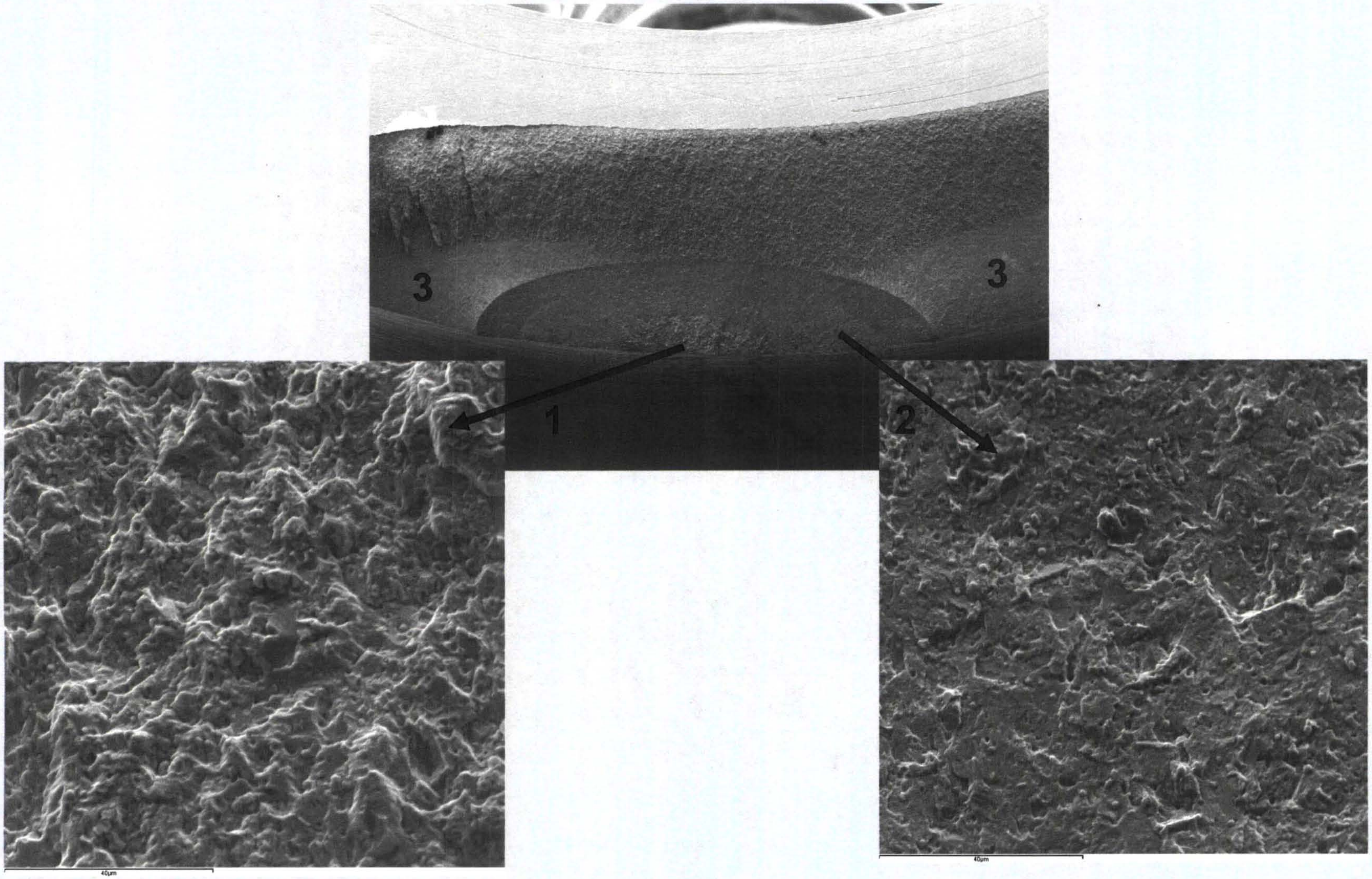
Zone 2: Outer thumbnail

- 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.



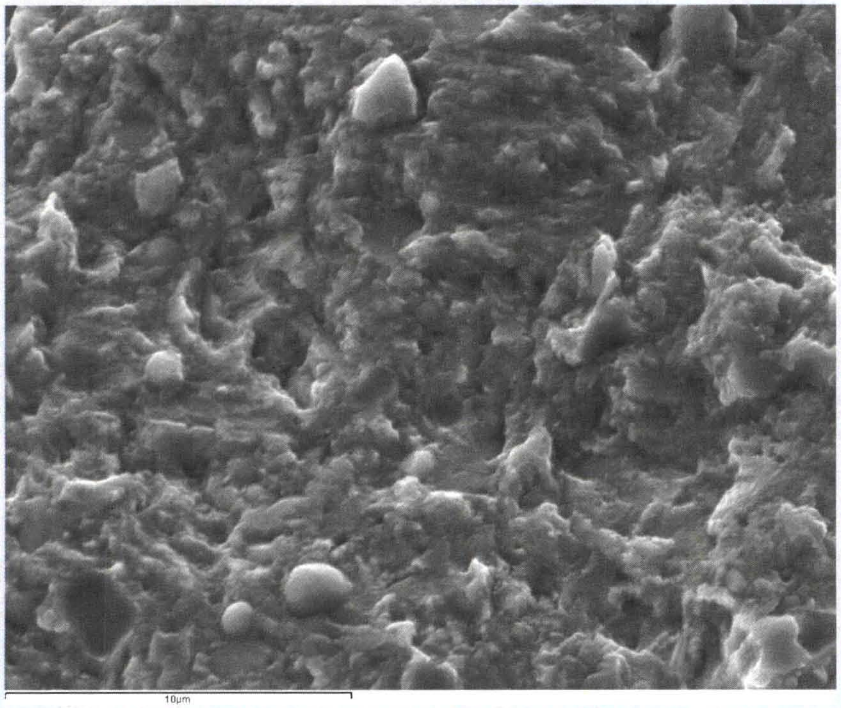
A. Large blocky carbide typical of CRES 440

Zones 1 & 2



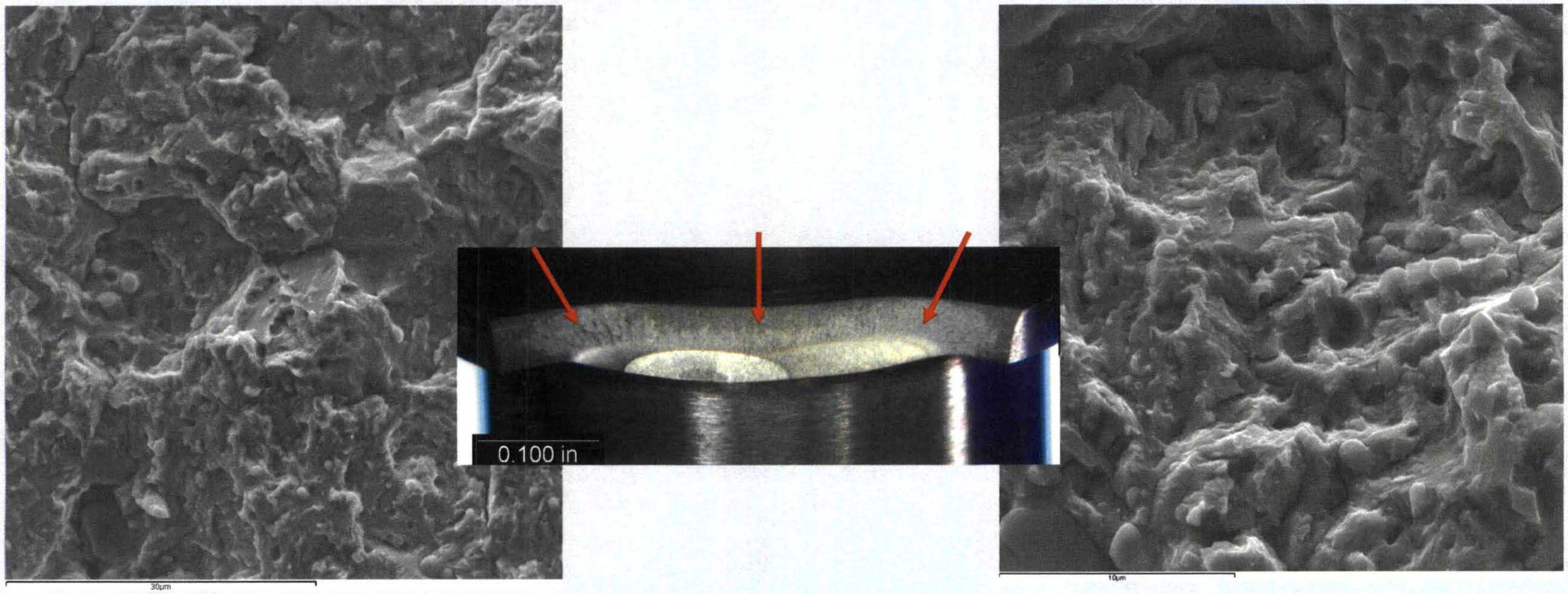
Zone 3 "Wings"

- 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 GH_2 environment clearly demonstrated that the features of Zone 4 were consistent with a sustained load cracking mechanism



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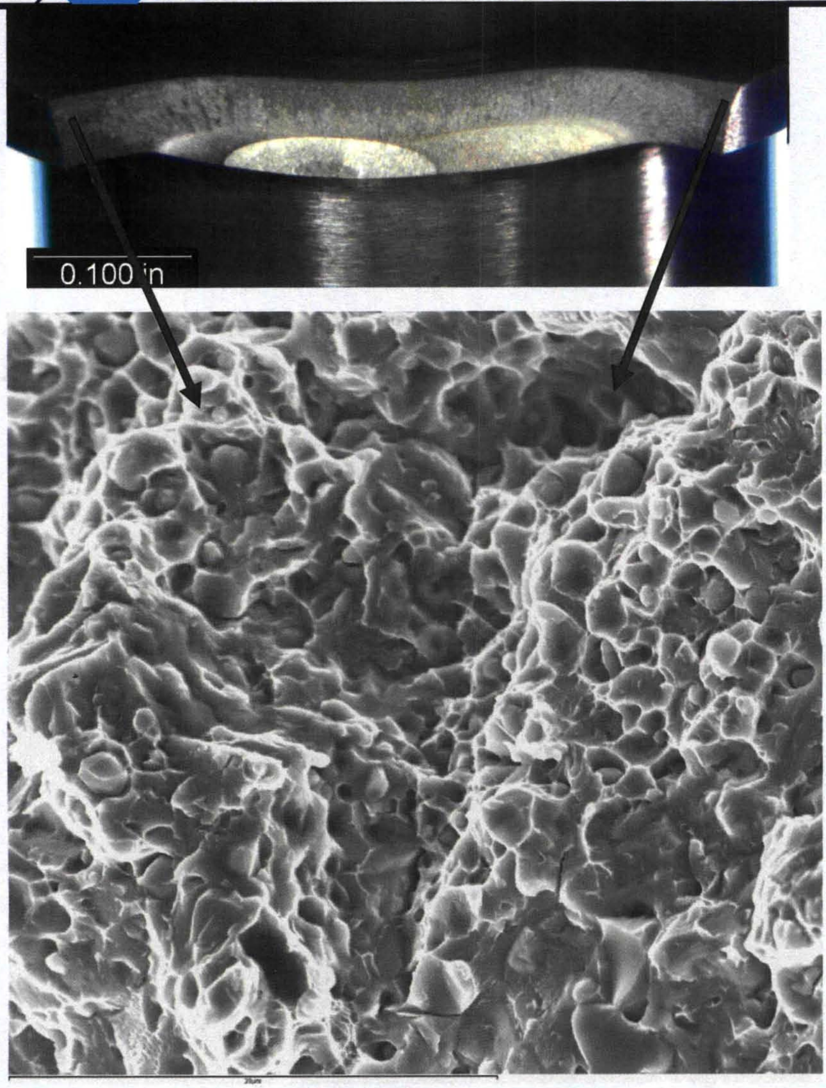
Zone 5: Final fracture



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

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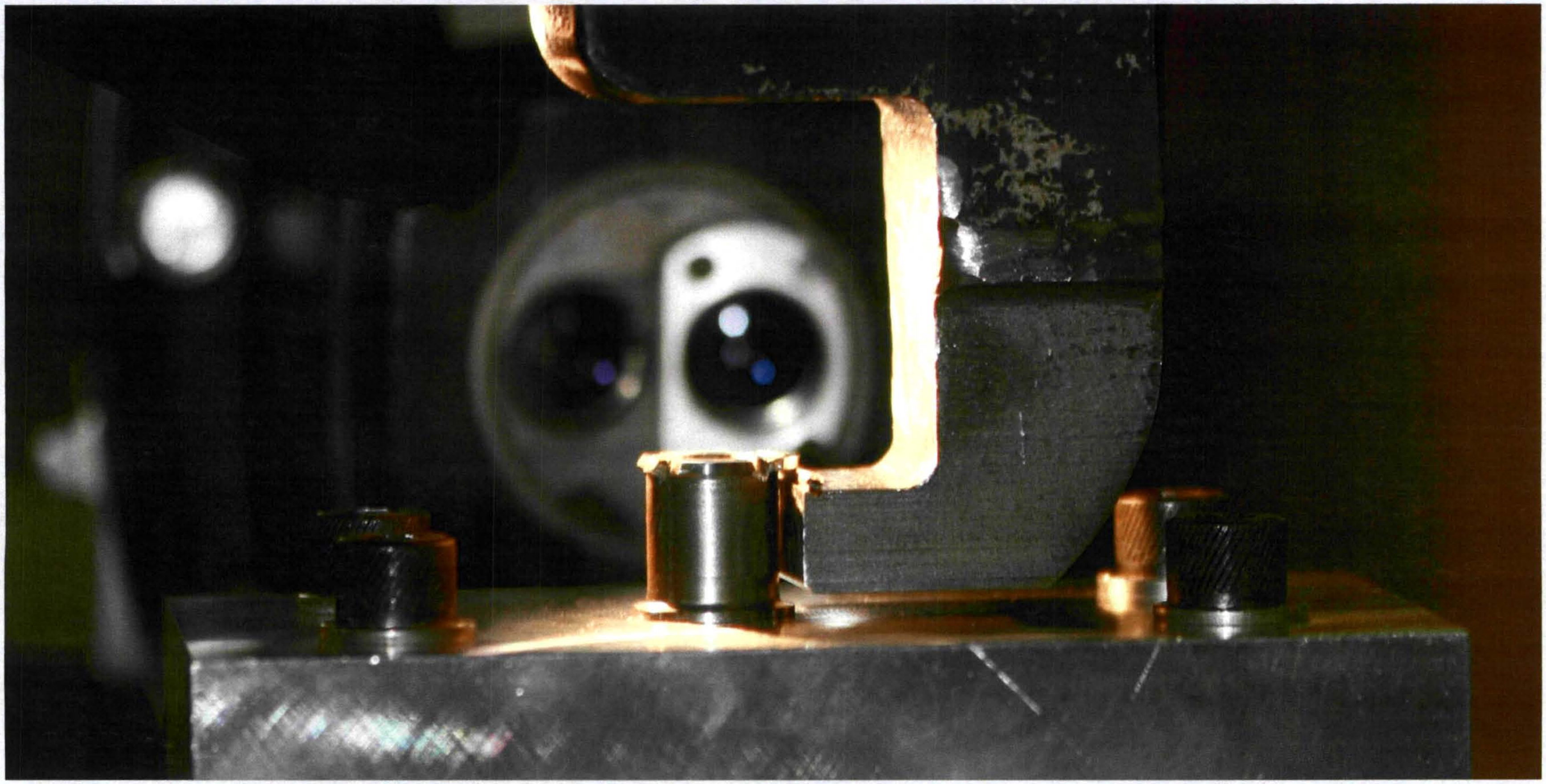
Summary of Poppet Analysis

- 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



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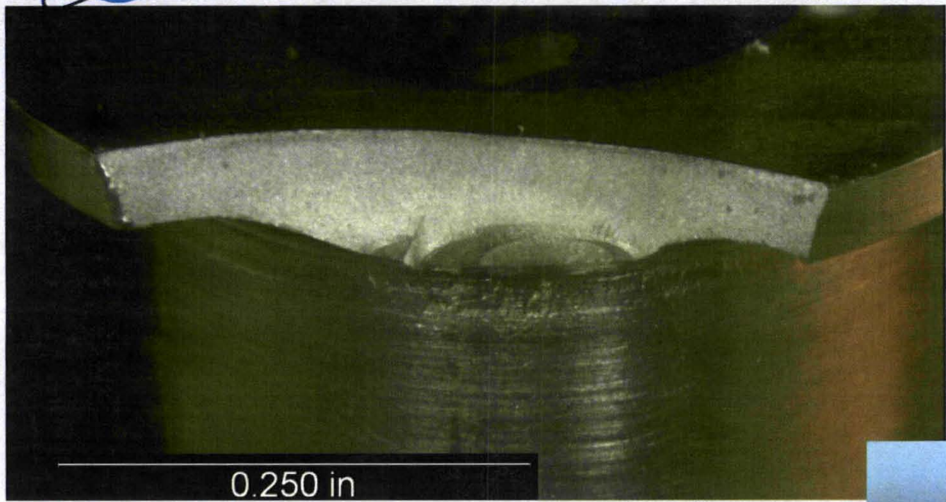
Test Results

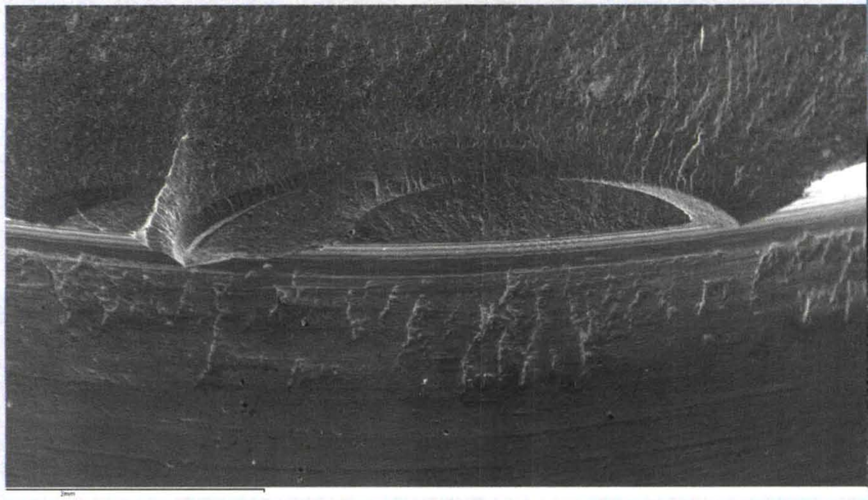
- The test results were very inconsistent, with lighter test loads resulting in relatively fast failures
- More importantly, the "quick failures" exhibited the thumbnail zones characteristic of the original failure
- Conclusion: The thumbnail cracks were pre-existing

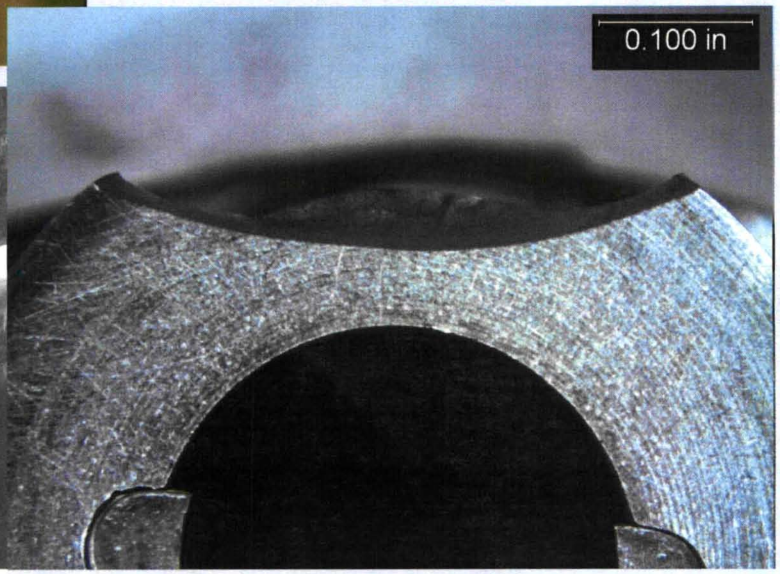
S/N / Test	Load (lbs.) @ R = 0.1	Cycles to Failure	Thumbnail
530-01 First	150 lbs 250 lbs	1M cycles 12K cycles	No
530-06	175 lbs	3600 cycles	Yes (2)
530-01 Second	175 lbs	1684 cycles	Yes (2)

Test Article Fractography



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

Cracked Zero-Flight Poppets

- 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 effecting 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