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FAA Center for Aviation Systems Reliability

Engineering Studies of Fluorescent Penetrant Inspection: Introduction

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http://www.cnde.iastate.edu/faa-casr/fpi/index.html

Program Timeline

- 1999 – 2002 – Cleaning and Drying Studies performed as part of the Engine Titanium Consortium
- 2002 – 2006 – Engineering Assessment of Fluorescent Penetrant Inspection performed as part of Center for Aviation Systems Reliability effort

http://www.cnde.iastate.edu/faa-casr/fpi/index.html

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Engineering Assessment of FPI

- Provide engineering data to support decisions regarding the safe application and relevant use of FPI
- Includes data to support changes in specifications
- Generate tools for use by airlines and OEMS that improve FPI processes
- Strong industry team with extensive experience

BOEING

Delta
delta.com

D&W Enterprises, LTD.
Consulting Services

General Electric Company

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Pratt & Whitney
A United Technologies Company

Rolls-Royce

SHERWIN
INCORPORATED

UNITED

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Program Partners

Cooperative university/industry program which brings together aircraft and engine OEMs, airlines, vendors, as well as technical expertise from the NDE community.

ISU: Lisa Brasche, Rick Lopez, Dave Eisenmann, Bill Meeker

FAA: Al Broz, Paul Swindell, Dave Galella

Industrial Advisory Panel

- Boeing - Long Beach
  - Dwight Wilson, John Petty
- Boeing - Seattle
  - Steve Younker, Mike Davis
- Delta Airlines - Atlanta
  - Lee Clements
- United Airlines - Indianapolis
  - Dave Arms, Bob Stevens
- Pratt & Whitney - EH and WPB
  - Kevin Smith, John Lively
- Rolls Royce - Indianapolis and Darby
  - Pramod Khandelwal, Keith Griffiths, Bill Griffiths, Tom Dreher
- GE Aircraft Engines
  - Terry Kessler, Thadd Patton, Wayne Kitchen, Phil Keown
- Sherwin - Cincinnati
  - Sam Robinson
- D&W Enterprises - Denver
  - Ward Rummel

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Technical Approach

- Define factors for which engineering data is deficient
  - Change in process, e.g., environmental changes
  - Change in applications
  - Data not available in the public domain
- Design engineering study that provides quantitative assessment of performance
  - Brightness measurements
  - Digital recording of UVA indication
  - Probability of Detection
- Complete study using either lab or shop facilities as appropriate
- Distribute results through use of web
- Support changes to industry specifications as warranted
- Utilize results to update/create guidance materials
- Transition process to airlines for internal, self-assessment

http://www.cnde.iastate.edu/faa-casr/fpi/index.html

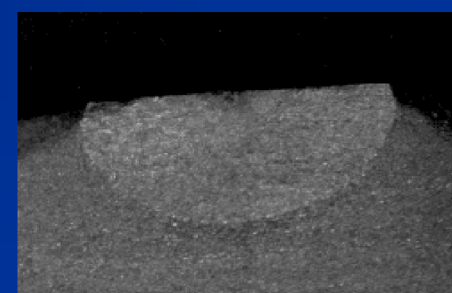
Sample Fabrication

- Titanium 6Al-4V
  - ASTM-B-265, Grade 5 and AMS 4911
- Inconel 718
  - AMS 5596
- EDM notches used as starter notches
- Three point bending to generate cracks with 2:1 to 3:1 crack aspect ratio
- Crack sizes ranging from 20 to 180 mils, most at 80 mils
- Sample dimensions: 6” x 1” x ½”

(a)

(b)

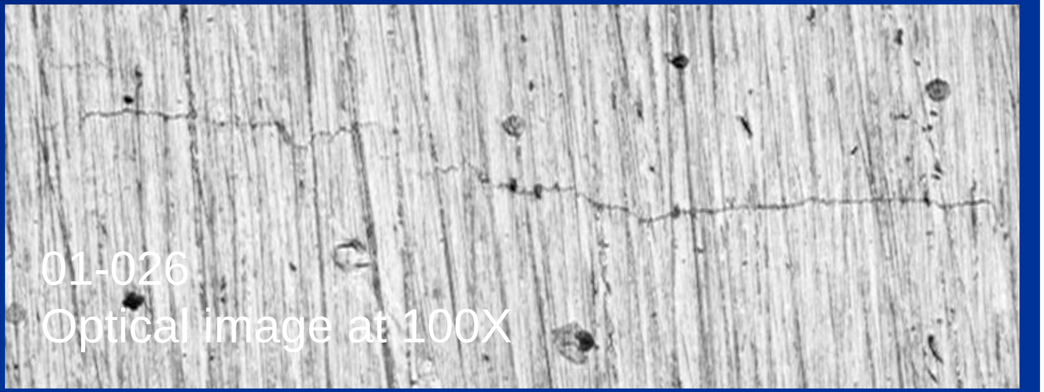
(c)



Sample Characterization

- Final surface polish to 32 Ra
- Optical photographs (100X digital)
- Brightness measurements and UVA image capture to establish baseline and remove samples that showed variability

(a)



(b)

http://www.cnde.iastate.edu/faa-casr/fpi/index.html

Brightness Measurement

- Used rigid fixturing to assure repeatability with transportability for brightness measurements
- Photo Research PR-880 Photometer used to record indication brightness in ft-Lamberts

Field Studies

- Requires access to typical drying, cleaning and FPI methods used in commercial aviation
- Several partners have provided access to their facilities
  - Access to cleaning lines for Ti and Ni as well as mechanical blasting facilities
  - FPI line for sample processing
  - Inspection booth for characterization and brightness measurements

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Field Studies

- 15 - 20 samples per basket
- 20 minute penetrant dwell
- 90 second pre-wash
- 120 seconds emulsifier contact with vertical motion
- Two 30 second cycles of air agitated water rinse, then a 90 second post-wash

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Field Studies

- Samples dried for 10 minutes at 160ºF (or until dry)
- Dip/drag application of developer for baseline runs
- 10 minute minimum development time
- Brightness reading using Spotmeter
- Length reading using UVA and image analysis software

Engineering Studies

- Topics for engineering studies selected and prioritized by team
- Subteams developed for experimental design with review by the full team
- Experimental efforts to take place at various industry locations

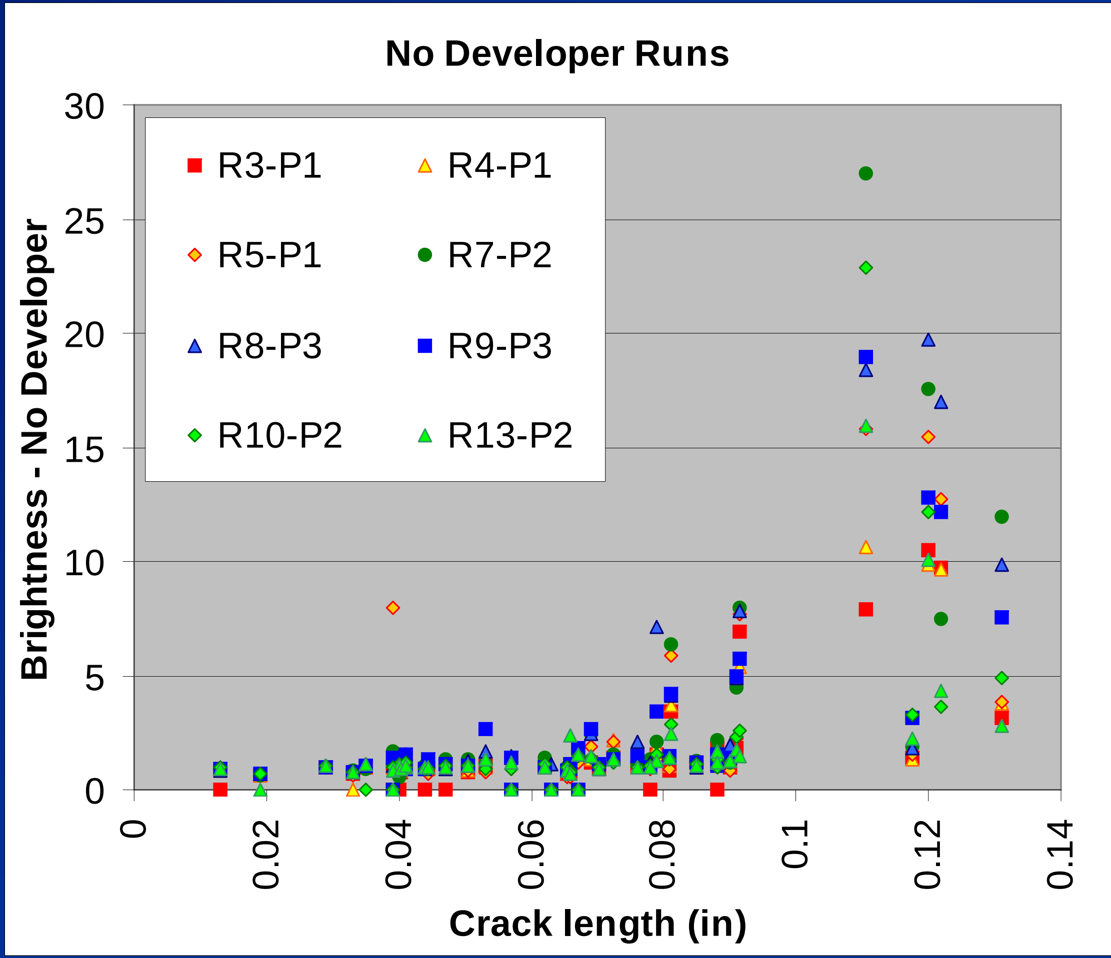
- ES – 1 – Developer Studies
- ES – 2 – Cleaning Studies for Ti, Ni and Al
- ES – 3 – Stress Studies
- ES – 4 – Assessment tool for dryness and cleanliness
- ES – 5 – Effect of surface treatments on detectability
- ES – 6 – Light level Studies
- ES – 7 – Detectability Studies
- ES – 8 – Study of Prewash and Emulsification Parameters
- ES – 9 – Evaluation of Drying Temperatures
- ES – 10 – Part geometry effects
- ES – 11 – Penetrant Application Studies
- ES – 12 – Relationship of part thickness to drying method

Developer Studies

- Do penetrants self-develop?
- How does dry powder developer compare to non aqueous wet developer?
- How do different penetrant/developer families compare?
- How do developer application methods compare (dust chambers, bulb, spray wand, electrostatic)?
- How do different developer forms compare?

Need for Developer

- Brightness of three penetrants was evaluated without developer for cracks ranging from 13 to 130 mils
- While some larger cracks (> 80 mils) had acceptable brightness (>5), this was not true for all large cracks or for small cracks (< 80 mils)
- No difference found in ability of penetrants to "self develop" for small cracks (< 80 mils)
- Effective inspection sensitivity requires developer



Dry Powder vs. NAWD Comparison

- Level 4 Penetrant – 20 minute dwell, 30 sec spray wash, 120 sec emulsification with agitation, 60 sec spray wash
- Dry powder developer (form a) with dip/drag application – Two penetrant products
  - DP1 used as baseline
  - DP2
- NAWD (form d) alcohol based
  - 2 applications
- NAWD (form d) acetone based
  - 3 applications
- For NAWD, followed Manufacturers recommendation for 10" distance

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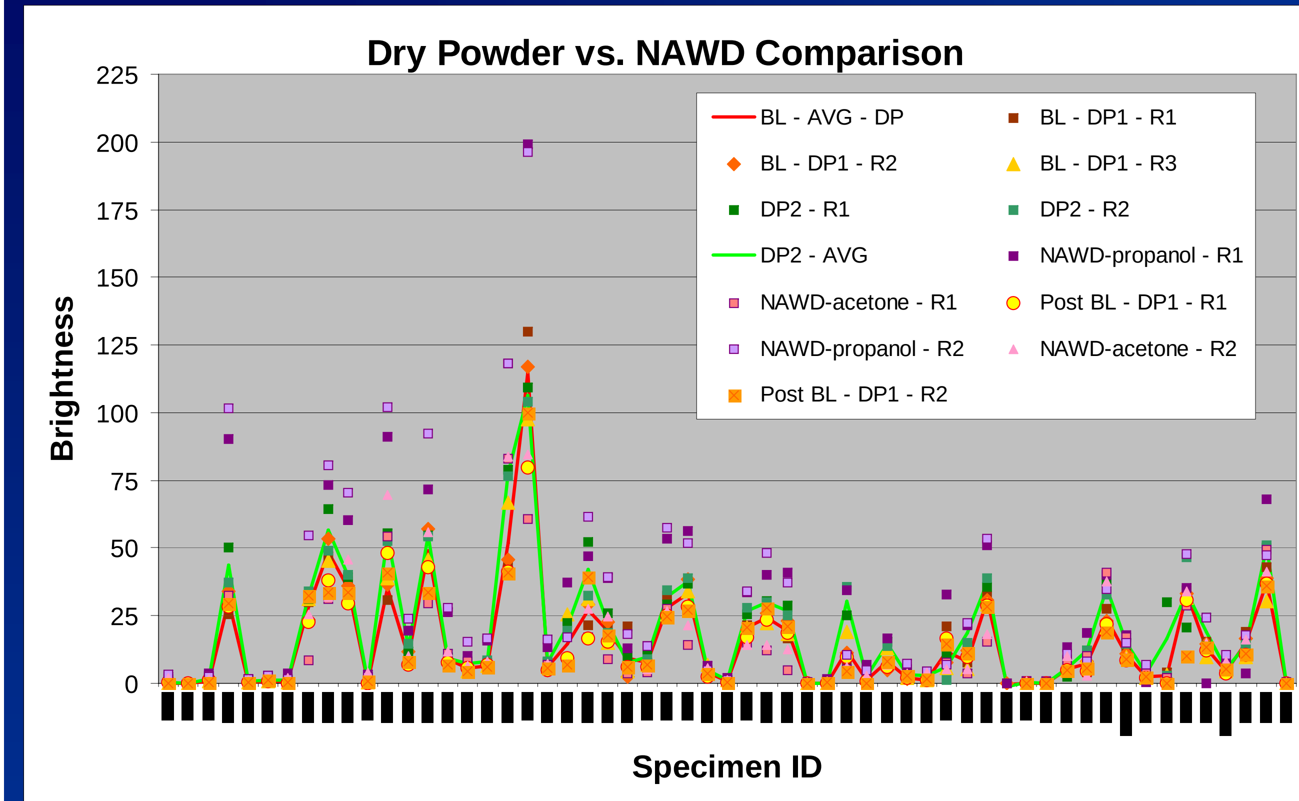
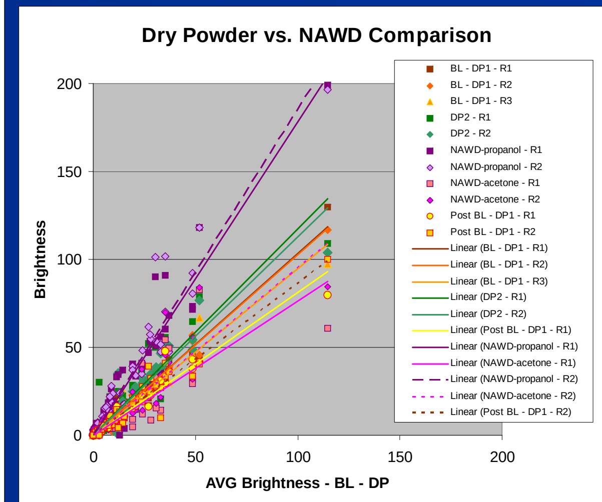
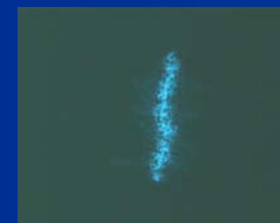
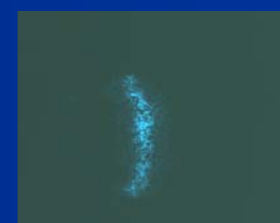
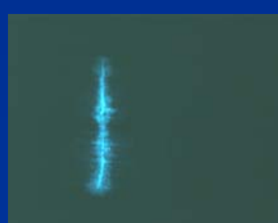
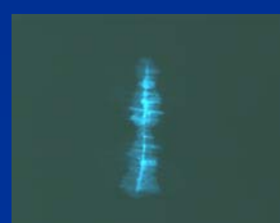
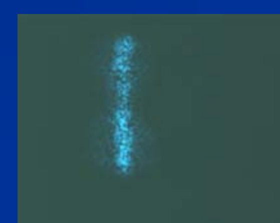
Form A vs. Form D Comparison



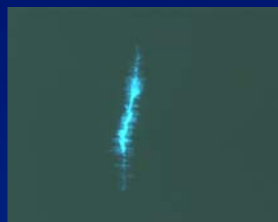
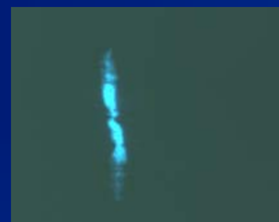
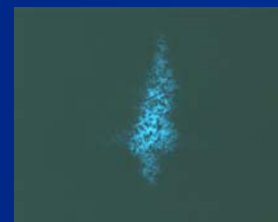
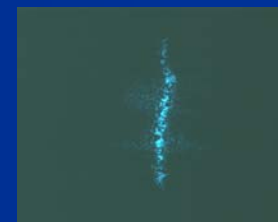
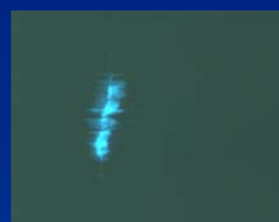
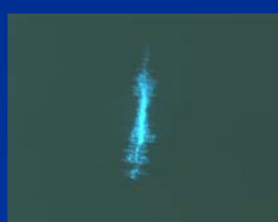
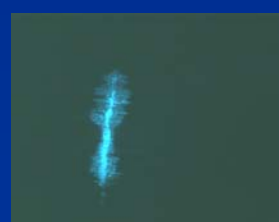
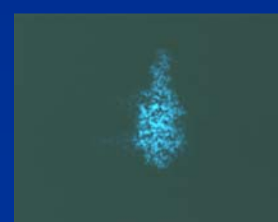
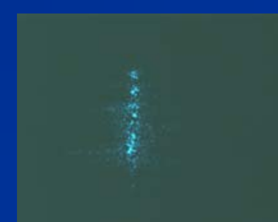


- Data shown for Al, Ti and Ni samples with some differences in surface condition associated with alloy
- DP2 yielded brighter indications than DP1
- Isopropyl-based NAWD yielded brightest indications which is a result of “blooming” of the indication
- Acetone-based NAWD yielded lowest brightness but also “crisper” images than propanol-based NAWD

Aluminum Samples

	DP1	DP2	NAWD - Propanol	NAWD - acetone
02-733				
Area →	0.00142252	0.00247134	0.00215055	0.00264958
02-738				
	0.00230841	0.00263646	0.00256451	0.00260592
02-754				
	0.00248095	0.00358498	0.0043331	0.00363175

Titanium Samples

	DP1	DP2	NAWD - Propanol	NAWD - acetone
02-415				
Area →	0.0014715	0.00159755	0.00367583	0.00140007
02-431				
	0.00171245	0.0017963	0.00288122	0.00097764
02-475				
	0.00188998	0.00268864	0.0036684	0.0011268

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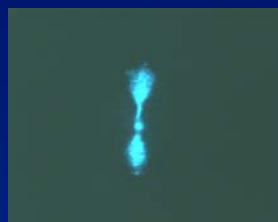
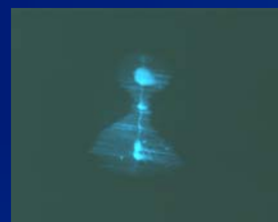
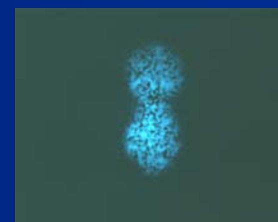
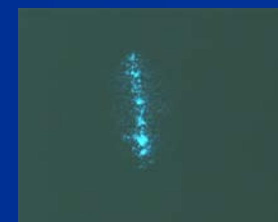
Nickel Samples

	DP1	DP2	NAWD - Propanol	NAWD - acetone
02-035				
Area →	0.001746	0.00497503	0.00549359	0.00154019
02-057				
	0.00051902	0.0011116	0.00285967	0.00073288
02-059				
	0.00046172	0.00090909	0.00194606	0.00045183

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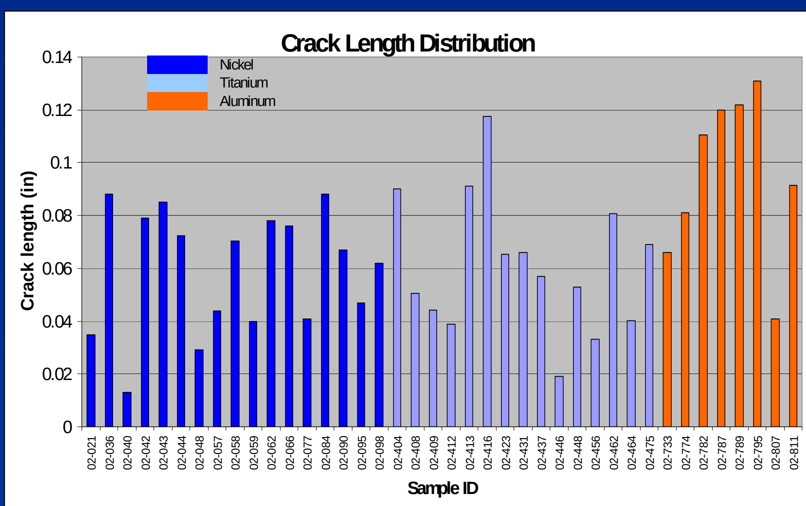
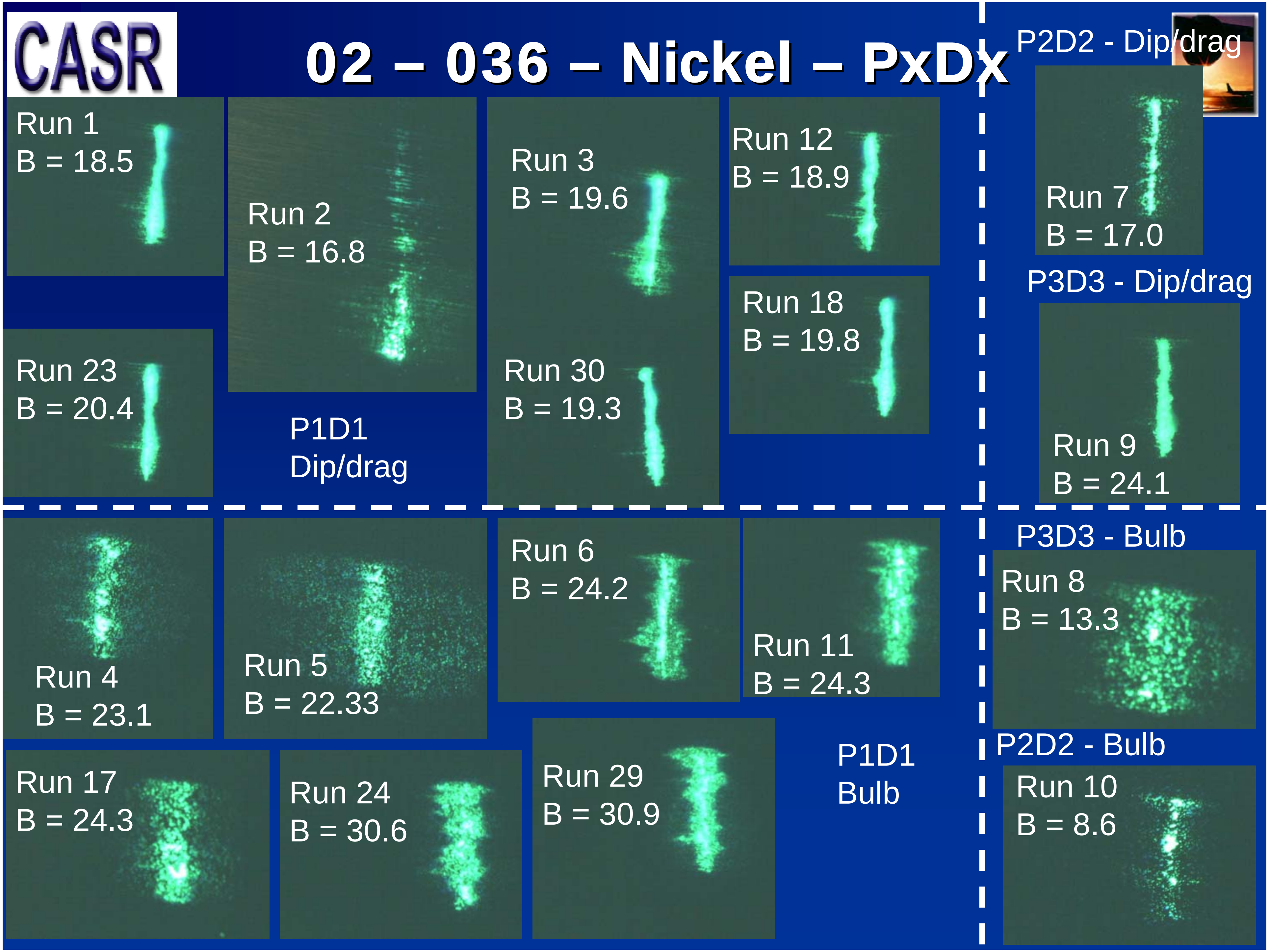
Comparative Study of Penetrant / Developer Combinations

- Testplan and crack size distribution was determined using samples from three alloys
- Number of samples:
  - Ni – 17
  - Ti – 15
  - Al – 8

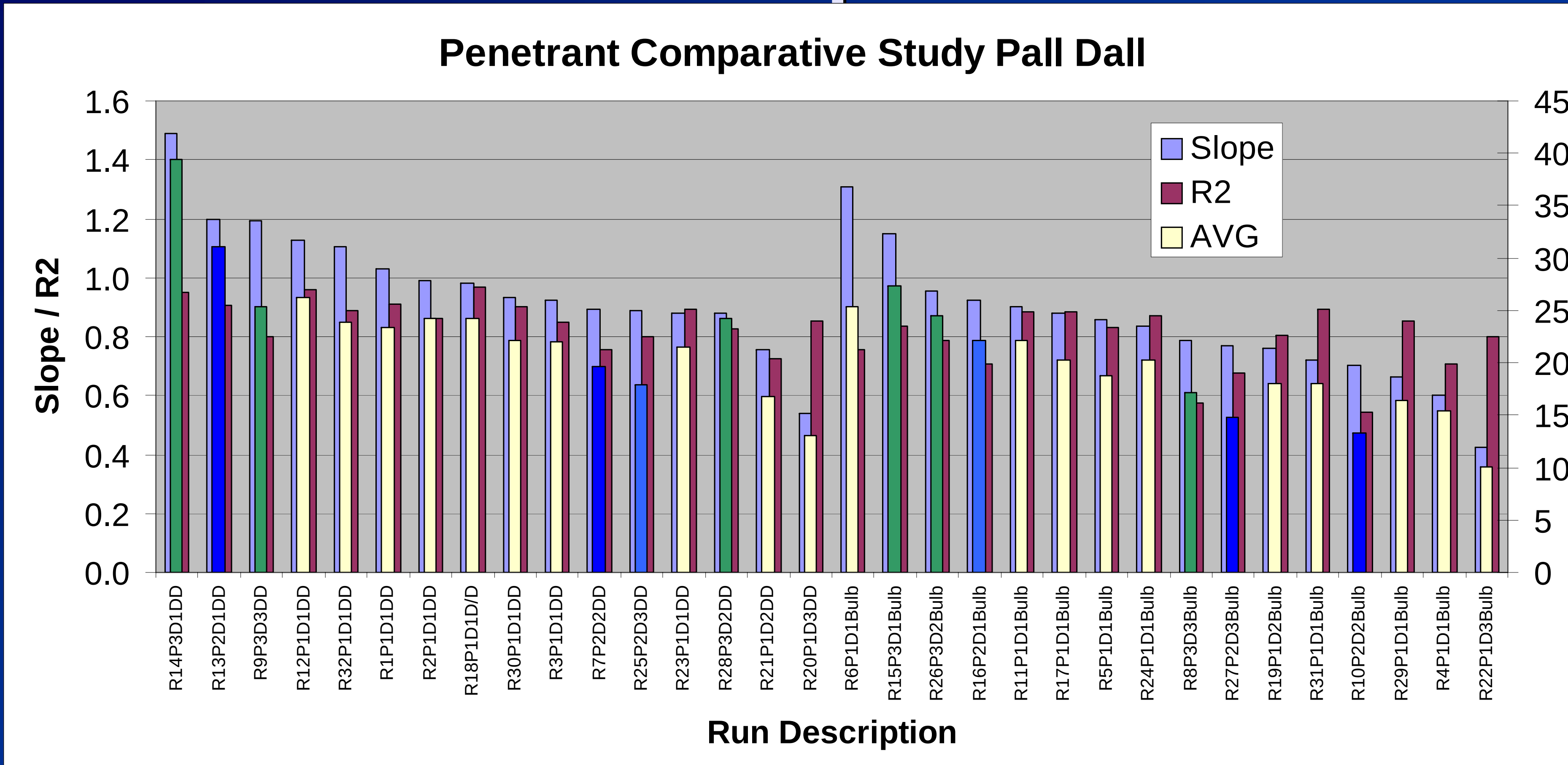
Run #	Penetrant	Developer	Application method	Notes
1	P-1	D-1	dip/drag	
2	P-1	D-1	bulb	
3	P-1	D-1	bulb	
4	P-1	D-1	dip/drag	
5	P-1	D-1	bulb	
6	P-1	D-1	dip/drag	
7	P-2	D-2	dip/drag	penetrant with it's own developer
8	P-3	D-3	bulb	
9	P-3	D-3	dip/drag	
10	P-2	D-2	bulb	
11	P-1	D-1	bulb	
12	P-1	D-1	dip/drag	
13	P-2	D-1	dip/drag	penetrant with baseline developer
14	P-3	D-1	dip/drag	
15	P-3	D-1	bulb	
16	P-2	D-1	bulb	
17	P-1	D-1	bulb	
18	P-1	D-1	dip/drag	
19	P-1	D-2	bulb	baseline penetrant with other developers
20	P-1	D-3	dip/drag	
21	P-1	D-2	dip/drag	
22	P-1	D-3	bulb	
23	P-1	D-1	dip/drag	
24	P-1	D-1	bulb	
25	P-2	D-3	dip/drag	other penetrants with other developers
26	P-3	D-2	bulb	
27	P-2	D-3	bulb	
28	P-3	D-2	dip/drag	
29	P-1	D-1	bulb	
30	P-1	D-1	dip/drag	
31	P-1	D-1	bulb	
32	P-1	D-1	dip/drag	



02 – 036 – Nickel – PxDx



Comparative Study of Penetrant / Developer Combinations



arranged in order of decreasing average brightness with P1Dx shown in white, P2Dx shown in blue, and P3Dx shown in green

Comparative Study of Penetrant/Developer Combinations

- Differences in penetrant/developer families are observed but all cracks gave acceptable performance
- In general, dip/drag gave better brightness values than bulb
- Linear regression analysis showed better performance for P3D3 followed by P1D1 and P2D2
- Runs limited to one per combination

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Developer Application Methods

- Chamber a – Developer applied through linear diffuser located at top and bottom of chamber
- Chamber b – Developer applied from circular diffuser located at top and bottom of chamber
- Chamber c – Developer applied from circular diffuser located at top of chamber
- Chamber d – Developer applied from two nozzle diffusers located at bottom of chamber
- Manual spray – Low pressure, high volume manual application
- Dip/drag – Hand application of individual samples. Used for baseline measurements.

Chamber D Characterization

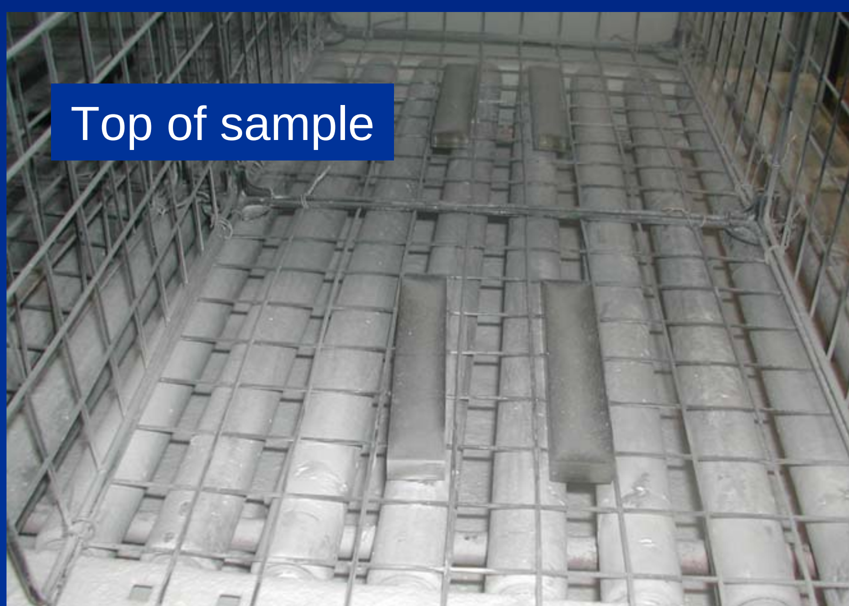
- Chamber contains two jets, at approximately ¼ and ¾ of the chamber length
- Jets located below rollers
- Typical operation of 5 sec developer application followed by 10 min dwell in chamber

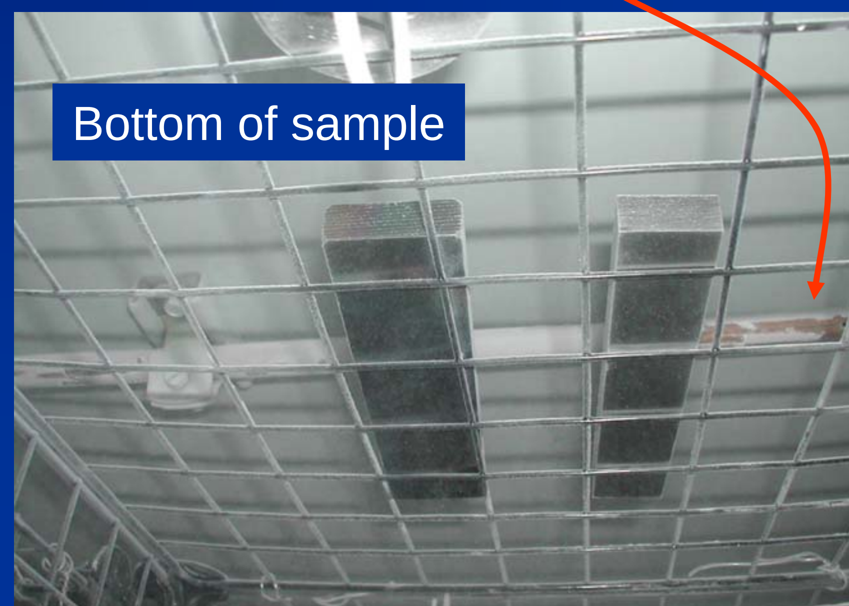
Chamber A Characterization

- Developer applied through linear diffusers located at top and bottom of chamber
- Developer time of 20 or 60 sec followed by 2 min dwell, 1 min evacuation and removal at 5 min
- Samples placed with cracks in up or down position

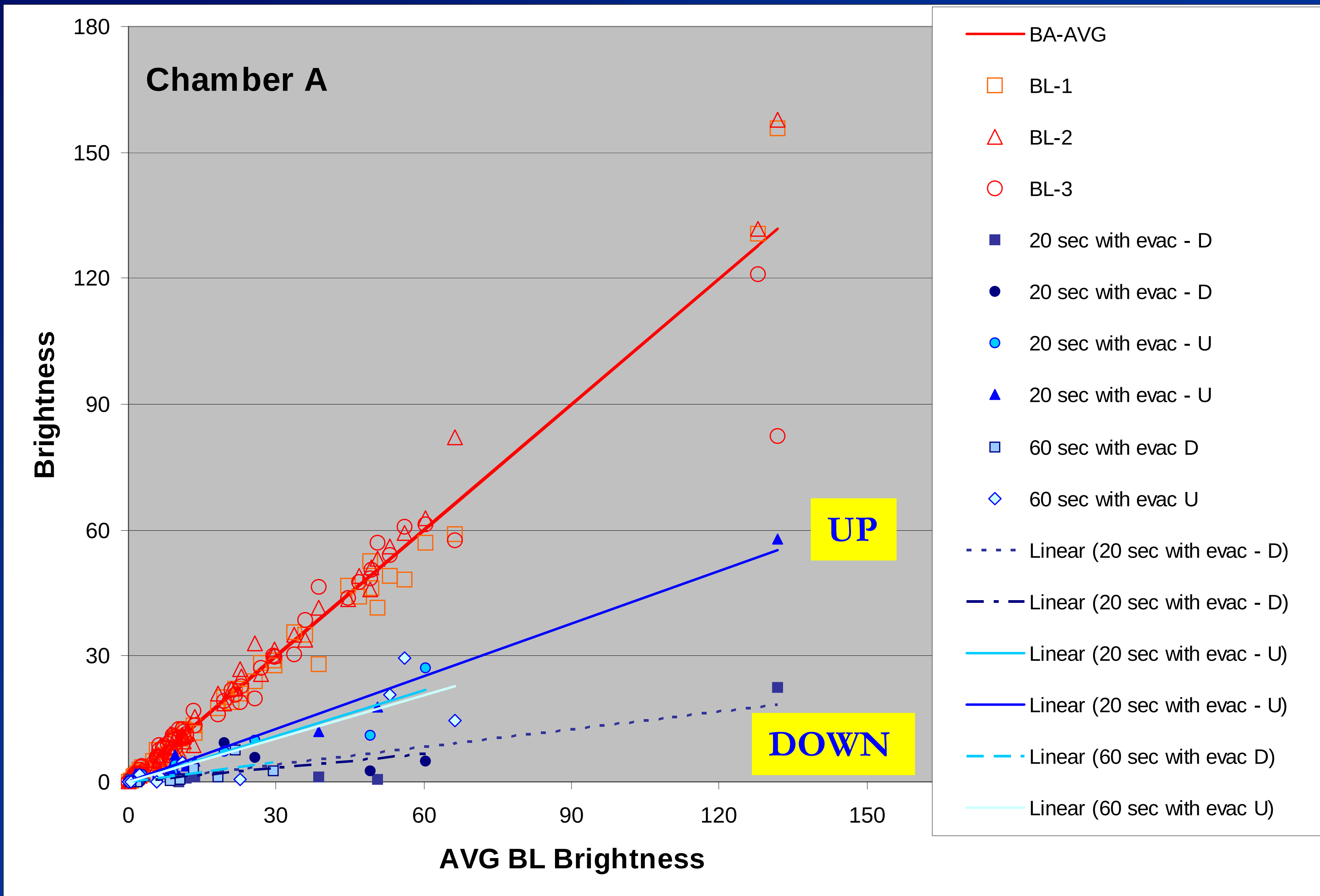
Samples prior to removal

Linear diffusers

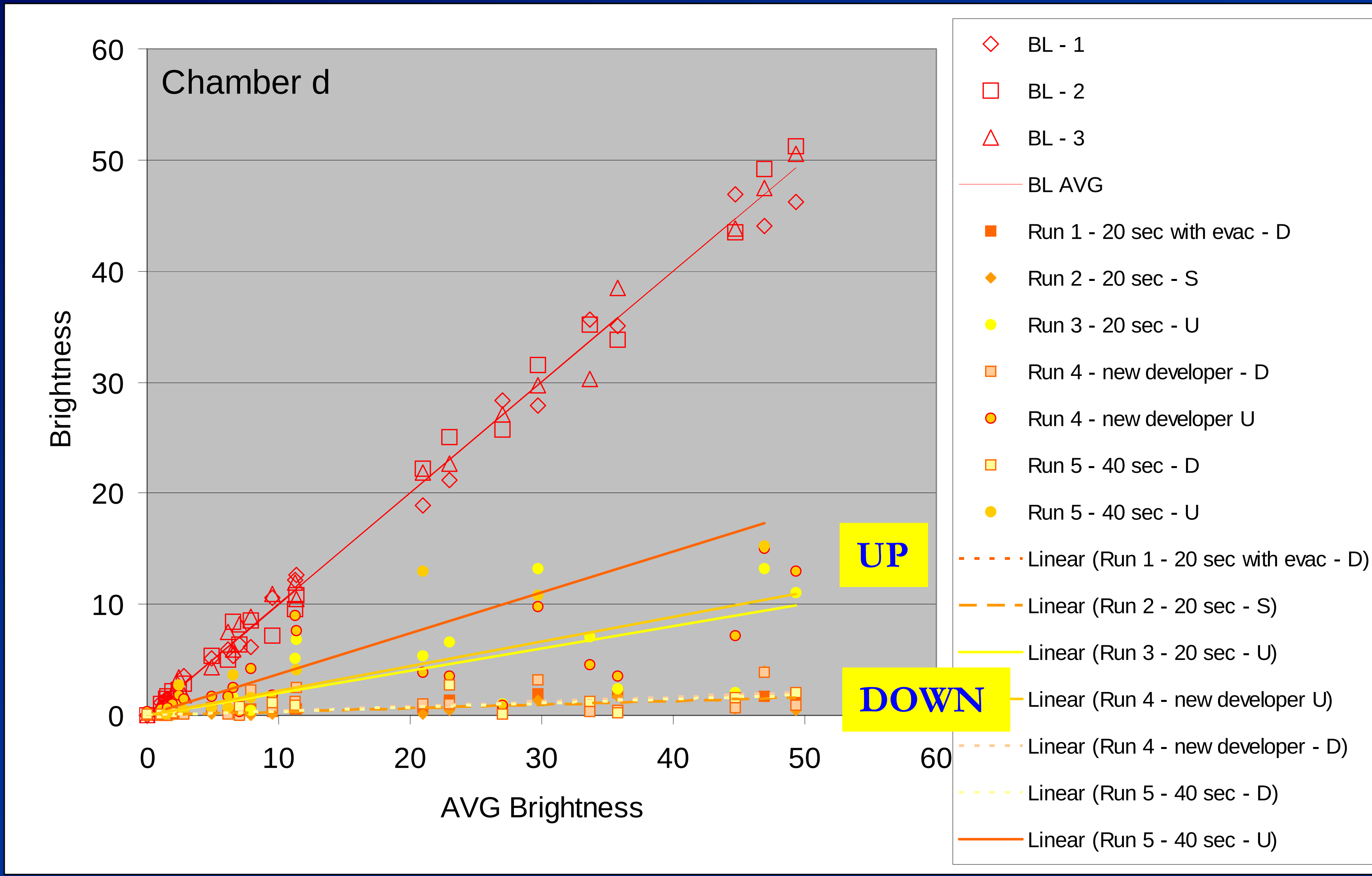




Chamber A Characterization



Chamber D Characterization



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Statistical Analysis of Chamber Effects

- Statistical analysis showed:
  - Differences were found in location within the chambers
    - Right/left effects in Chamber B but not Chamber A for cracks in up position
    - Improved brightness in middle of Chamber B compared to either end for cracks in up position
    - More variation at front of Chamber D than middle and back of chamber
    - No right/left, front/back or level effects for cracks in down position
    - No level (top, middle bottom) effect found in Chamber A, B or D
  - Most significant effect was crack orientation (up, down, sideways)
- Suggest consider approaches which enhance contact of the developer with potential crack locations
  - Localized developer in areas of concern
- Characterization of chamber performance needed for routine use in line maintenance

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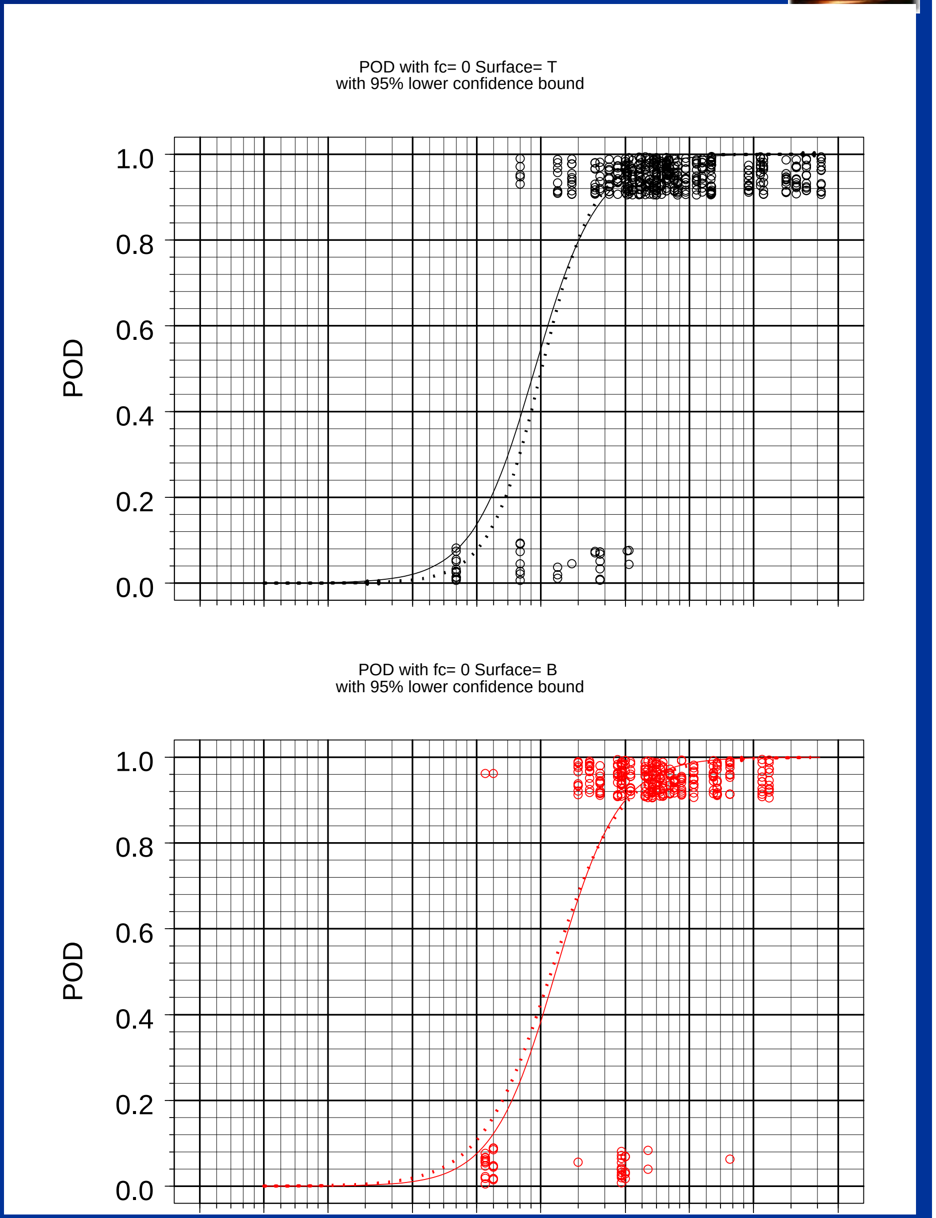
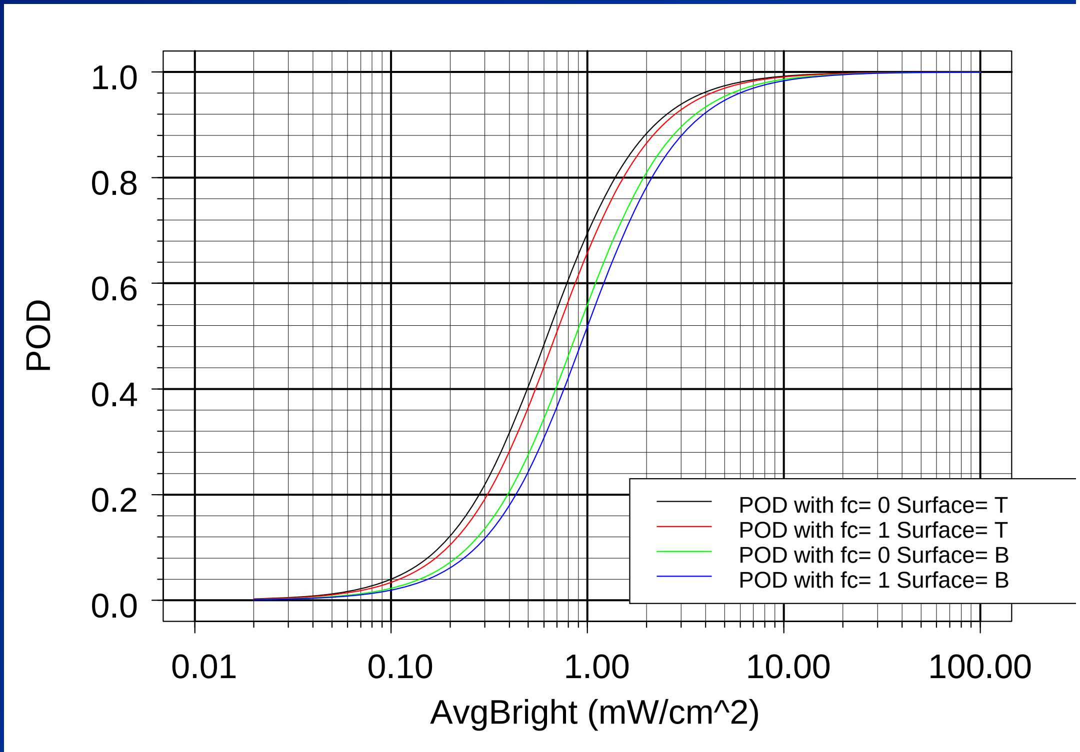
Importance of Sample Orientation

- Completed POD study which correlates brightness to detectability
- Used two sample sets, two inspectors under multiple UV intensity level, white light level combinations
- Evaluated indication location (top or bottom) of panel
- Significant differences can occur

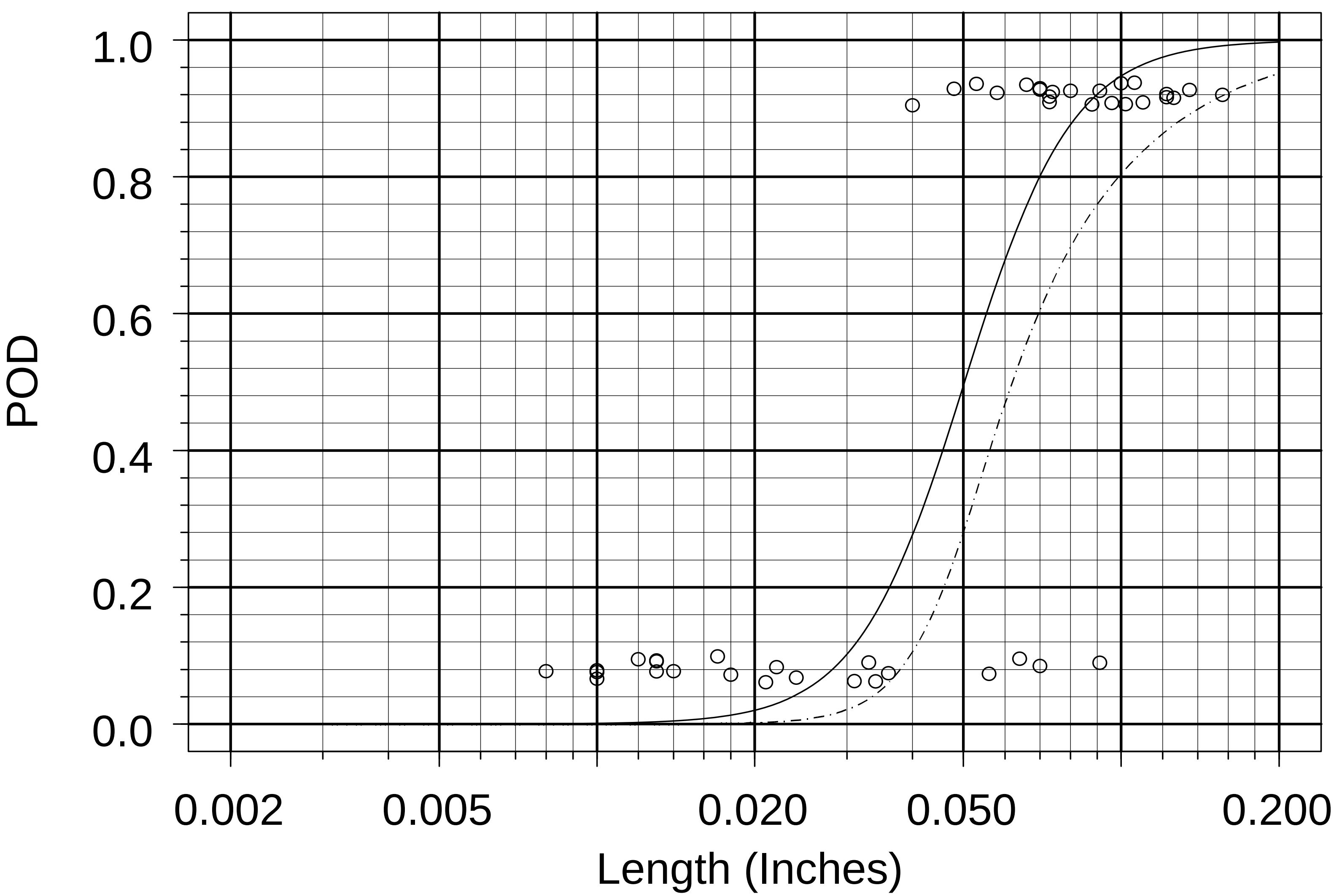


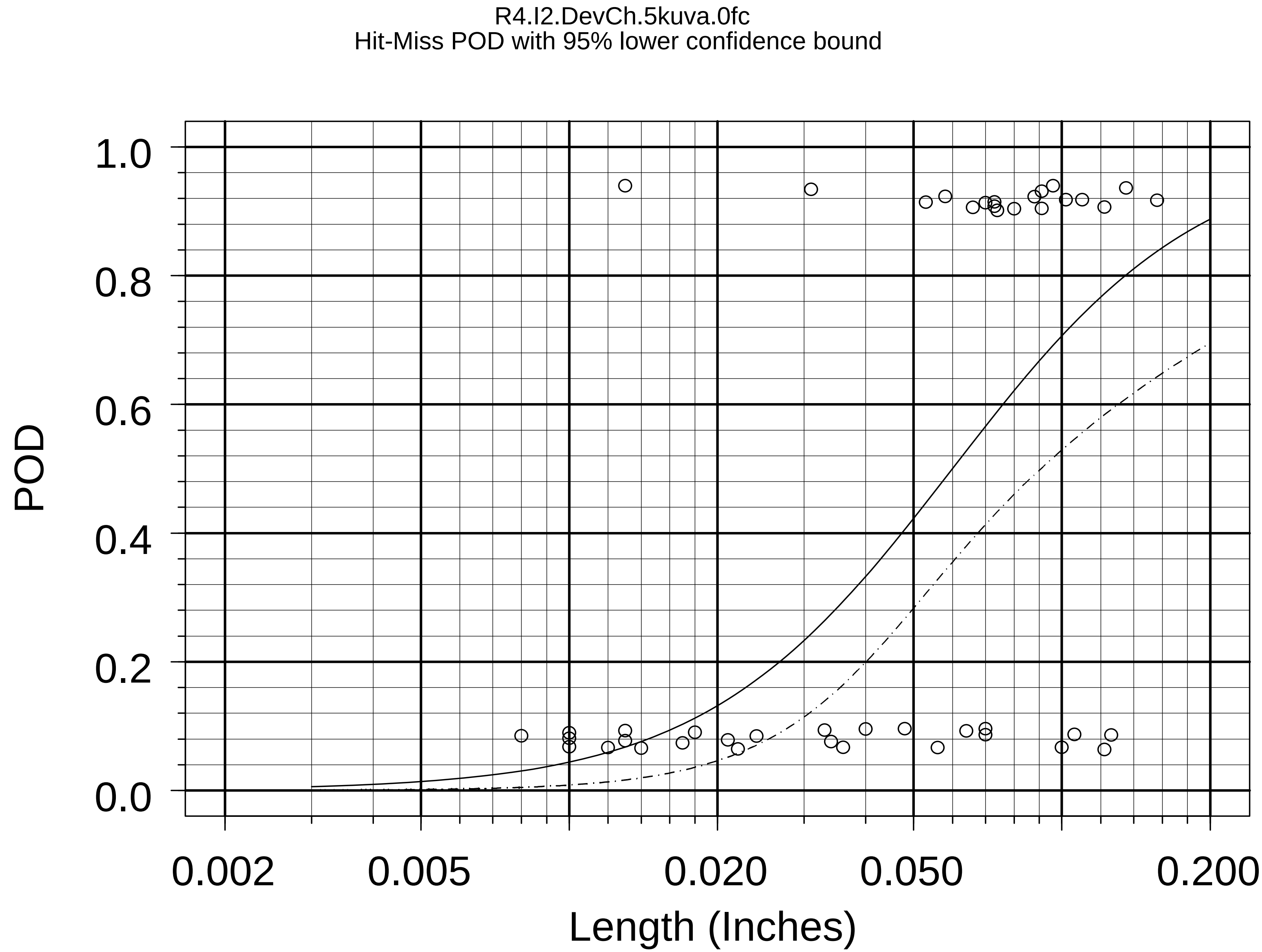
Importance of Brightness

- POD is correlated to brightness
- UVA intensity of 5000 µwatts/cm^2 lead to ~15 mil improvement in POD when compared to 1000 and 3000 µwatts/cm^2
- Increasing whitelight contamination led to significant reductions in POD in excess of 100 mils



R3.I2.5kuva.0fc
Hit-Miss POD with 95% lower confidence bound



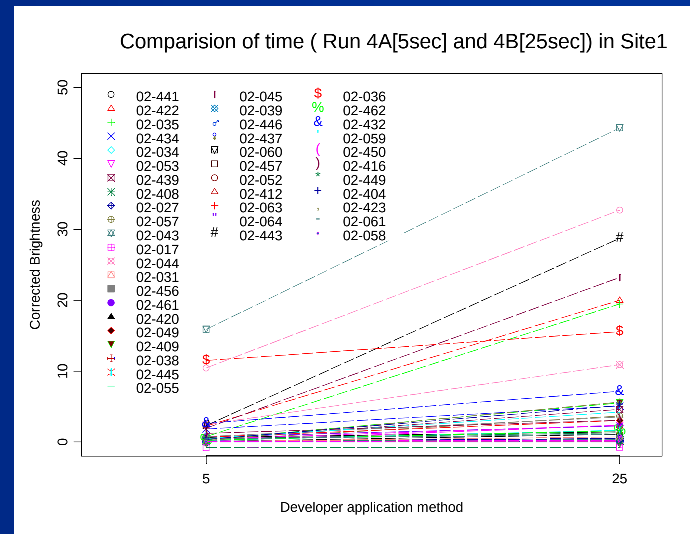

R4.I2.DevCh.5kuva.0fc
Hit-Miss POD with 95% lower confidence bound
POD
1.0
0.8
0.6
0.4
0.2
0.0
0.002
0.005
0.020
0.050
0.200
Length (Inches)

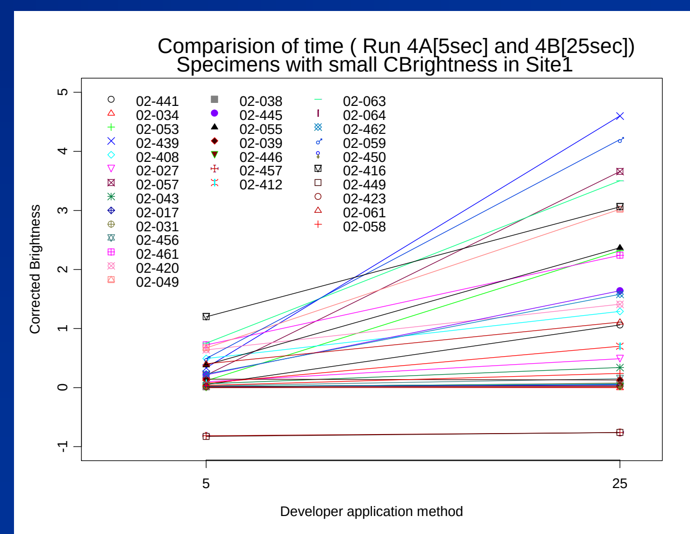
Manual Spray Application

- Low pressure, high volume spray
- 5 and 25 sec runs completed using lobster cage with cracks in D, S or U position
- 60 and 120 sec runs completed with samples all in U position

Manual Spray Application

- Increasing time of manual spray application from 5 to 25 sec showed significant improvements in brightness





CASR Preliminary Conclusions – Form A

- Developer application is critical to overall FPI performance
- Developer application by dip/drag yields brighter indication than with any of the developer chamber or wand application methods
- No indications were “lost” but detectability improves with brightness – optimal process will yield bright indications
- Sample orientation matters
  - Avoid barriers that prevent direct application of the developer
  - Ensure chamber configuration or part handling fixtures (rollers, baskets, etc.) don’t hamper application
  - No metal-to-metal contact
  - May require multiple trips through the chamber to ensure adequate coverage on all surfaces
- White light contamination matters

Form B and C

- Current industry standards allow the use of several developer forms, including:
  - Dry powder (Form a)
  - Water soluble (Form b)
  - Water suspendible (Form c)
  - Non-aqueous wet developer (Form d)
- Past studies have shown that application of dry powder using a dust storm cabinet produces an indication brightness that varies between cabinets, and with defect location
- Spray or dip application of water suspendible or water soluble developer has the potential of avoiding this defect location sensitivity

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What Work Was Done

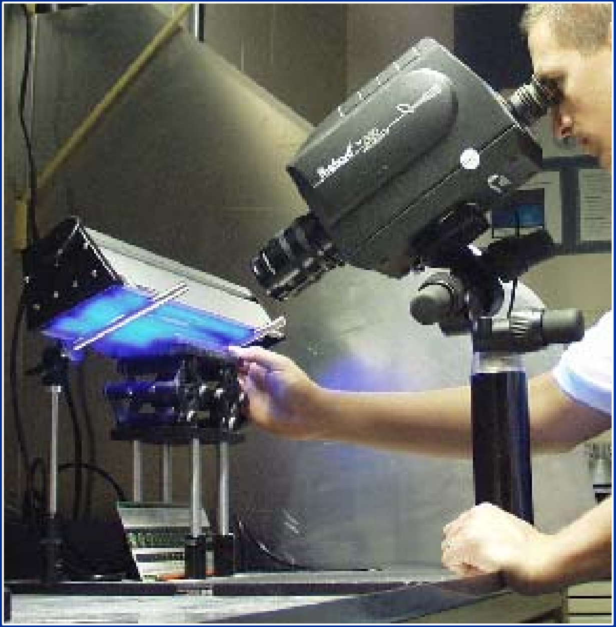
This work monitored the change in FPI indication brightness while varying:

Developer Type
- Dry powder
- Water soluble
- Water suspendible
- NAWD

Developer Concentration (for soluble/suspendible)
- Recommended
- Low

Developer Application Method
- Immersion
- Spray (performed at Tinker)
- Dip/drag
- Bulb

Crack Orientation (for Bulb application)
- Facing up
- Facing sideways



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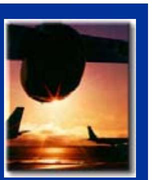
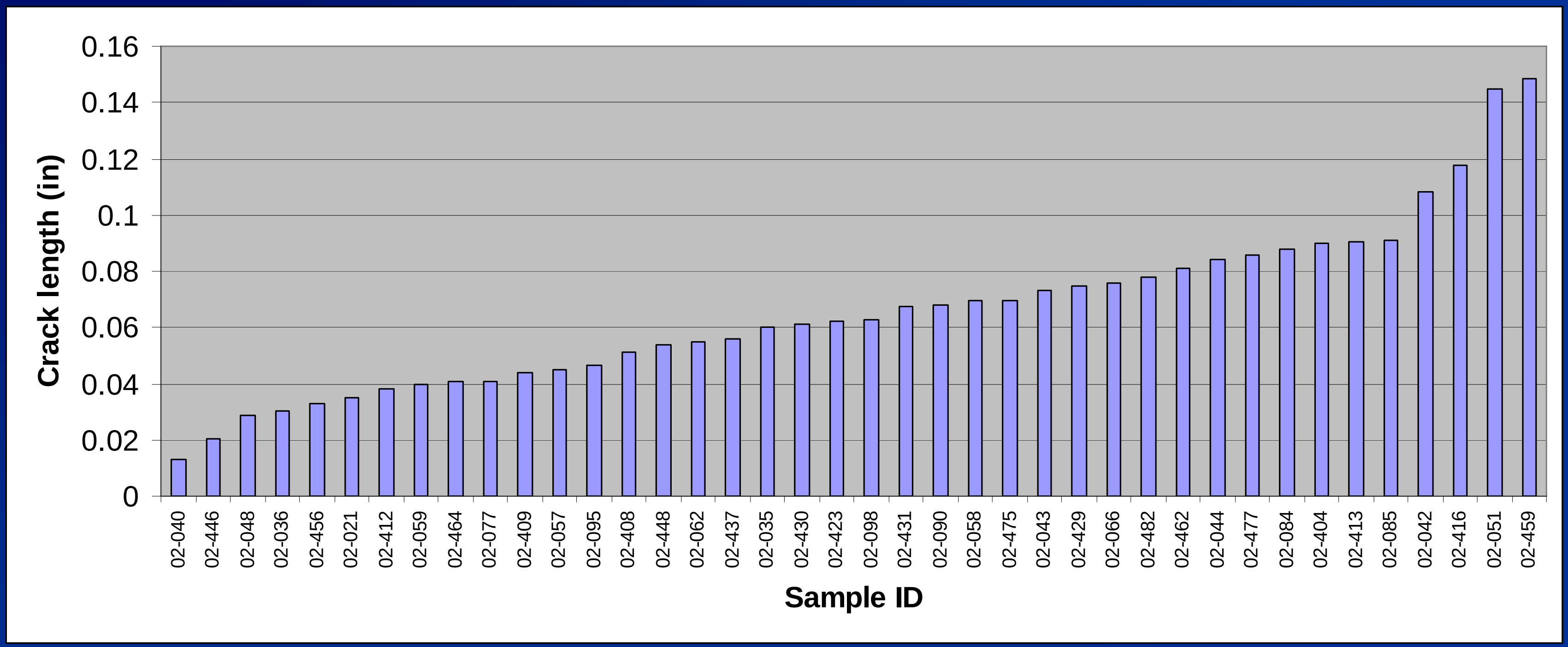
Sample description





- 39 samples (Ti, Ni) selected with crack sizes shown in the distribution above
- Included 16 samples from prior emulsification studies completed at ISU

How Was It Performed

Inspection Process

- 20 minute penetrant dwell
- 90 second pre-wash
- 120 second emulsification (15-second agitation interval)
- 90 second post-wash
- developer apply (soluble or suspendible)
- 10 minute dry @ 155°F
- 10 minute development (dry powder)
- photometer brightness and UVA microscope imaging
- NAWD Application and 10 minute development
- photometer brightness and UVA microscope imaging
- 30 minute UT-agitated acetone clean
- 60 minute dry @ 155°F

Variation depending upon experimental run

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How Was It Performed

When divided by developer form, experimental runs included:

Dry powder developer

- Dip/drag application
- Crack facing upward – Bulb application
- Crack facing sideways – Bulb application

Water suspendible developer

- Recommended concentration – immersion application
- Low concentration – immersion application
- Low concentration – spray application (Tinker)

Water soluble developer

- Recommended concentration – immersion application
- Low concentration – immersion application
- Low concentration – spray application (Tinker)

NAWD

- Applied as a follow-up to any developer combination above

Study Summary

- Baseline runs completed at ISU using dip/drag processing
- Shipped emulsifier, penetrant and dry powder developer to Tinker for use in baseline processing
- One baseline run at Tinker to verify good compatibility between ISU baseline and OKC results
- Three runs each with Form B and Form C processes
  - Two runs with baseline penetrant/emulsifier and form b/c developer
  - One run through inspection line using penetrant/emulsifier/developer
- More detailed runs completed at ISU

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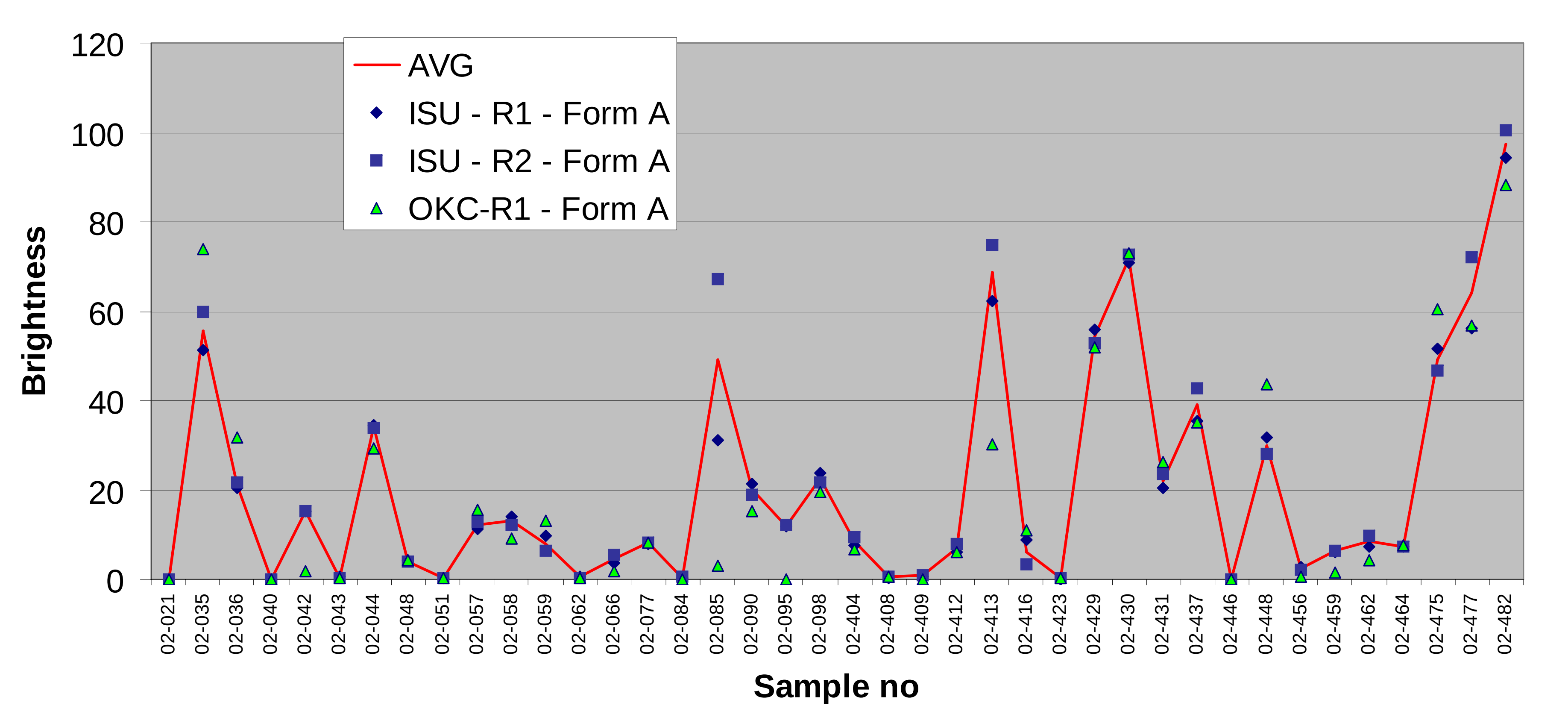
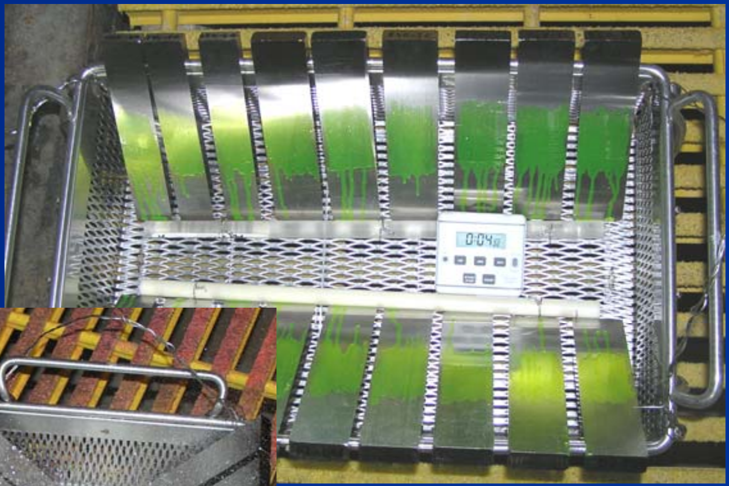
Baseline Comparison

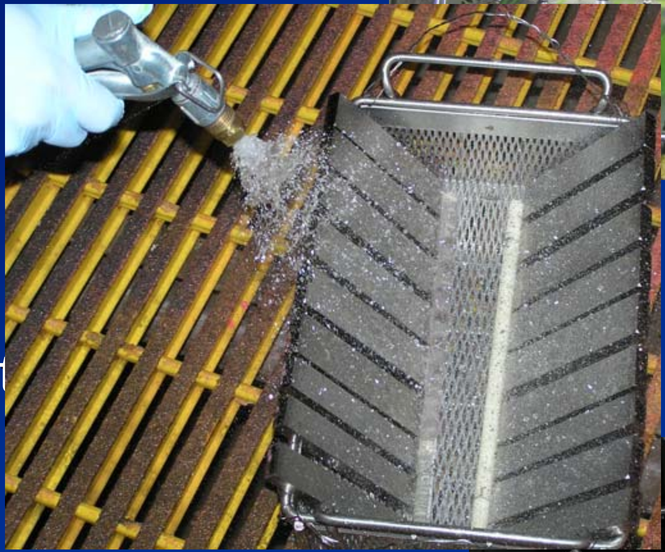


- Reasonable agreement between baseline runs at ISU and OKC

Sample Processing

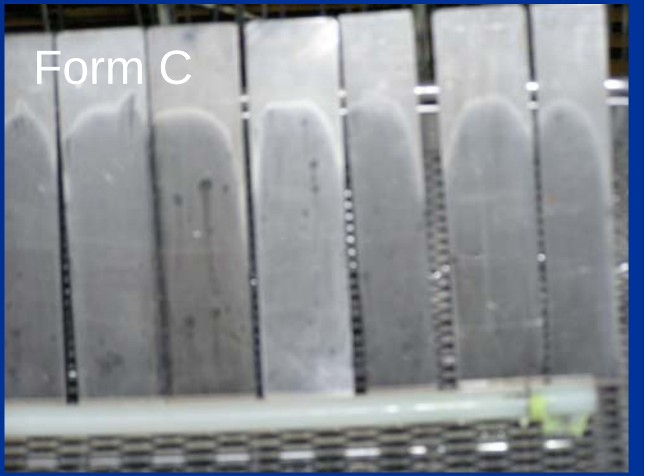
- Penetrant
  - Applied with applicator over crack location
  - Dwell time of 20 minutes
- Pre and Post-rinse
  - 90 sec each
- Emulsification
  - 120 sec total contact time
  - Mild agitation every 15 sec, 30 sec for transition to rinse station





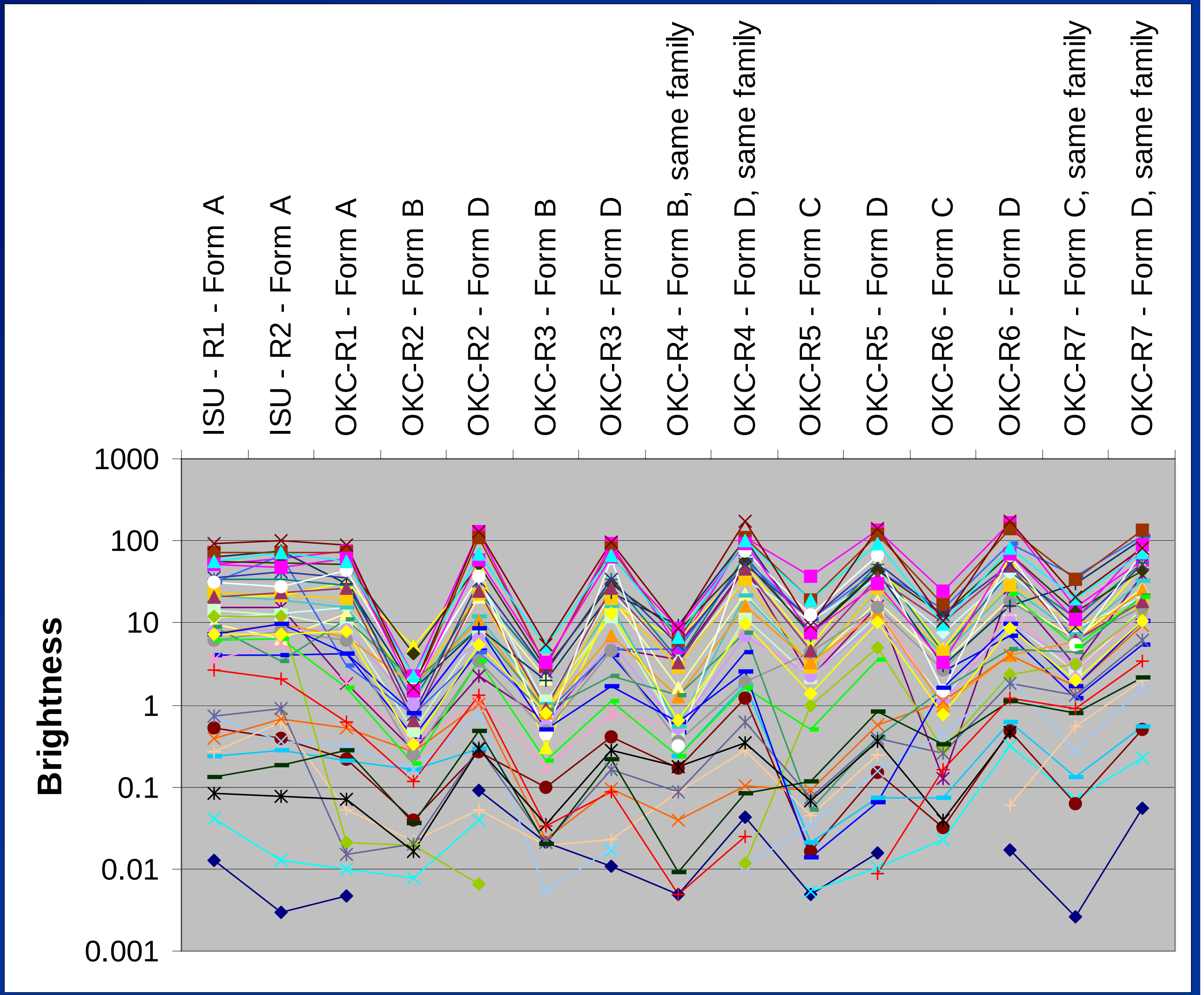
Sample Processing – Developer Application

- Form A – Dip/drag processing using baseline materials
- Form B – Water soluble applied with spray system
- Form C – Water suspendible applied with spray system
- Form D – NAWD, isopropanol-based spray can, single pass



Data Summary

- Brightness results plotted on log scale
- Form B and C results on average show lower brightness than Form A or Form D
- Form C slightly better than Form B



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Post Baseline Characterization

- Repeat baseline runs at ISU using dip/drag followed by NAWD
- Repeat baseline runs at ISU using bulb application followed by NAWD
- Additional Form B and Form C runs

How Was It Performed

Surface Appearance After Developer Application at ISU

Dip / Drag

How Was It Performed

Surface Appearance After Developer Application at ISU

Bulb

Comparison of Surface

Form B

Form C

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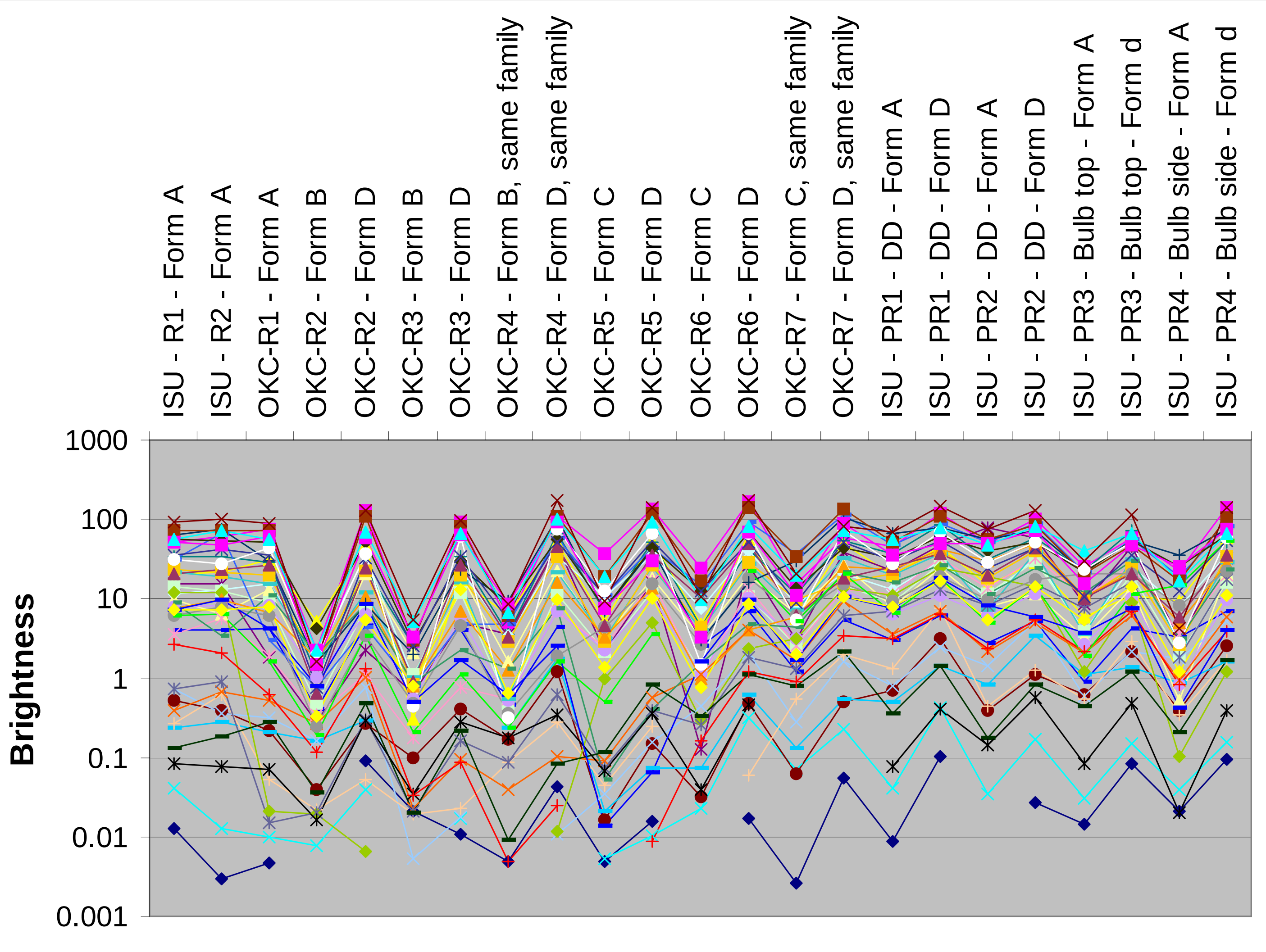
How Was It Performed

Water Soluble/Suspendible developers used at acceptable concentration, and at a lower concentration to determine the relative effect on indication brightness

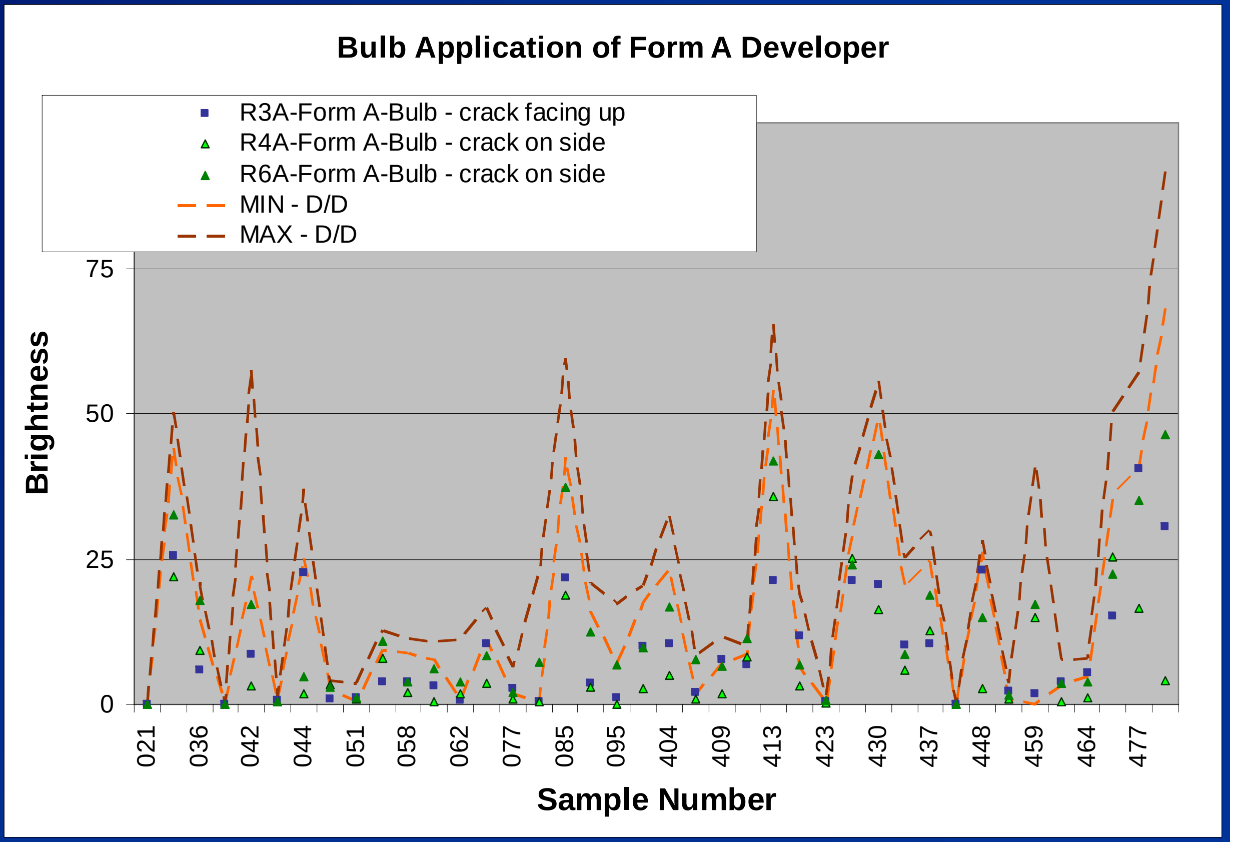
QPL Listed and Manufacturer's Recommended	Form B	2.0 lbs/gal 1.055 sp. grav.
	Form C	0.5 lbs/gal 1.035 sp. grav.
Lower than Standard	Form B	0.25 lbs/gal 1.01 sp. grav.
	Form C	0.25 lbs/gal 1.008 sp. grav.

Post Baseline Results



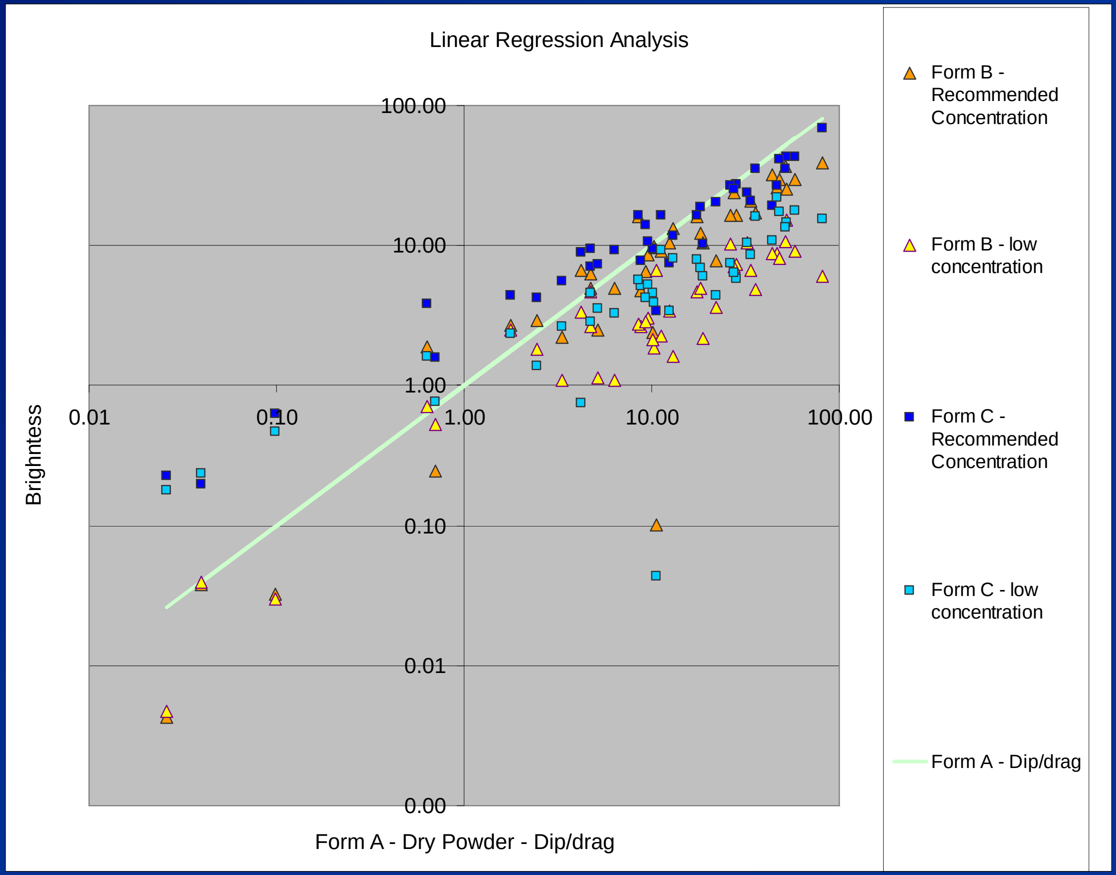
Comparison of D/D to Bulb Application

- Bulb application lower than dip/drag application
- Could be a reasonable addition to characterization of penetrant performance



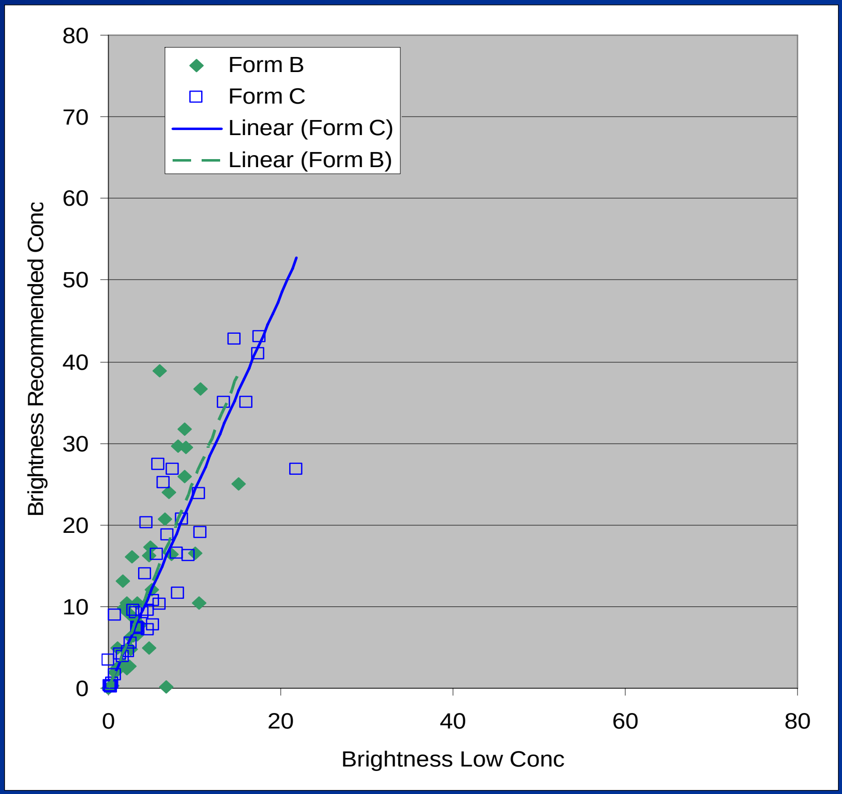
Laboratory Results

- Form C brightness similar to Form A baseline with enhanced brightness at "smaller brightness" range



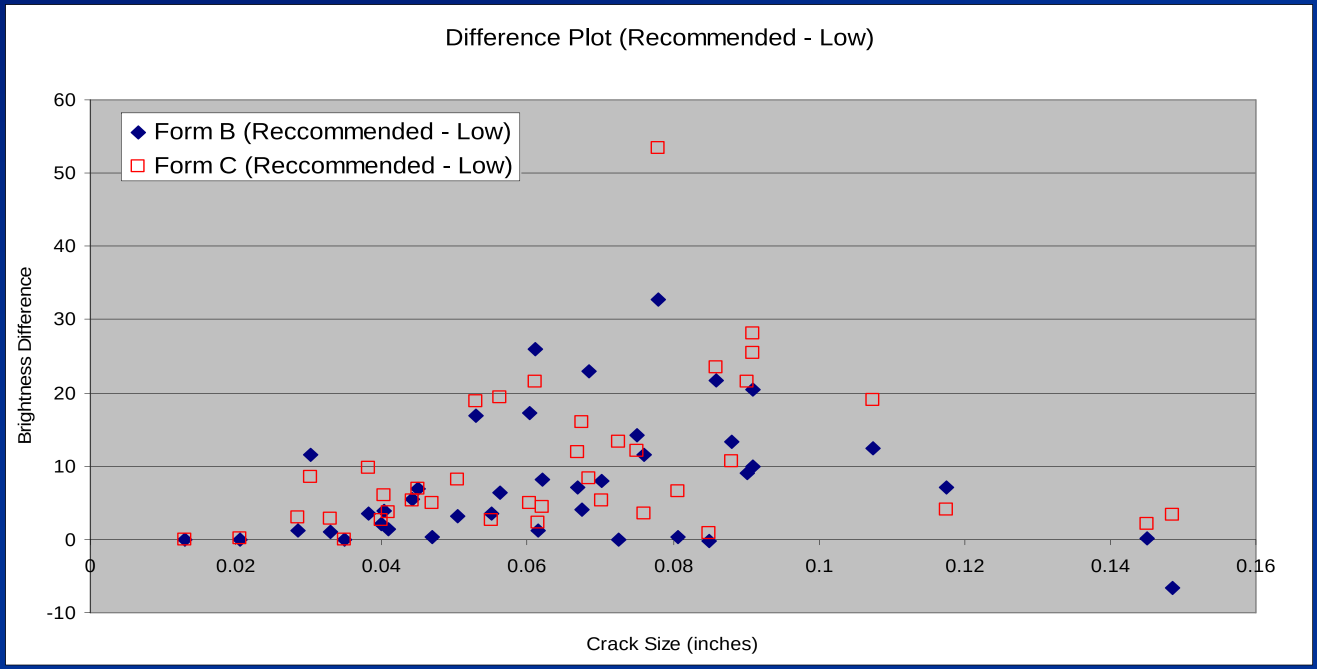
Laboratory Results

- Using the recommended concentration led to significant improvements in brightness for both Form B and C

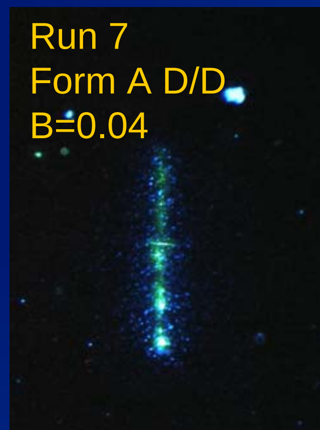


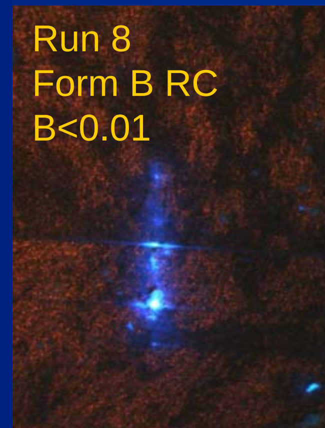
Laboratory Results

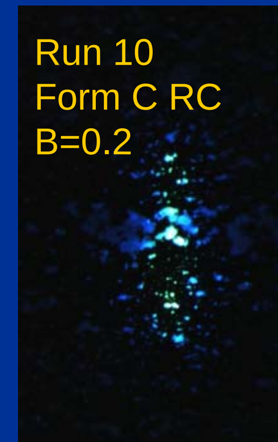
- Question ask about better performance using the lower concentration at smaller crack sizes
- Generating difference plot did not find advantage

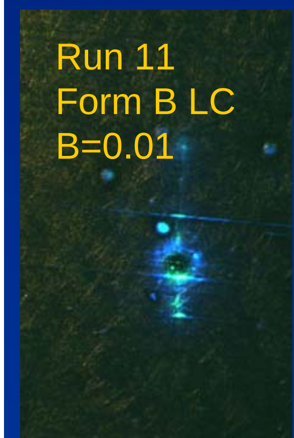


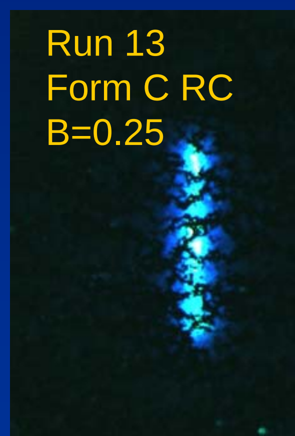
Sample 021 – 0.035”

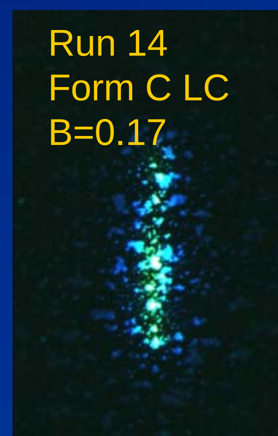


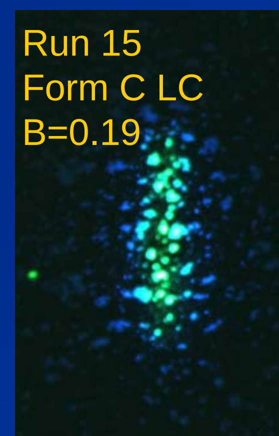


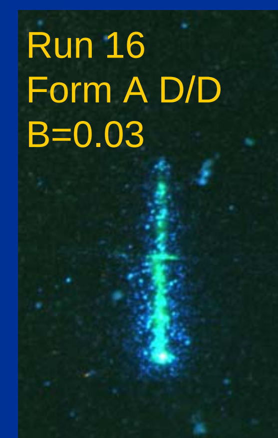






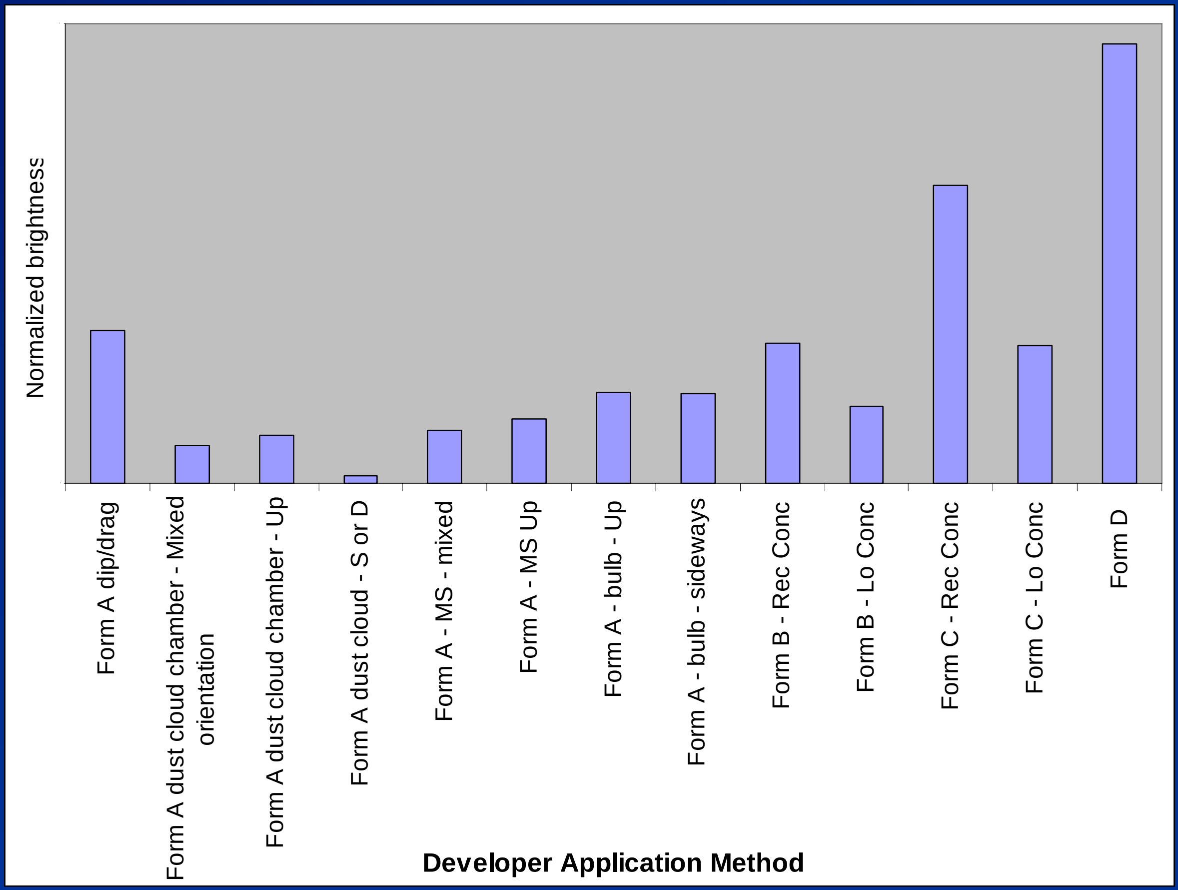






CASR Developer Form Comparison

- Brightness comparison normalized to Form A dip/drag
- Only samples common to all runs were used which leads to a small sample set (10 samples)
- Additional statistical analysis underway – results considered preliminary
- Form D brightness results from more “spread-out” nature of the indication
- Additional analysis of UVA images is warranted to complement the brightness comparisons



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Conclusions

- Use of Form B and Form C developers at the recommended concentration lead to a 140% increase in brightness.
- Masking of small cracks was not evident
- Form B and Form C indications were more diffuse in nature, particularly when compared to the linear indications generated by the Form A developer. It is important that inspectors be aware of these differences and the implications for detectability. Consideration should be given to the implications for training.
- Form C at recommended concentration resulting in brightness similar to Form A dip/drag

Engineering Studies

- Much more information on the CASR website
-

- ES – 1 – Developer Studies
- ES – 2 – Cleaning Studies for Ti, Ni and Al
- ES – 3 – Stress Studies
- ES – 4 – Assessment tool for dryness and cleanliness
- ES – 5 – Effect of surface treatments on detectability
- ES – 6 – Light level Studies
- ES – 7 – Detectability Studies
- ES – 8 – Study of Prewash and Emulsification Parameters
- ES – 9 – Evaluation of Drying Temperatures
- ES – 10 – Part geometry effects
- ES – 11 – Penetrant Application Studies
- ES – 12 – Relationship of part thickness to drying method

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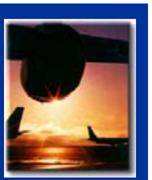
Results Lead to Change



- Airline has implemented a dust chamber characterization procedure to understand positional effects of their systems
- Airline now uses bulb or spray wand application on critical geometry features to enhance developer adherence
- Wet glass bead use restricted for parts that well undergo FPI
- OEM has modified Penetrant Testing, Quality Assurance Subject, of their Nondestructive Testing Standard Practice Manual
- Facility has modified concentration of Form B and Form C developers
- Aspects of the work has been incorporated into AMS 2647 – Rev. C
- Drum rotor best practice has been used as part of AD’s

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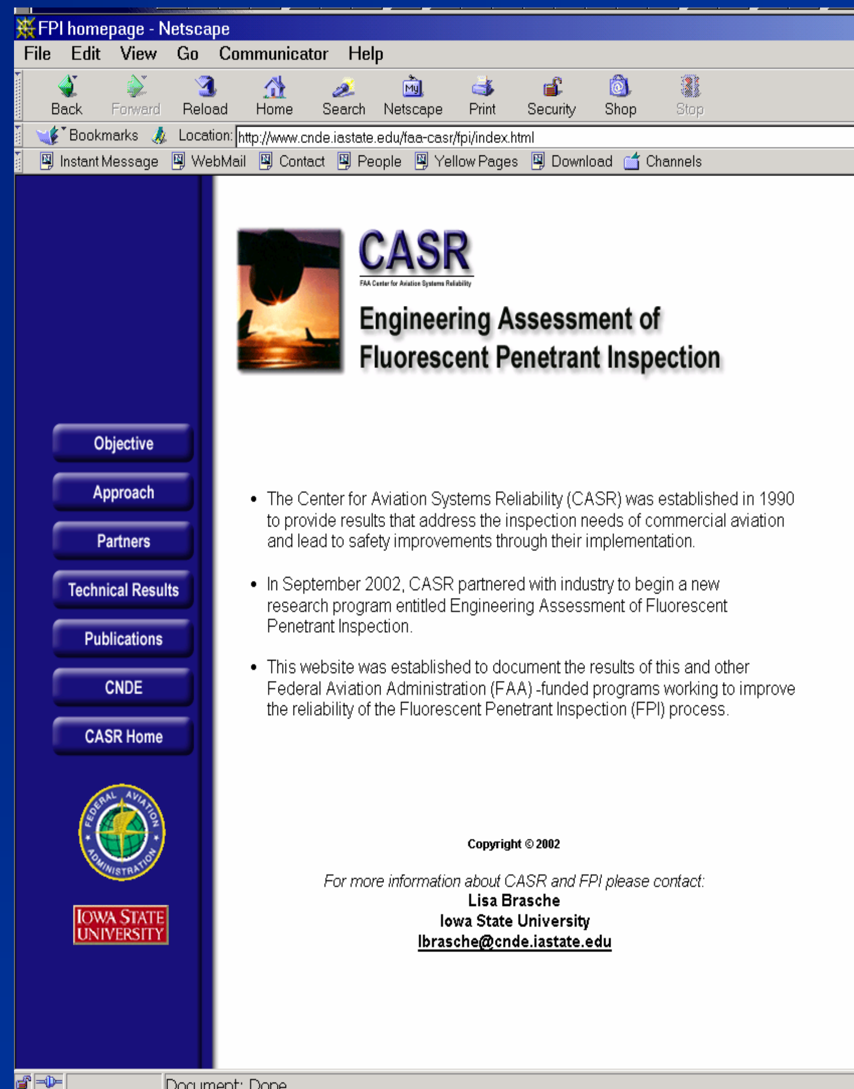
More information

- Website to provide background info and publish technical results
- Link to FAA Reports available



- **http://www.cnde.iastate.edu/faa-casr/fpi/index.html**