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Nondestructive Crack Detection in a Fuel System Component

2010 Aircraft Airworthiness & Sustainment

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Background and Objective

Background

- Space shuttle orbiter uses three cryogenic liquid hydrogen fuel and liquid oxygen oxidizer rocket engines called main engines
- Space Shuttle Mission STS-126 (December 2008) had a main engine anomaly during launch
- During ascent, one of the hydrogen flow control valves changed to more open state without command
  - The flow control valve controls the back pressure of the rapidly depleting liquid hydrogen fuel in the hydrogen tank which is one of the two chambers of the external tank
- Post-flight, the FCV poppet head was found to be damaged
- Concerns:
  - ET LH2 tank overboard venting (fire)
  - Potential for liberated material

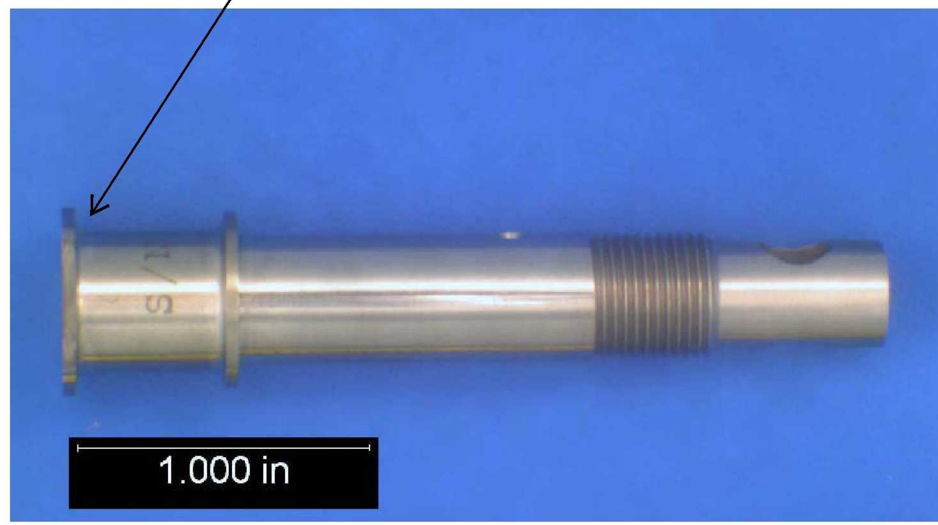
Objective

- Provide information on selected NDE development work for detection of cracks in the poppet
  - Eddy Current and Ultrasonic NDE

Flow Control Valve Assembly and Poppet

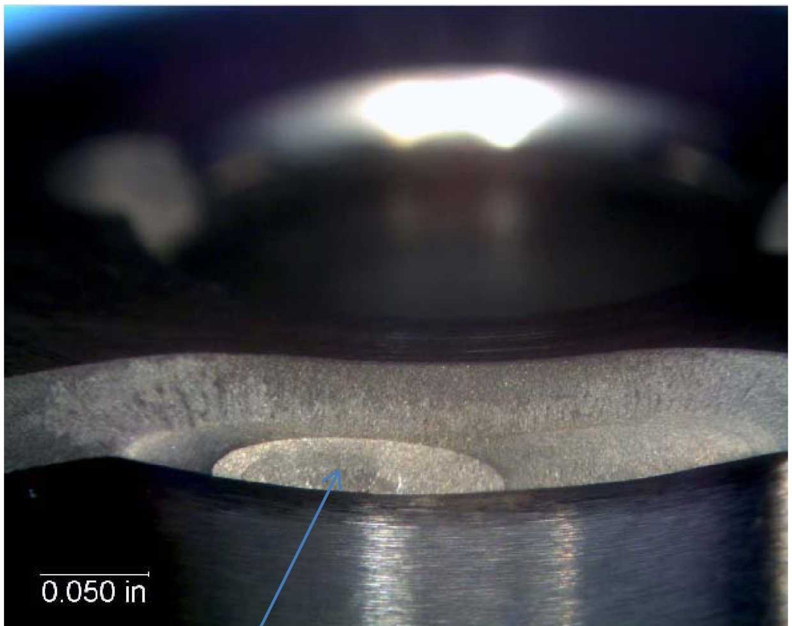
Assembly

NDE needed in the radius

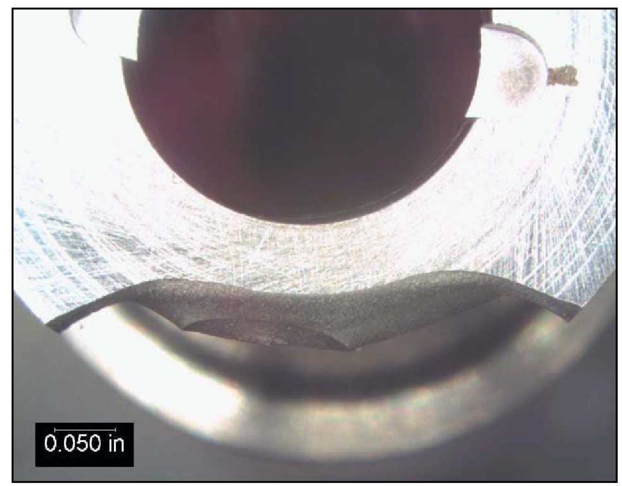


Poppet

Post Flight Evaluation



Fracture surface



Cause: High cycle fatigue during several launches. Crack formation and growth.
Typical surface crack opening = 0.25 micron

Poppet Material: 440A Steel

- In annealed condition, type 440A steel consist of **ferrite** and chromium carbides. 440A has large scattered primary carbides. When the alloy is heat treated at 1800-1950°F, **austenite** is formed, which transforms to **martensite** upon cooling to room temperature (i.e. air cool or **oil quench**).
- If retained austenite is known to be present after the austenitizing and quench to room temperature, additional hardening response may be achieved by sub-zero cooling to about -100°F (-73°C). The as quenched structure of fresh martensite is quite brittle and should be stress-relieved or tempered at approximately 400°F to 500°F (204-260°C) to restore some ductility. During **tempering** between approximately 300°F (149°C) and 600°F (316°C), a relaxation of the martensite structure occurs whereby the volumetric stresses associated with the formation of martensite upon quenching are relieved. As a result, the martensite still exhibits its high hardness and wear resistance properties but some ductility is introduced at the loss of a few points of hardness.

Material Properties

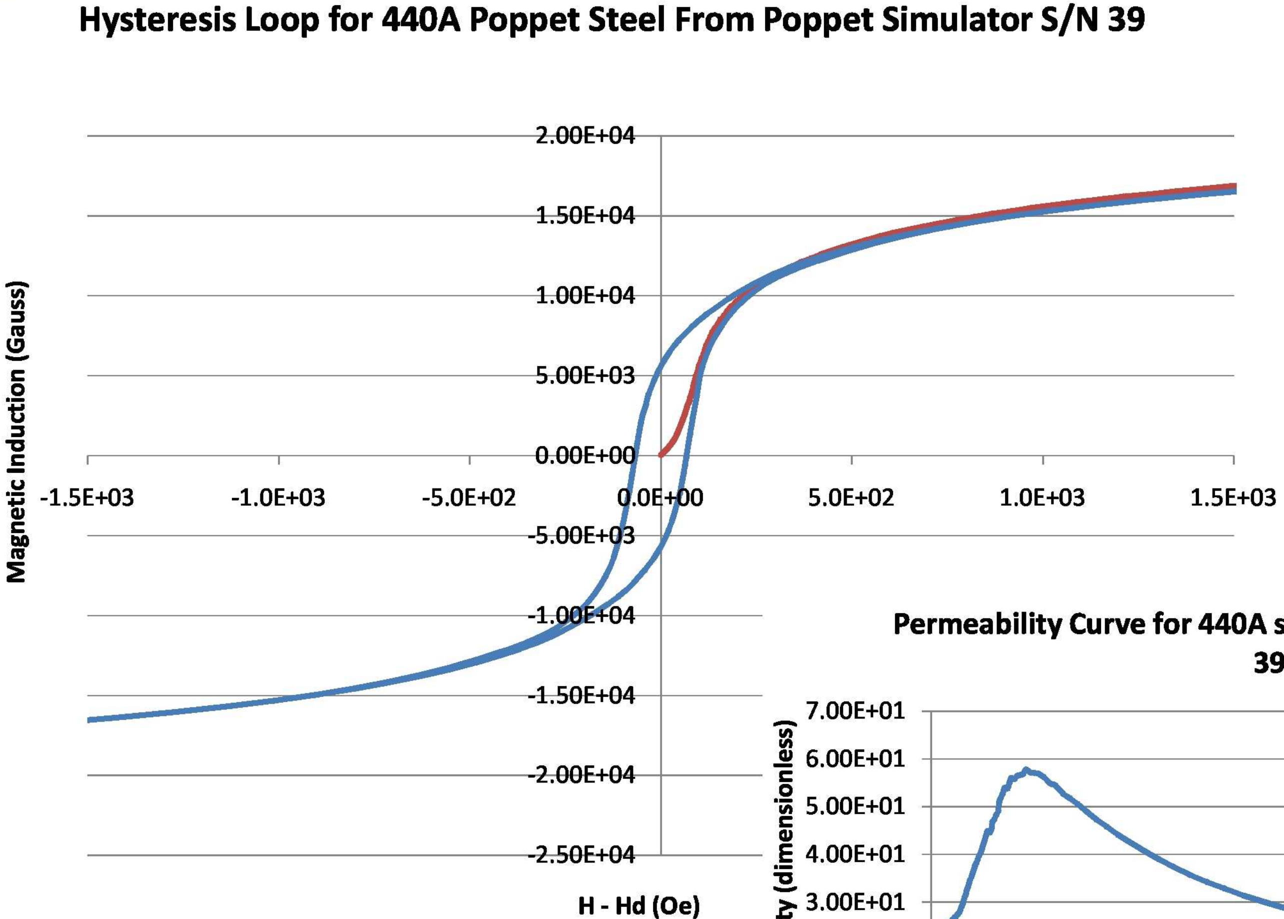
- 440 A Martensitic Steel
- Electrical Resistivity (microhm-cm (at 68 Deg F))= 360 or
  - 0.48 %IACS
- Maximum Relative magnetic permeability ~ 60 (at ~ 100 Oe).
- All Martensitic steels are ferromagnetic. Due to the **residual stresses** induced by the hardening transformation, these grades exhibit permanent magnetic properties if magnetized in the hardened condition. For a given grade, the coercive force (Hc ~ 65 Oersted), tends to increase with increasing hardening, rendering these alloys more difficult to demagnetize.
- **Stress** (applied and residual) may affect magnetic properties (magnetic permeability, residual magnetism and coercive force)
- Varying magnetism due to varying microstructure

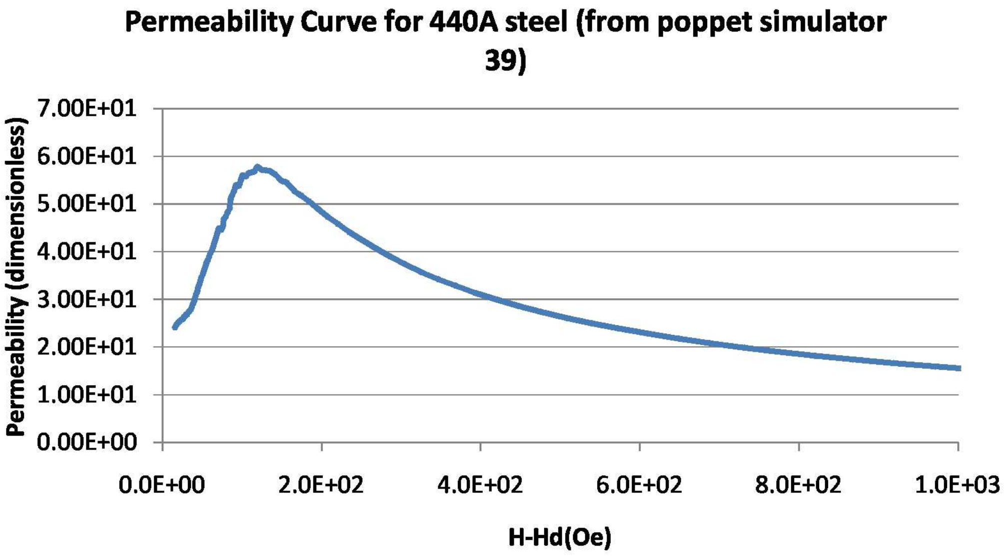
Mechanical Properties 440A Steel

Typical Mechanical Properties of Heat Treated Martensitic Stainless Steels

Heat Treatment	T410 (0.14 %C) Hardened 1800°F (982°C)			T420 (0.25 %C) Hardened 1900°F (1038°C)			T425 Mod (0.55 %C) Hardened 1900°F (1038°C)			T440A (0.62 %C) Hardened 1900°F (1038°C)		
	Rockwell Hardness	0.2% YS, Ksi (MPa)	UTS, Ksi (MPa)	Rockwell Hardness	0.2% YS, Ksi (MPa)	UTS, Ksi (MPa)	Rockwell Hardness	0.2% YS, Ksi (MPa)	UTS, Ksi (MPa)	Rockwell Hardness	0.2% YS, Ksi (MPa)	UTS, Ksi (MPa)
Annealed*	81 HRB	45.4 (313)	80.4 (554)	85 HRB	51.5 (355)	85.8 (592)	90 HRB	57.4 (396)	86.3 (595)	94 HRB	51.6 (354)	108.4 (747)
Hardened+ Tempered 400°F (204°C)	43 HRC	156.1 (1076)	202.9 (1399)	48 HRC	190.1 (1311)	255.2 (1759)	53 HRC	200.9 (1385)	270.9 (1868)	54 HRC	229.0 (1579)	293.3 (2022)
Hardened+ Tempered 550°F (288°C)	40 HRC	148.3 (1022)	187.0 (1289)	44 HRC	176.0 (1213)	229.6 (1583)	50 HRC	197.2 (1360)	250.8 (1729)	50 HRC	220.2 (1518)	272.6 (1879)
Hardened+ Tempered 600°F (316°C)	40 HRC	148.8 (1026)	186.1 (1283)	45 HRC	179.0 (1234)	232.9 (1606)	53 HRC	196.0 (1351)	245.1 (1690)	53 HRC	222.0 (1531)	273.2 (1883)
Hardened+ Tempered 800°F (427°C)	41 HRC	132.9 (916)	188.5 (1300)	46 HRC	185.6 (1280)	236.0 (1627)	53 HRC	210.6 (1452)	255.1 (1759)	53 HRC	233.6 (1610)	272.8 (1881)
Hardened+ Tempered 900°F (482°C)	41 HRC	122.6 (845)	188.3 (1298)	46 HRC	179.3 (1236)	233.0 (1606)	52 HRC	198.4 (1368)	234.8 (1619)	52 HRC	212.6 (1466)	269.5 (1858)
Hardened+ Tempered 1000°F (538°C)	35 HRC	127.9 (882)	154.3 (1063)	36 HRC	137.9 (951)	158.5 (1093)	43 HRC	176.6 (1218)	208.0 (1434)	41 HRC	147.0 (1013)	177.5 (1224)
Hardened+ Tempered 1200°F (649°C)	98 HRB	85.5 (589)	111.2 (767)	23 HRC	94.6 (652)	121.6 (838)	29 HRC	107.8 (743)	135.7 (936)	31 HRC	105.5 (727)	135.4 (933)

Magnetic Property Characterization Lab Data





The part has a low residual field during EC testing. At low levels of residual magnetic field, the relative permeability is measured to be about 25.

Data provided by Russell Wincheski

M&P Evaluation

- SEM evaluation concluded poppet failed due to high cycle fatigue
  - Several unique "thumbnail" features
  - Multiple loading events
  - Transgranular
  - Unsure of effect of hydrogen, but not significant contributor (testing in work)
  - Material change recommended
  - It is believed that failure did not occur within one flight

[redacted]

NDE History

- Inspection by dye pen during manufacture
- Initial examination of flight units included optical, high resolution dye pen and SEM
  - Thought (at the time) that cracks ~0.005” could be found
    - 0.040” Optical
    - 0.005” SEM
    - 0.050” High res dye pen
  - No cracks found

[redacted]

Improved NDE

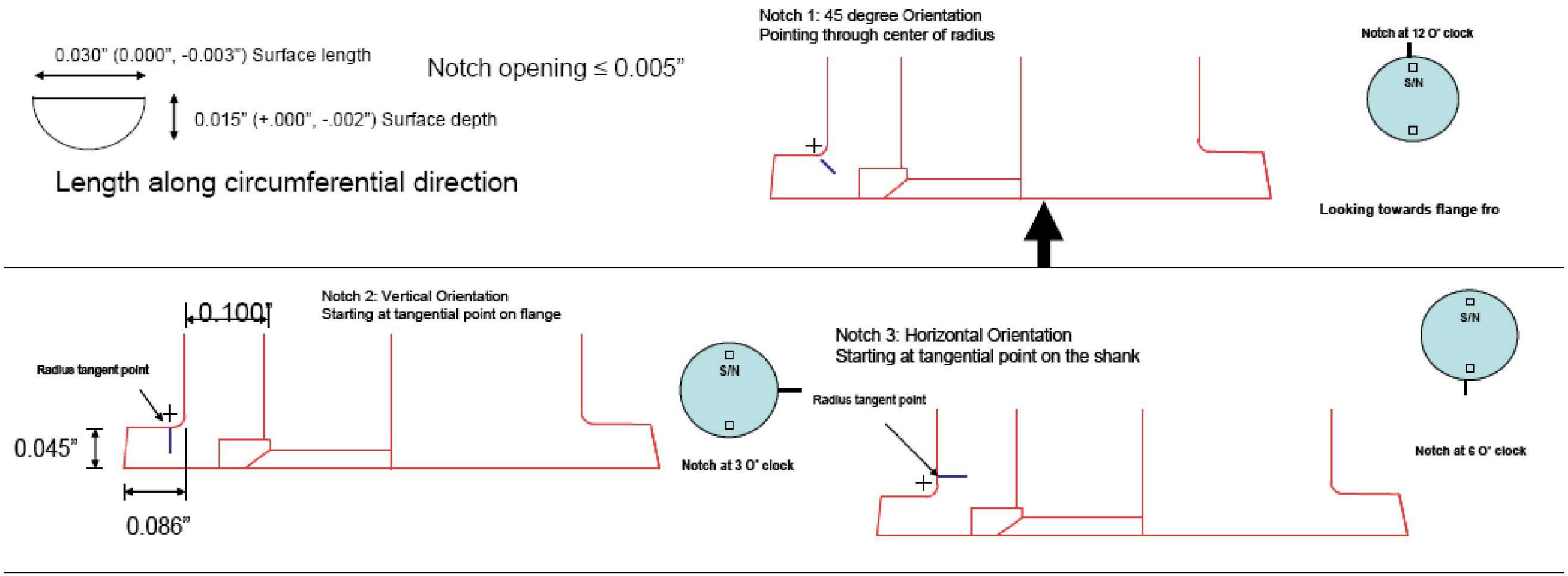
- The discovery that cracks from unpolished specimens was missed lead to the development of higher fidelity inspection techniques
  - Polish/ Magnetic Particle/SEM
  - Later Eddy Current Technique was Developed and Implemented
    - Used as key flight rationale prior to STS-119
    - Refinement of technique has occurred over next 3 flights
    - POD study completed by NASA Engineering Safety Center
    - Provides the best results among the techniques tried
  - Ultrasonic technique was not implemented due to lower sensitivity

Considerations for Using Eddy Current

- Concerns for regular eddy current inspection
  - Relatively low relative magnetic permeability (up to ~60) material.
  - Expect residual magnetic field due to high coercively (65 Oersted) and its effect on eddy current baseline response
  - Non-uniform magnetic permeability may add noise to eddy current inspection and potentially induce non-uniform Vpp change (amplification or attenuation) of crack indications
  - Localized variation in material composition (higher carbide concentration, microstructure) may provide higher permeability
  - Eddy current phase signature angle from very small magnetic indication may not be always distinguished from non-magnetic crack indications
  - Eddy current indication is a resultant effect from
    - Crack (length, depth, crack face contact)
    - Magnetic permeability (residual stress, martensite/carbide microstructure)
      - Global magnetic permeability and localized changes in the permeability

NDE Notch Standards for EC Technique

Each standard has three EDM notches



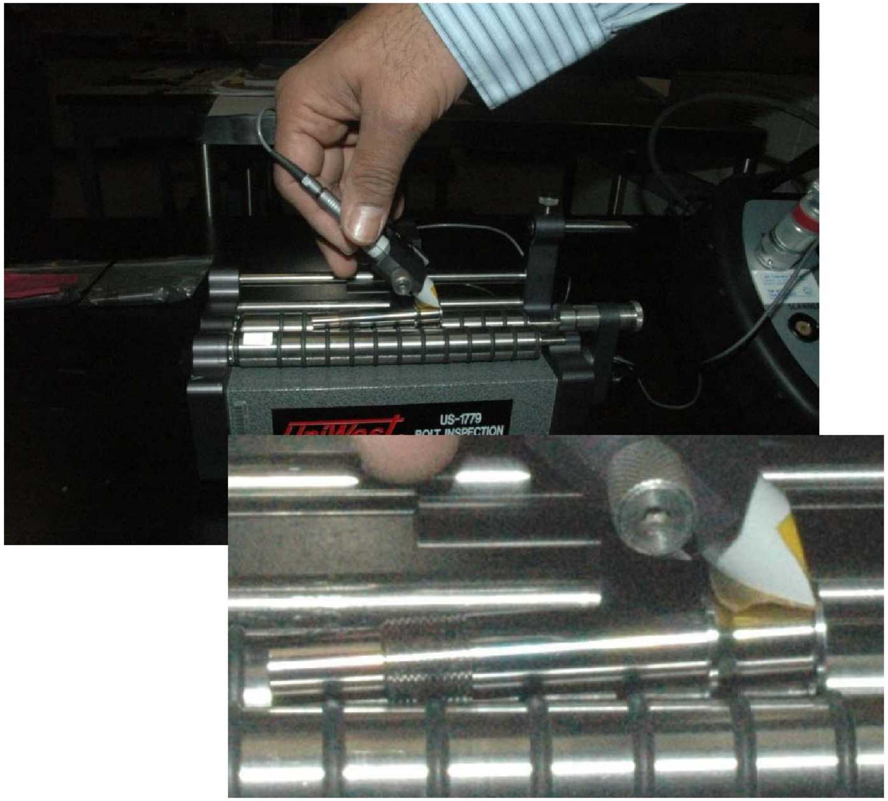
S/N 33 Poppet Standard

Poppet Simulator Standard (1 each)

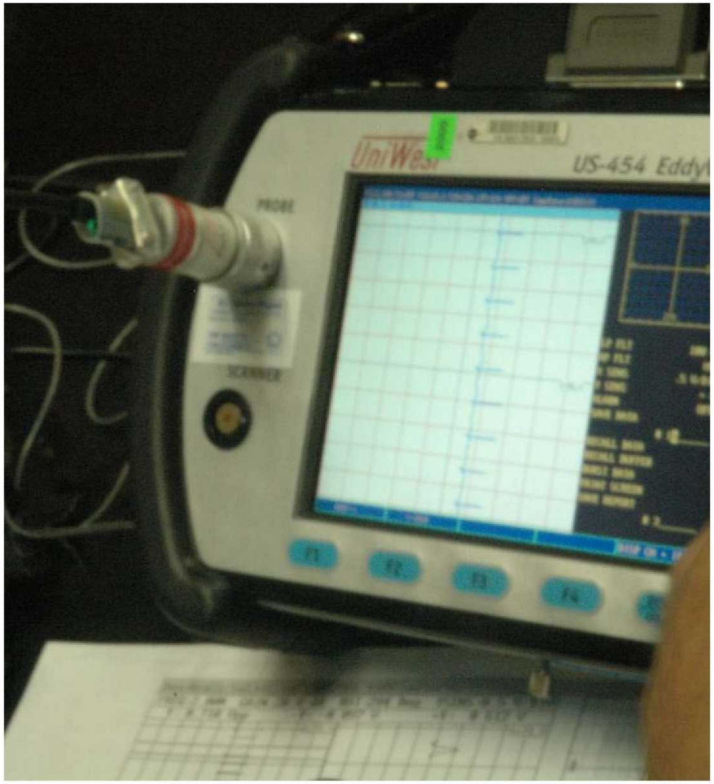
A286 Poppet Standard

PRELIMINARY

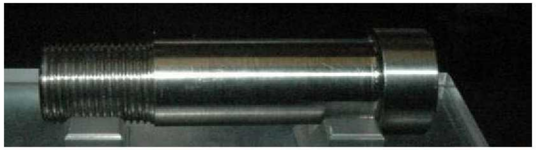
Eddy Current Technique



US 1779 (Uniwest) Bolt Inspection Scanner



US-454 (UniWest) Eddy Current Flaw Detector



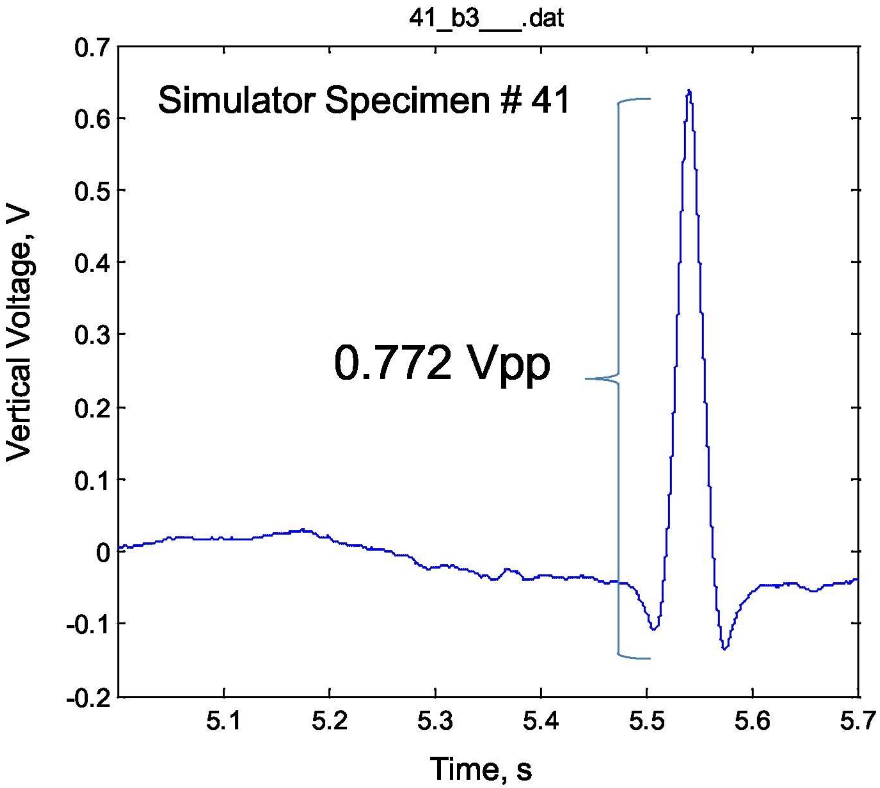
Ti Bolt Standard with Circumferential Notches

Driver-pickup construction 0.08 inch spacing

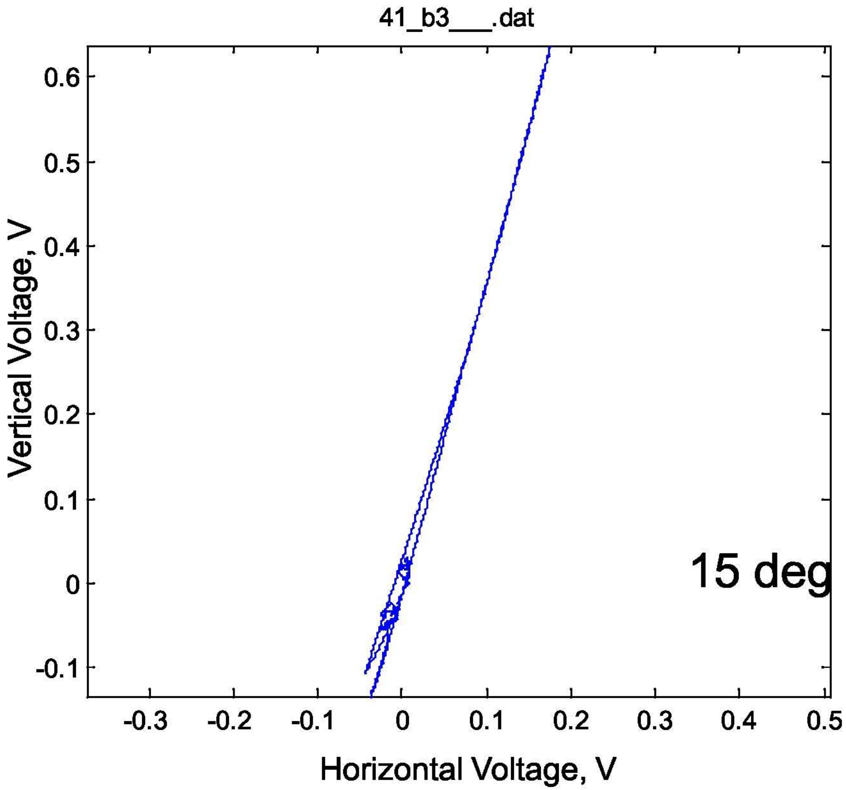
Eddy Current Bolt Thread Root Inspection probe

Frequency: 2 MHz

Matlab Analysis of EC Data



Time Scan: One revolution



Phase Diagram

Vpp – Positive peak to negative peak voltage

Provided by Russell Wincheski

POD Study on Simulator Specimens

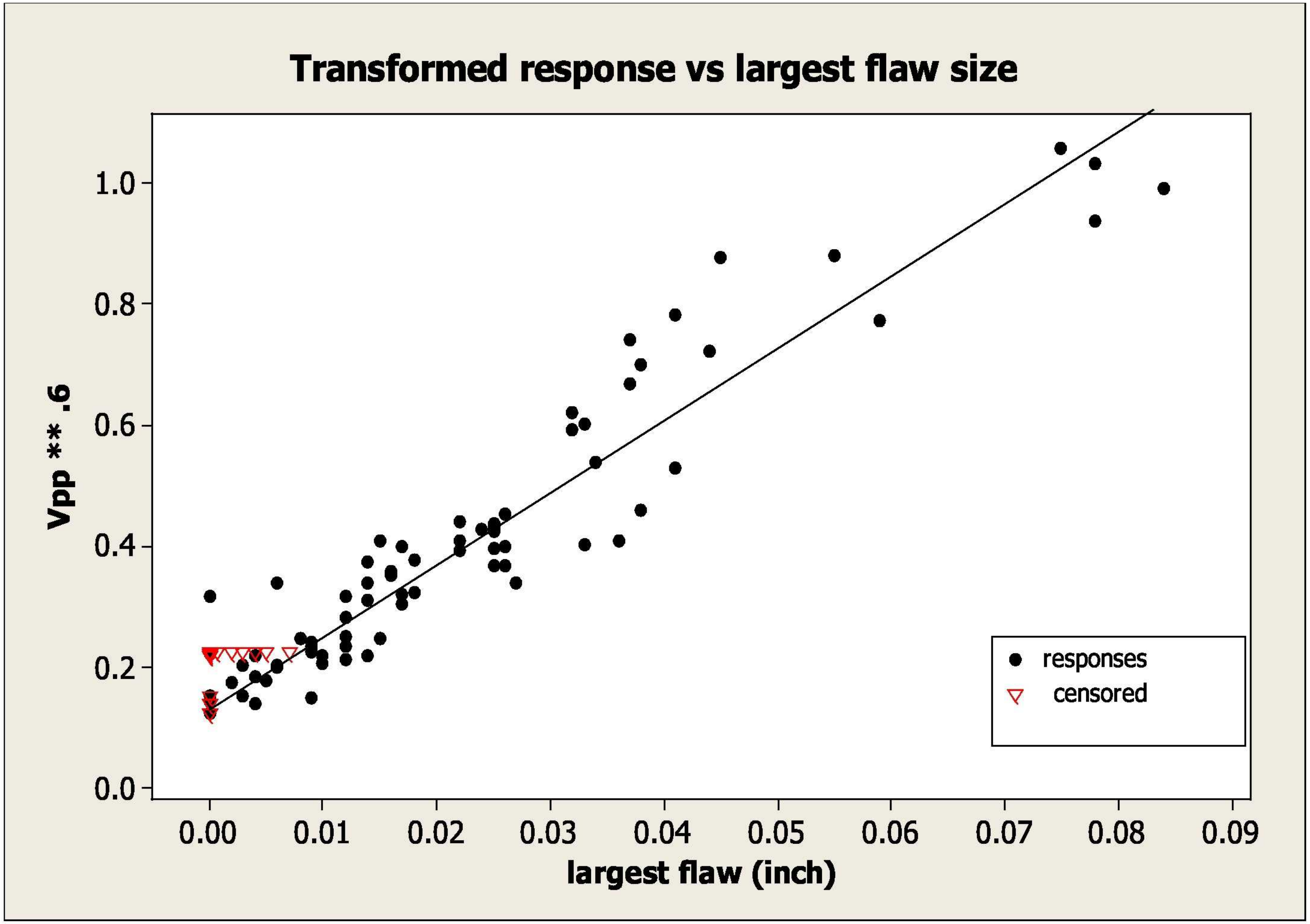
- 51 poppet simulators
    - Cracks grown in mechanical fatigue load set-up
    - Some with multiple flaws
    - Opposite sides
- 4 unflawed poppets
- Flaws sized with SEM
- 2 Inspectors
    - Recorded call and signal (peak-to-peak voltage)
    - Repeat each poppet 6 times

Simulator extender

Poppet simulator

Simulator crack specimens provided by Robert Piascik and William Prosser

Simulator POD Data

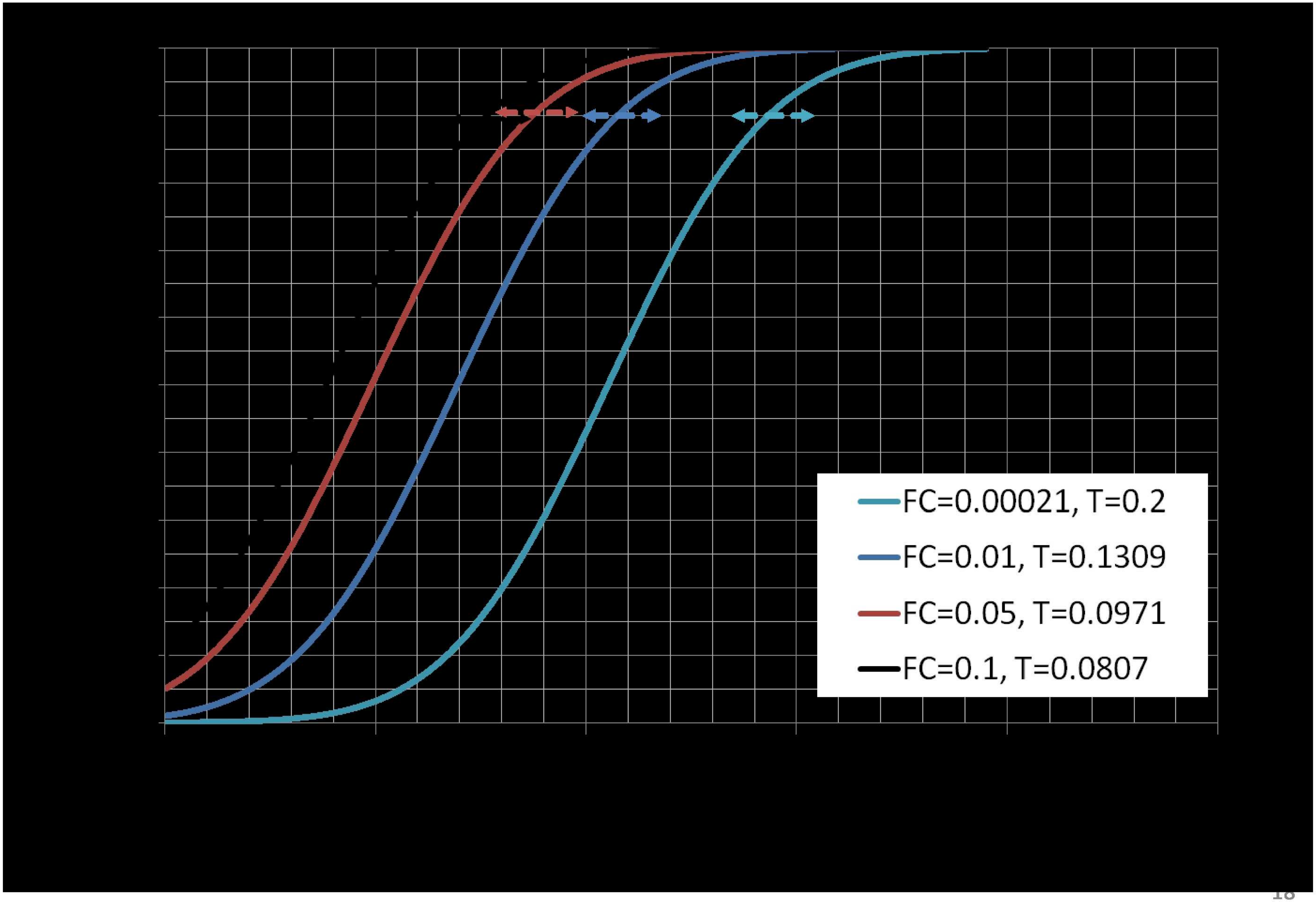


$\sigma_{Vpp} = 0.01$

$$\hat{V}^{.6} = 0.1299 + 11.9398 \cdot flaw\ size$$

$$\hat{\sigma} = 0.0712$$

Estimated POD & FC Rate by Threshold Settings on Simulators

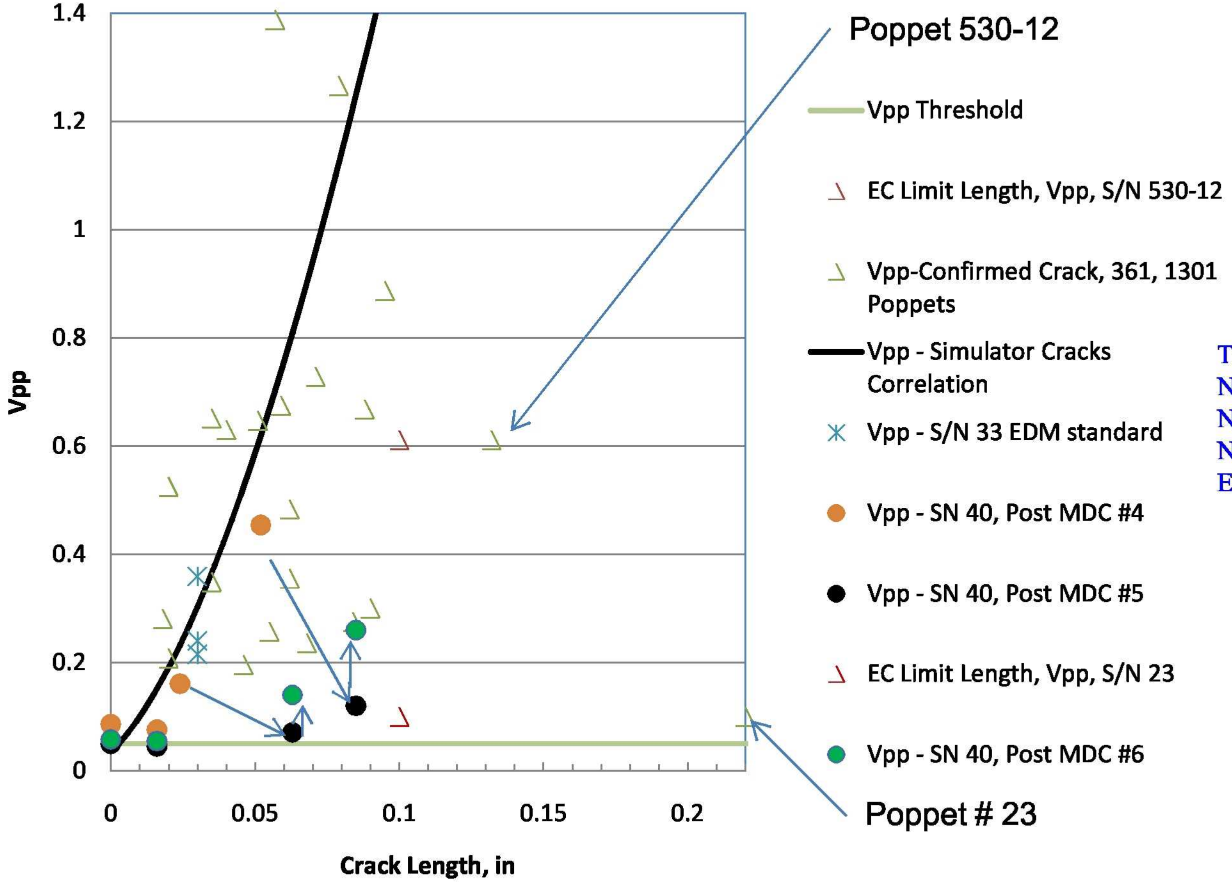


Establishing EC Criteria

- Considerations
  - Establish conservative criteria
    - May reject good part
    - Also use Scanning Electron Microscope and magnetic particle examination of suspect high EC reading areas
    - Use trending of EC Scans and assess change in EC reading for each mission
  - Survey EC response from measured cracks, simulator cracks, Titanium bar EDM notches, poppet #33 EDM notches
  - Establish correlation of EC response from simulator cracks
  - Establish calibration on a nonmagnetic material (Titanium bar) electro discharged machined (EDM) notches
  - Establish EC threshold as low as possible to detect tight cracks with no magnetic effect.

[redacted]

Survey of EC Data



Titanium Bar (4% IACS) EDM Notch Responses
Notch A: 0.210 Vpp 0.030" l X 0.015" d
Notch B: 0.536 Vpp 0.050" l X 0.025" d
Notch C : 0.829 Vpp 0.070" l X 0.035" d
EC Depth of penetration: 0.011"

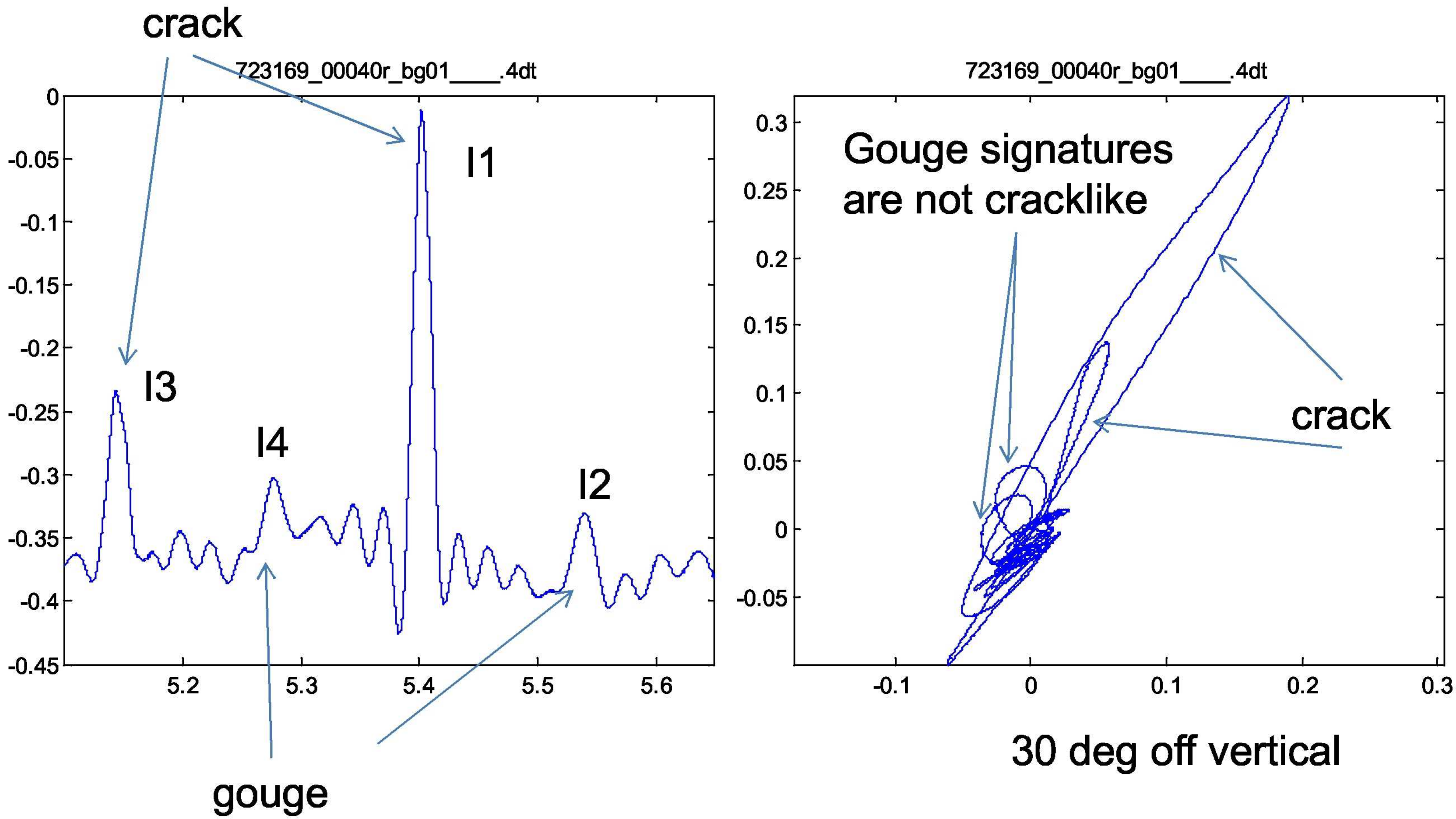
- Note: The crack signal is saturated beyond a crack length of 0.1" approx.
- Therefore, two data points have been shown shifted to 0.1" limit length.

Simulator cracks (1 micron) are more open compared to the poppet cracks (0.25 micron). Simulator magnetic permeability = 25.
The Vpp from the EDM notch of the S/N 33 poppet EDM standard provides response close to simulator response.
Titanium standard provides slightly lower Vpp responses compared to the poppet simulator response.
Higher responses have been observed for some cracks compared to the comparable EDM notches indicating Vpp change possibly due to the higher magnetic permeability at crack locations.
Greater variation in poppet crack responses compared to the simulator responses.
Acceptance criteria to account for the lowest crack responses from the poppets.

Poppet s/n 40 Mission Duty Cycle Testing

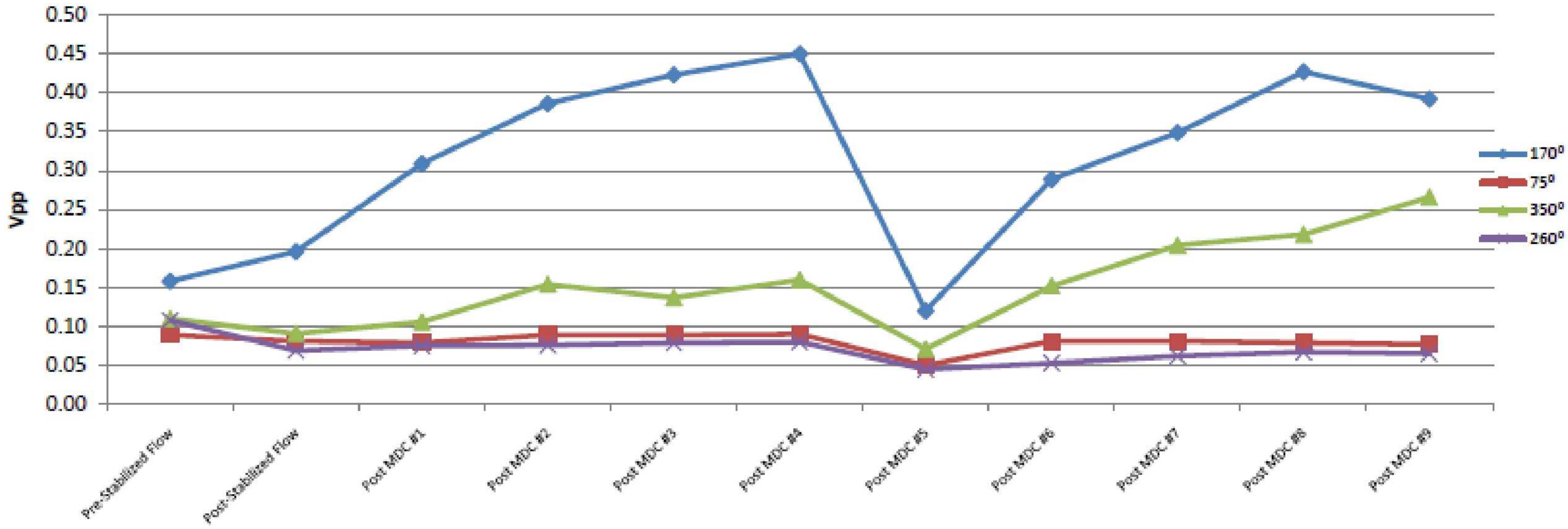
- In order to create crack growth data, one poppet (s/n 40) is subjected test environment that simulates a single mission (launch load). The cycle is called mission duty cycle (MDC).
- EC data is taken before and after every MDC run.
- Four indications
  - Two from visible cracks
  - Two from surface gouges (changes slightly more than the measurement error)
- Minimum change in Vpp of 0.02 (2σ) is considered credible
- Trend in poppet indications
  - Vpp growth without surface crack (SEM analyzed) growth (Pretest through post MDC# 4, Post MDC# 5 through post MDC # 8)
  - Vpp drop (0.33 Vpp) with surface crack (SEM analyzed) growth (post MDC# 4 to Post MDC# 5)
  - Small Vpp drop (0.03 Vpp) without surface crack (SEM analyzed) growth (post MD # 8 to post MDC #9)
- Many causes have been investigated including the set-up error, effect of residual stress (increase and relief) on magnetic permeability, crack closure, branching growth of the crack

Poppet 40 Post MDC #4



Gouge signatures are not cracklike. They can mask small crack signatures.

HFCV Poppet S/N 00040 Eddy Current Vpp Trends
Quick Glance (03/04/2010)



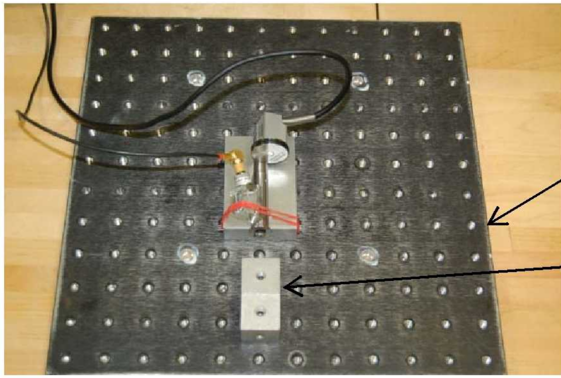
	Eddy Current Vpp (MatLab Processed)					SEM Indication Length (inches)			
	Indication ID	1	2	3	4	1	2	3	4
Inspection Phase	(Clock Position)	170°	75°	350°	260°	170°	75°	350°	260°
Pre-Stabilized Flow		0.158	0.089	0.11	0.108	0.050	0.200	0.024	0.016
Post-Stabilized Flow		0.196	0.081	0.091	0.069	0.050	0.200	0.024	0.016
Post MDC #1		0.309	0.079	0.106	0.075	0.052	0.200	0.024	0.016
Post MDC #2		0.386	0.089	0.154	0.076	0.052	0.200	0.024	0.016
Post MDC #3		0.423	0.089	0.137	0.079	0.052	0.200	0.024	0.016
Post MDC #4		0.45	0.09	0.16	0.08	0.052	0.200	0.024	0.016
Post MDC #5		0.12	0.05	0.071	0.045	0.085	0.200	0.063	0.016
Post MDC #6		0.289	0.081	0.152	0.053	0.085	0.200	0.063	0.016
Post MDC #7		0.349	0.081	0.204	0.062	0.085	0.200	0.063	0.016
Post MDC #8		0.427	0.079	0.218	0.067	0.085	0.200	0.063	0.016
Post MDC #9		0.392	0.077	0.266	0.065	0.085	0.200	0.063	0.016
							Gouge		Gouge

Chart Provided by Darren Cone

Poppet NDE Criteria

- Ensure that each poppet is demagnetized (no residual magnetic field) using a Gaussmeter before the EC inspection
- EC Matlab scans of all flight poppets will be tracked for comparison
  - Matlab analysis will measure individual indications and evaluate phase of the indication
- Criteria
  - Individual indications ≥ 0.2 Vpp result in "NDE rejection" of the poppet
  - Individual indications ≤ 0.05 Vpp will be accepted
    - Rationale
      - Not all EC responses ≤ 0.05 Vpp with correct phase angle have been verified to be from cracks yet.
      - It may be difficult to identify cracklike indications from non-cracklike indication under 0.05 Vpp due to permeability and surface roughness noise.
    - Vpp measurement < 0.05 Vpp may not be individually measured if no localized indications can be identified. In this situation, Vpp measurements are obtained in a time window covering at least one rotation.
  - Any indication between 0.05 to 0.2 Vpp may be flagged "suspect"
    - All indications are identified "individually"; measured and tracked
  - Any change > 0.02 Vpp (phase angle and positive response) will be considered to be growth in the indication and flagged suspect
    - An indication may be accepted, if its current reading shows growth of ≤ 0.02 Vpp from the previous reading
- All poppets with "suspect" EC crack indications should be also evaluated under SEM and other NDE (magnetic particle*) before the decision is made about the poppet acceptance/rejection
  - MPS PRT is responsible for acceptance of suspect poppets
  - * Post magnetic particle, complete demagnetization of the poppet will be ensured

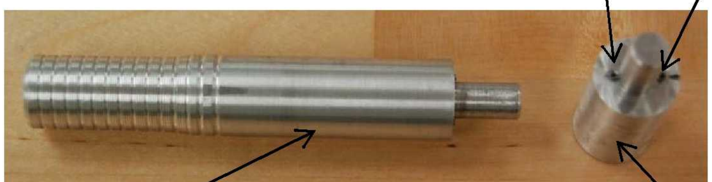
Ultrasonic Surface Wave for Crack Detection



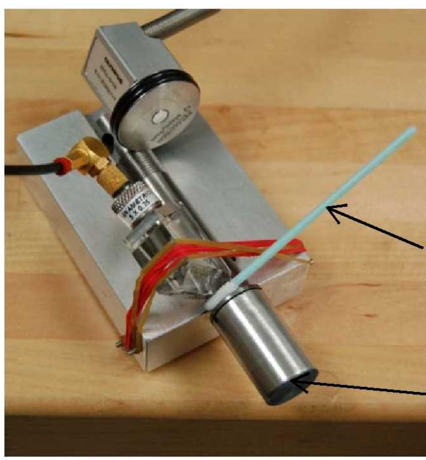
Base plate

1” High pedestal

Pin Pin



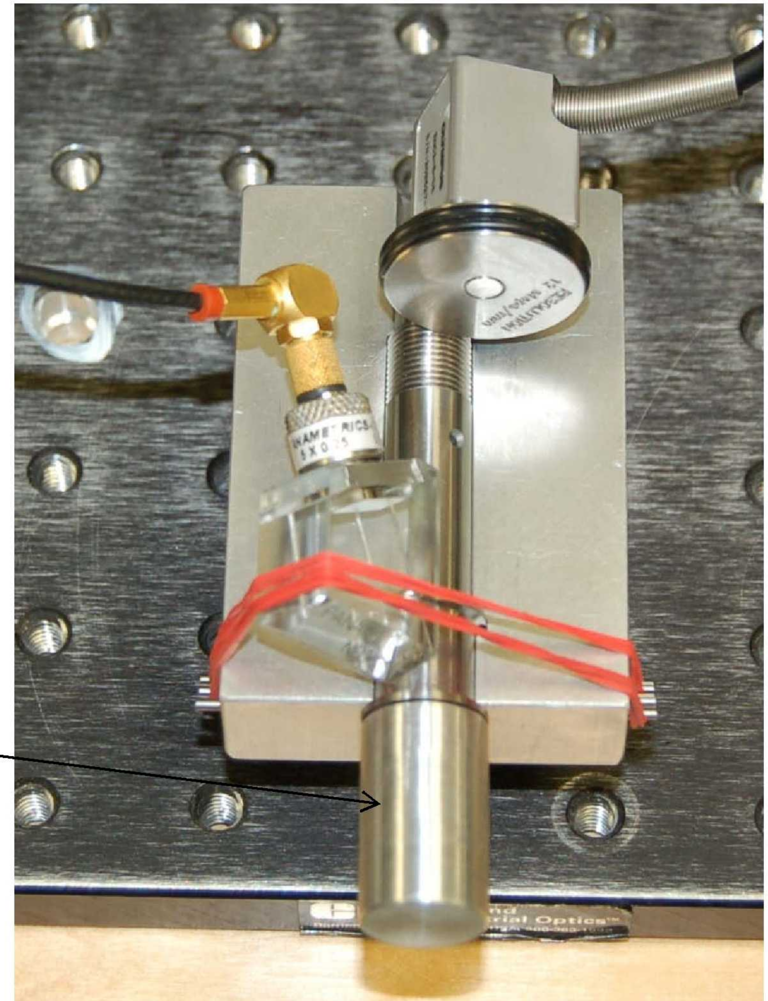
Long driver Short driver



Q-tip
used to wipe
extra couplant
ahead of wedge tip

Short Driver

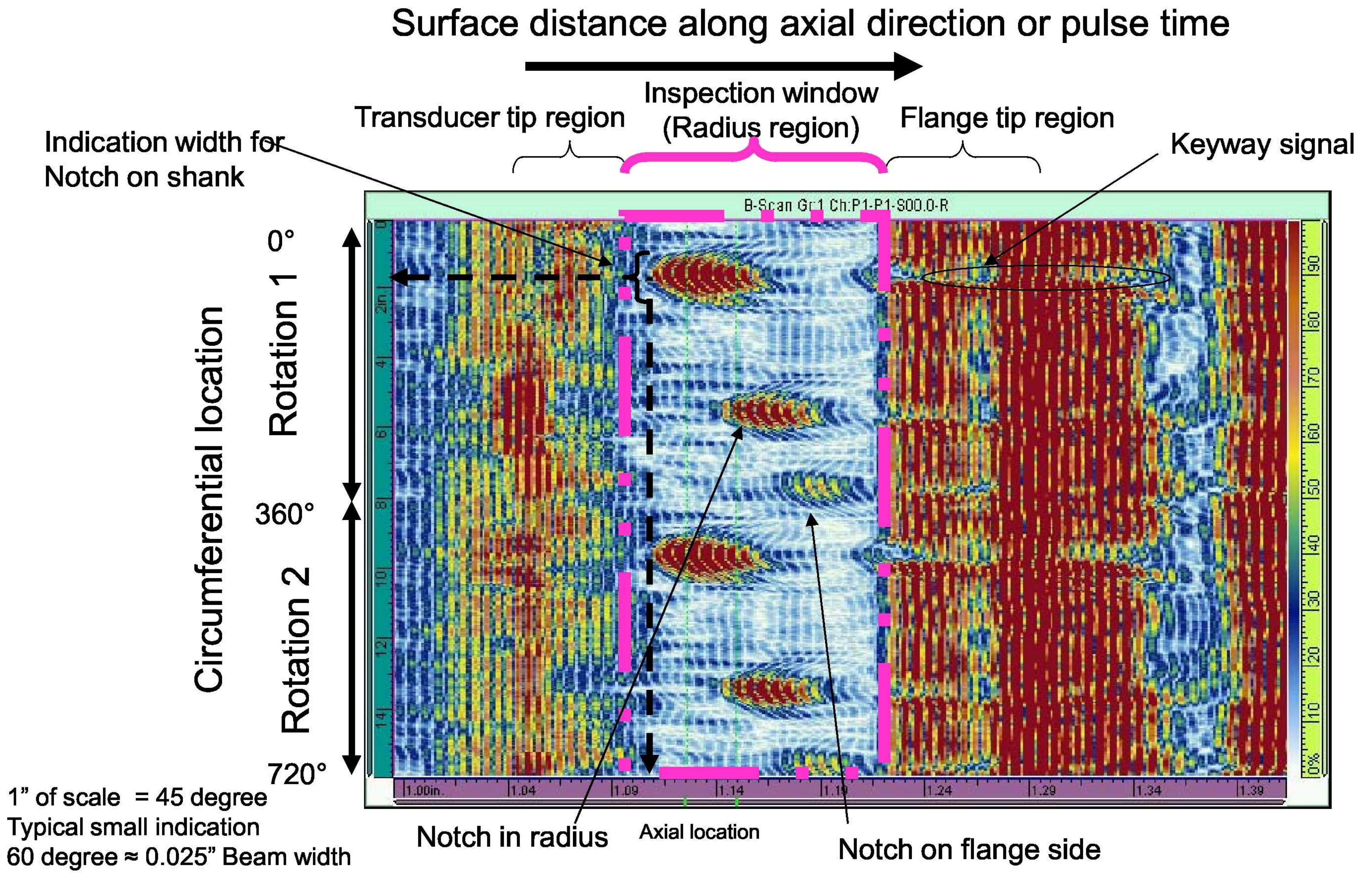
Short driver



Uses contoured wedge

Detects cracks longer than 0.050”

A 286 Notch Standard - B Scan Display of Olympus Omniscan



Two rotations of data acquisition to establish consistency in results

Conclusions

- Conclusions
  - Current EC criteria is conservative
  - Provides allowance for high/low readings (due to localized change in magnetic permeability and other factors)
  - Effect of stress induced permeability needs to be further assessed using lab tests
  - Continue to assess new crack EC data to determine if it meets the current criteria
- Future Work
  - Investigate magnetic permeability dependence on stress and its effect on EC response
  - Poppet #40 MDC testing may provide some data towards this work

Acknowledgements

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