2021-03-25

Limiter Redesign Process™

Bit and BHA Forensics

Energy lives here™

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Outline

- Forensics Analysis Learning Objectives
- Observations and Documentation
- Bit Forensics
  - Reading Fracture Initiation and Direction of Loading
  - Bit Wear Scars – Mechanical and Thermal
  - Erosion and Corrosion
- BHA Forensics
  - BHA Wear Scars and Direction of Motion
  - Torsion and HFTO Loads
- Bit Balling and Ribbon Flow

Forensic Analysis Learning Objectives

Incorporate forensic analysis of bit and BHA wear scars and fractures as a diagnostic tool for identifying key limiters and corrective actions.

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Forensic Analysis

- Foundation for continuous improvement
- Utilize on offsets as well as current well
- Document the bit and the BHA
- Photos required
- IADC dull grades are insufficient (that is why we have started to upgrade that system)

Dull Grade
1-1-BT-N-X-I-WT-TD

Observations and Documentation

- Bit Photos
  - Label Blades/Cones 1 to n
    - Blade #1 has inner most cutter
  - Head Shot
  - 45° Side Shot
    - Close up photo per blade
    - Close up photo per cone
  - Gauge Pads, Shank, and API Pin if damaged

- BHA Photos
  - Label stabilizer blades
  - Note location of even minor wear patterns
  - Note direction and depth of wear scars
  - Document diameter and location of stabilizers

- Close up – fill the screen
- In focus / blur free
- Utilize light source direction to highlight scars

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Observation and Documentation 1 of 9

RUN INFORMATION:

Date	November 26, 2011
Directional Company	Baker Hughes
DD name or other contact	Zoran Stekovic/ Tim Bennett-Odlum
Drill Team / Country	North Caspian Drill Team
Well name	KE-DC10-01
BHA number	9
Hole size	12 1/4"
MD drilled from / to	3013m / 3273m
Motor AKO, if applicable	N/A
Reason for trip	Penetration rate
Mudweight range	14.1-14.2ppg
Was backreaming required?	No
Backreaming RPM	NA
Backreaming axial speed	NA
ROP Limiters experienced	Whirl
Problems / dysfunctions encountered	The reason why bit was pulled is low penetration rate.

BIT INFORMATION:

Bit type (PDC, Inset, etc.)	PDC
Bit Serial #	144144
Bit manufacturer	ReedHycalog
Bit size	12 1/4 inch
Bit gauge length	6
# of blades (if applicable)	6
Bit condition before run (bit grade, "new", other notes)	New
Did bit drill out shoe?	Yes
Bit undergauge? How much?	No
Notes on areas of fracture	Shoulder area of the bit wore out.
Notes on areas of wear	
Other damage / notable features on bit	**1-8-RO-S-N-X-HC-PR**
Potential root cause of damage observed	Whirl is likely cause of damage.

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Operator ExxonMobil Kazakhstan Inc **Fields** Kashagan East **Facility** KE DC-10
Well DC 10-01 **Wellbore** DC 10-01 **Rig** Sunkar 257 **Job** DC 10-01

String Components

#	Component	S/N	Mfr	Gauge OD in	OD in	ID in	FN OD in	FN Len. m	Thread	Length m	Total Len m
18	Drill pipe		Parker		5 1/2	4.778			5 1/2" FH - 5 1/2" FH	3745.33	4000.49
17	Sub - X/O	3978-AK-1	EMKI		8 1/4	2 7/8	7 1/2	0.60	(BP) 5 1/2" FH - 6 5/8 FH	1.19	255.16
16	HWDP x 21		EMKI		6 5/8	4 1/2			(BP) 6-5/8 FH - 6-5/8 FH	200.41	253.97
15	Jar	Z3RD93630	Smith		8	3	8	0.76	(BP) 6-5/8 FH - 6-5/8 FH	10.00	53.56
14	HWDP x 2		EMKI		6 5/8	4 1/2			(BP) 6-5/8 FH - 6-5/8 FH	19.08	43.56
13	Sub - X/O	COR2183AD	INTEQ		9 1/2	3 1/2	9 1/2		(BP) 6-5/8 FH - 7 5/8" Reg	0.93	24.48
12	Sub - float	ME 200128	INTEQ,c/wNon- Ported Flapper		9 1/2	3	9 1/2		(BP) 7 5/8" Reg - 7 5/8" Reg	0.78	23.55
11	Sub - float	OMM-ME 200207	INTEQ,c/w Non-Ported Plunger		9 1/16	3	9 1/16		(BP) 7 5/8" Reg - 7 5/8" Reg	1.21	22.77
10	Sub - other	BBS0037	NOV, Black Box		9 9/16	3	9 9/16		(BP) 7 5/8" Reg - 7 5/8" Reg	1.22	21.56
9	Stab - string roller reamer	GU3492	REDBACK	12 1/4	9 11/16	2 3/4	9 11/16	0.83	(BP) 7 5/8" Reg - 7 5/8" Reg	2.69	20.34
8	Sub - filter	ME 200172	INTEQ		9 5/8	3	9 1/2		(BP) 7 5/8" Reg - 7 5/8" Reg	1.21	17.65
7	NM MWD - sub - stop	12049363	INTEQ		9 1/2	3 1/2	9 1/2		(BP) 7 5/8" Reg - 9 1/2 T2	0.76	16.44
6	BCPM	11655666	INTEQ		9 1/2	3	9 1/2	2.30	(BP) 9 1/2 T2 - 9 1/2 T2	3.67	15.68
5	OnTrak - MWD	11637598	INTEQ		9 5/8	3	9 5/8	4.16	(BP) 9 1/2 T2 - 9 1/2 T2	7.01	12.01
4	MWD - stab - mod	10105150	INTEQ	12 1/8	9 1/2	3 1/8	9 1/2	0.57	(BP) 9 1/2-T2 - 9 1/2-T2	1.80	5.00
3	ATK Steerable Stab	10369358	INTEQ		9 1/2	2 3/8	9 1/2	0.43	(BB) 9 1/2 T2 - 6 5/8" Reg	2.50	3.20
2	Sub - other	XW 594593-4	NOV, Black Box		8	2 3/4	9 1/2		(PB) 6 5/8" Reg - 6 5/8" Reg	0.35	0.70
1	Bit - PDC - fixed cutter	A144144	ReedHycalog	12 1/4	12 1/4				6 5/8" Reg	0.35	0.35

18 String components with a total length of 4000.49 m.

Run Details

Run #	Depth In m	Depth Out m	Time In	Time Out	Total Dist m	Hold Dist m	Steering Dist m	Ribs-Off Dist m	Buoyed BHA Wt tonne	Buoyed Wt below jars tonne
9	3013.00		11/23/11 08:30			0.00	0.00	0.00	30	10

Bit Details

Size in	Type/Mfr	Nozzles in/32	TFA in^2	Grading I	O	D	L	B	G	O	R	In MD/TVD m	Out MD/TVD m	Progress m	Time hours	TBR
12 1/4	MSR616M-A6D / ReedHycalog	6x20	1.8408						I			3013.00/2966.16	/			

Drillpipe Details

#	Size in	Grade	Connection OD in	Connection ID in	Act Linear Weight lb/ft	Nom Linear Weight lb/ft
18	5 1/2	G-105	7 1/4	3 1/2	26.62	21.90

Stabilizer Details

Comp. #	Description	Distance to Bit m	Spiral Type	Blade Type	Blade OD in	Blade Length in	Blade Width in
9	Stab - string roller reamer	19.22	Straight	Integral	12 1/4	26.00	10 1/4
4	MWD - stab - mod	4.15	Spiral	Integral	12 1/8	22.00	4 1/2

Page 1

BHA Documentation from Turekul Zhangbylov Kazakstan 2011

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Observation and Documentation 2 of 9

Bit is in gauge ?

Observation and Documentation 3 of 9

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Observation and Documentation 4 of 9

Blade 1-Shoulder is worn out

Blade 2- Shoulder is worn out

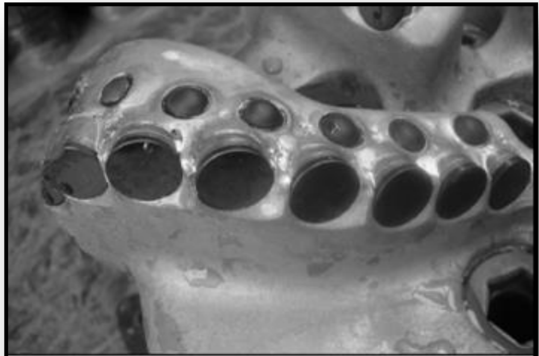
Blade 3- Shoulder is worn out

Blade 4- Shoulder is worn out

Blade 5- Shoulder is worn out

Blade 6- Shoulder is worn out

Observation and Documentation 5 of 9



Blade 1

Blade 2

Blade 3

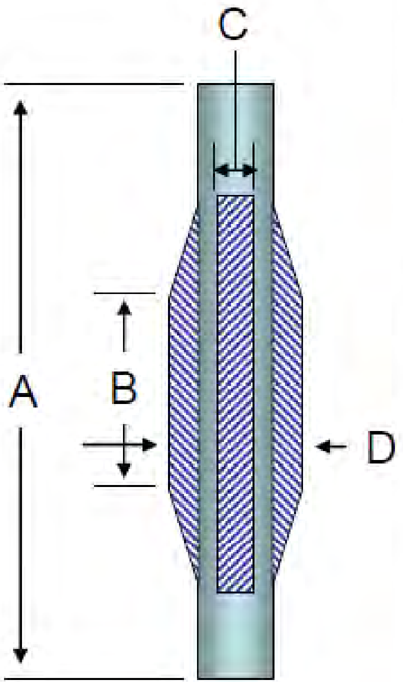
Blade 4

Blade 5

Blade 6

Observation and Documentation 6 of 9

STABILIZER FORENSICS INPUT TEMPLATE



Item number from BHA diagram (page 3)	4
Stabilizer manufacturer	BH Inteq
Serial Number	10105150
Straight blade or spiral?	Spiral
Center of blade distance to bit	3.65m
Sub Length (A)	1.8.m
Blade Length (B)	7 inch
Blade Width (C)	4 inch
Blade OD (D) upper (before / after)	12 1/8 inch
Blade OD (D) middle (before / after)	12 1/8 inch
Blade OD (D) lower (before / after)	12 1/8 inch
Stab condition prior to run	New
Type of Gauge Protection (TCI inserts, TCI welded, nothing, etc)	Bricking
Other Notable Features	

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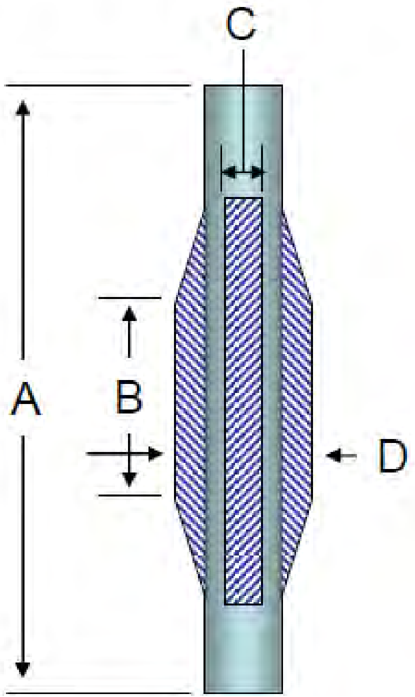
Stabilizer blade #3 has incurred some wear. Likely due to forward whirl.

BHA Documentation from Turekul Zhangbylov Kazakstan 2011

Observation and Documentation 8 of 9

ROLLER REAMER FORENSICS INPUT TEMPLATE



Item number from BHA diagram (page 3)	9
Stabilizer manufacturer	REDBACK
Serial Number	GU3492
Straight blade or spiral?	Straight
Center of blade distance to bit	19.06m
Sub Length (A)	2.69m
Blade Length (B)	28 inch
Blade Width (C)	6 inch
Blade OD (D) upper (before / after)	12 ¼ inch
Blade OD (D) middle (before / after)	12 ¼ inch
Blade OD (D) lower (before / after)	12 ¼ inch
Stab condition prior to run	New
Type of Gauge Protection (TCI inserts, TCI welded, nothing, etc)	TCI inserts
Other Notable Features	

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Observation and Documentation 9 of 9

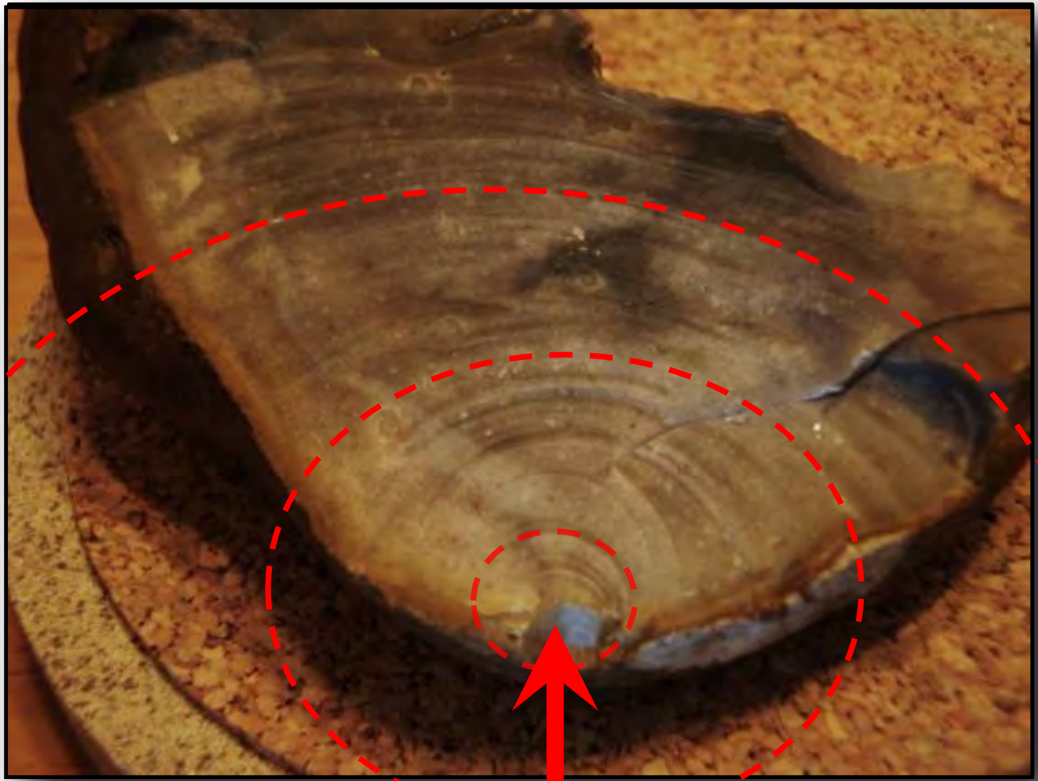
All sides look fine. In gauge.

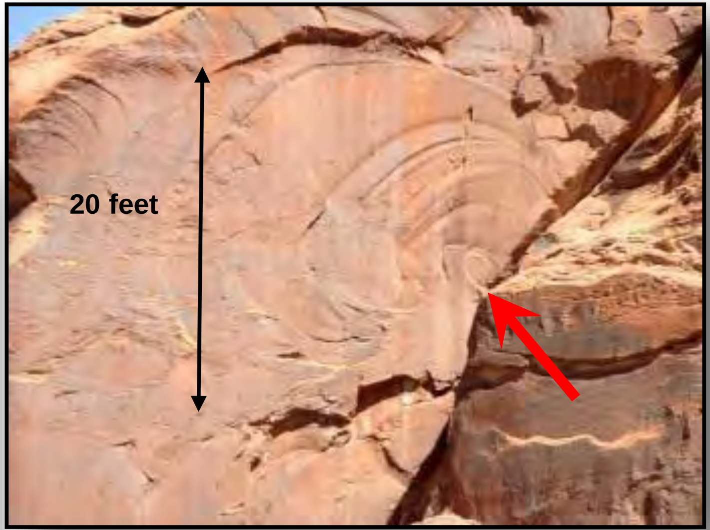
Fracture Patterns and Wear Scars

- Reading Fracture Initiation and Direction of Loading
  - Beach marks / spall - cone, nose, shoulder
  - Plastic hinge
  - Tangential cutter fracture
- Bit Wear Scars
- BHA Wear Scars
  - Forward whirl
  - Reverse whirl
  - Borehole patterns

Bit Forensics

Understanding Beach Marks





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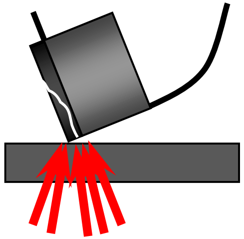
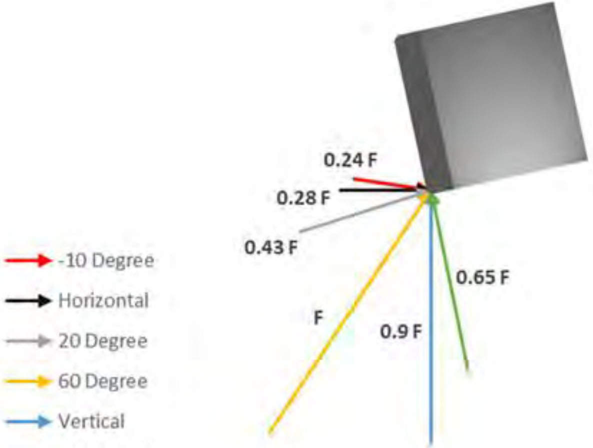
Beach Marks Due to Edge Load ~Normal to Profile



Load is Approximately Normal to Edge

Video courtesy of Varel International



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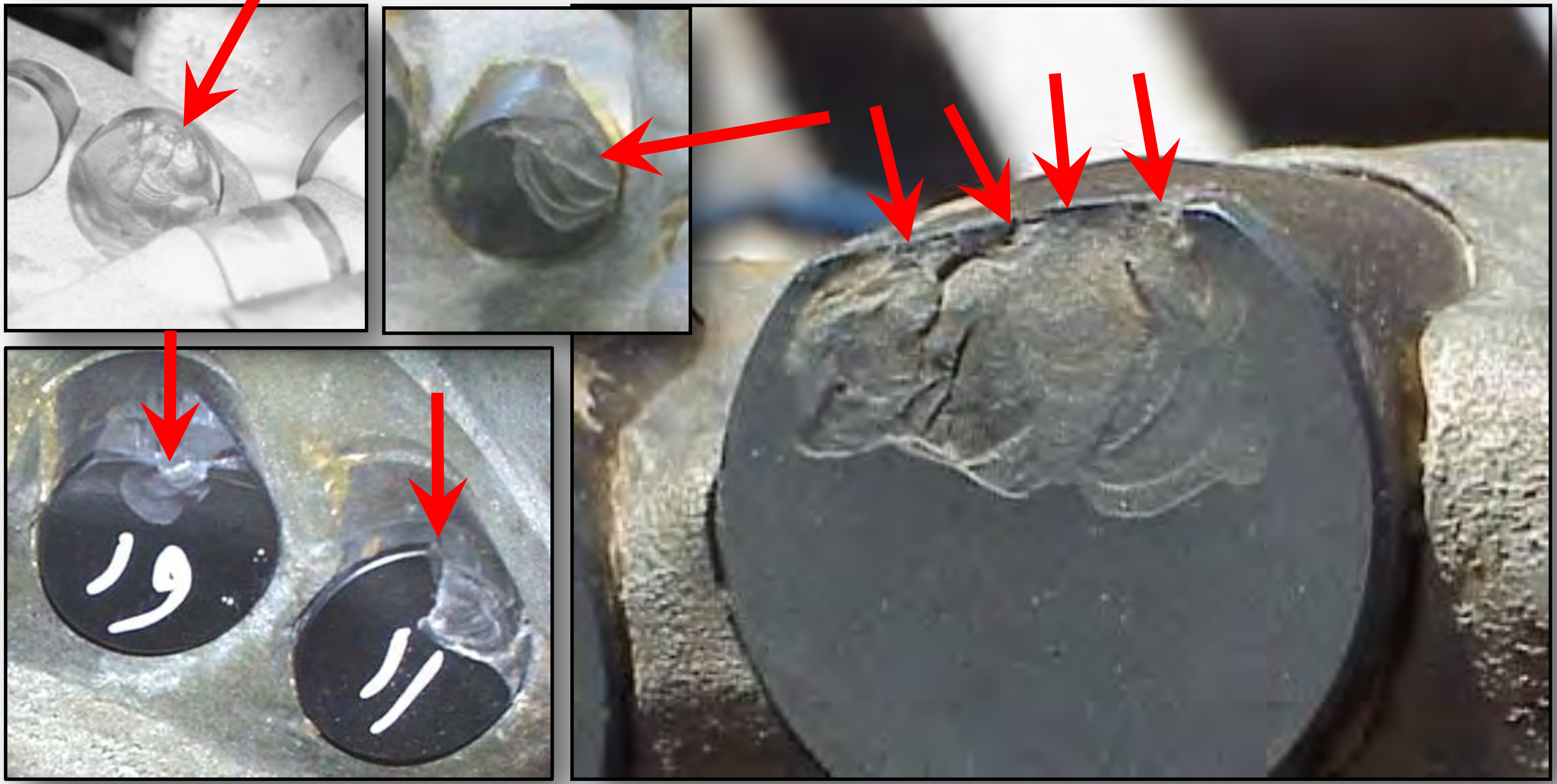
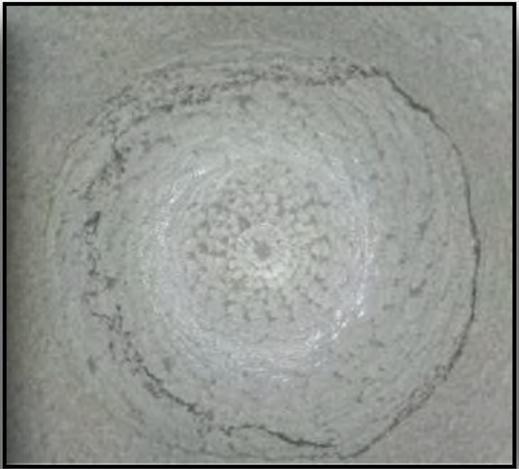
REF: SPE 199598 Rahmani 2020

Beach Marks Due to Edge Load ~Normal to Profile

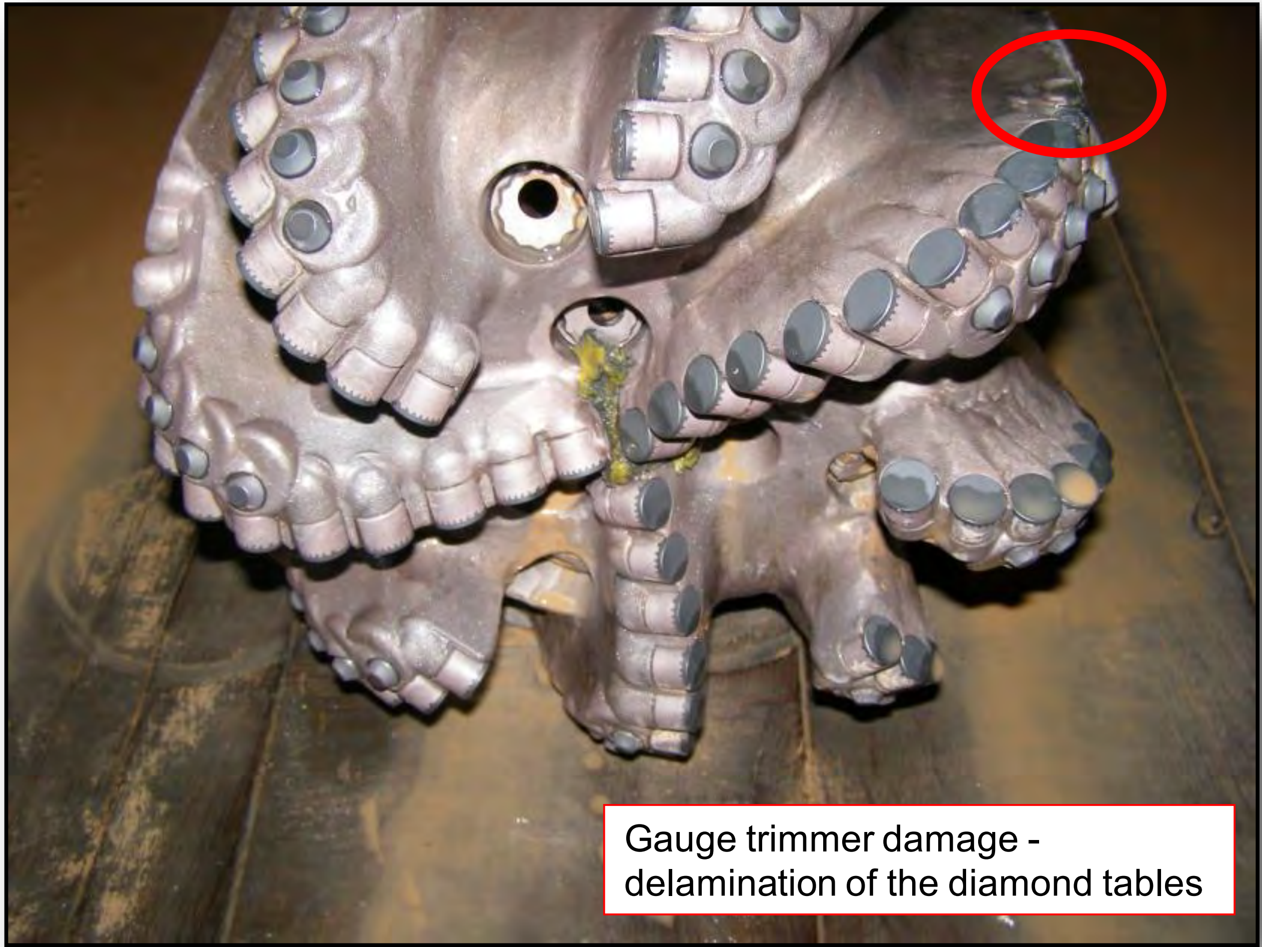


Axial Load Can be Combined with Thermal Loads

Lateral Vibration / Reverse Whirl



Damage During Drillout or Reaming Off Bottom



Gauge trimmer damage - delamination of the diamond tables

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Possible gauge pad rounding due to whirl….hard to confirm from this angle.

Note: gauge trimmer damage - delamination of the diamond tables, from drilling out inside of casing.

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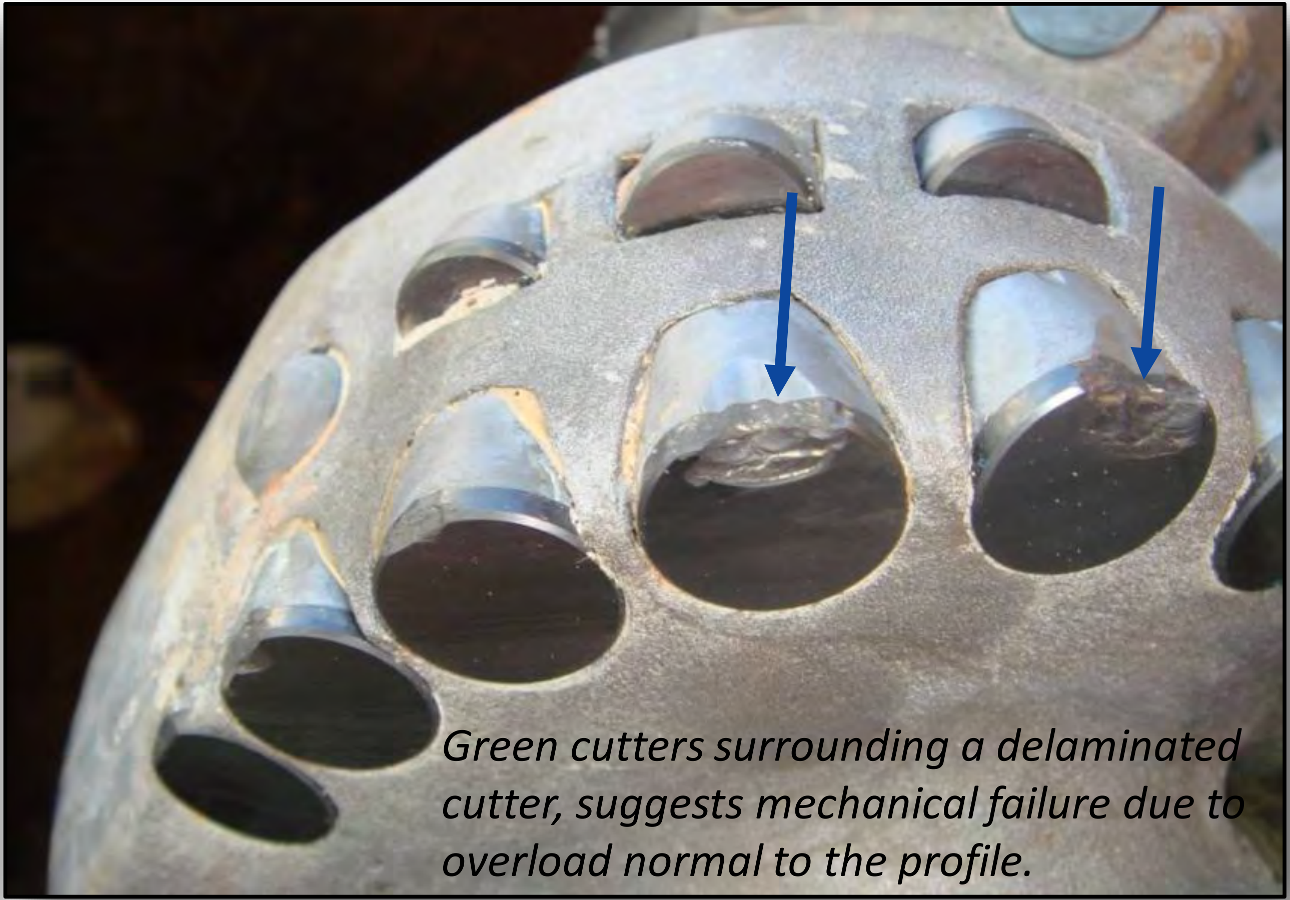
Axial Vibration and Impact



Green cutters surrounding a delaminated cutter, suggests mechanical failure due to overload normal to the profile.

Axial Load Primarily Damages Nose

Damage to nose/inner rows

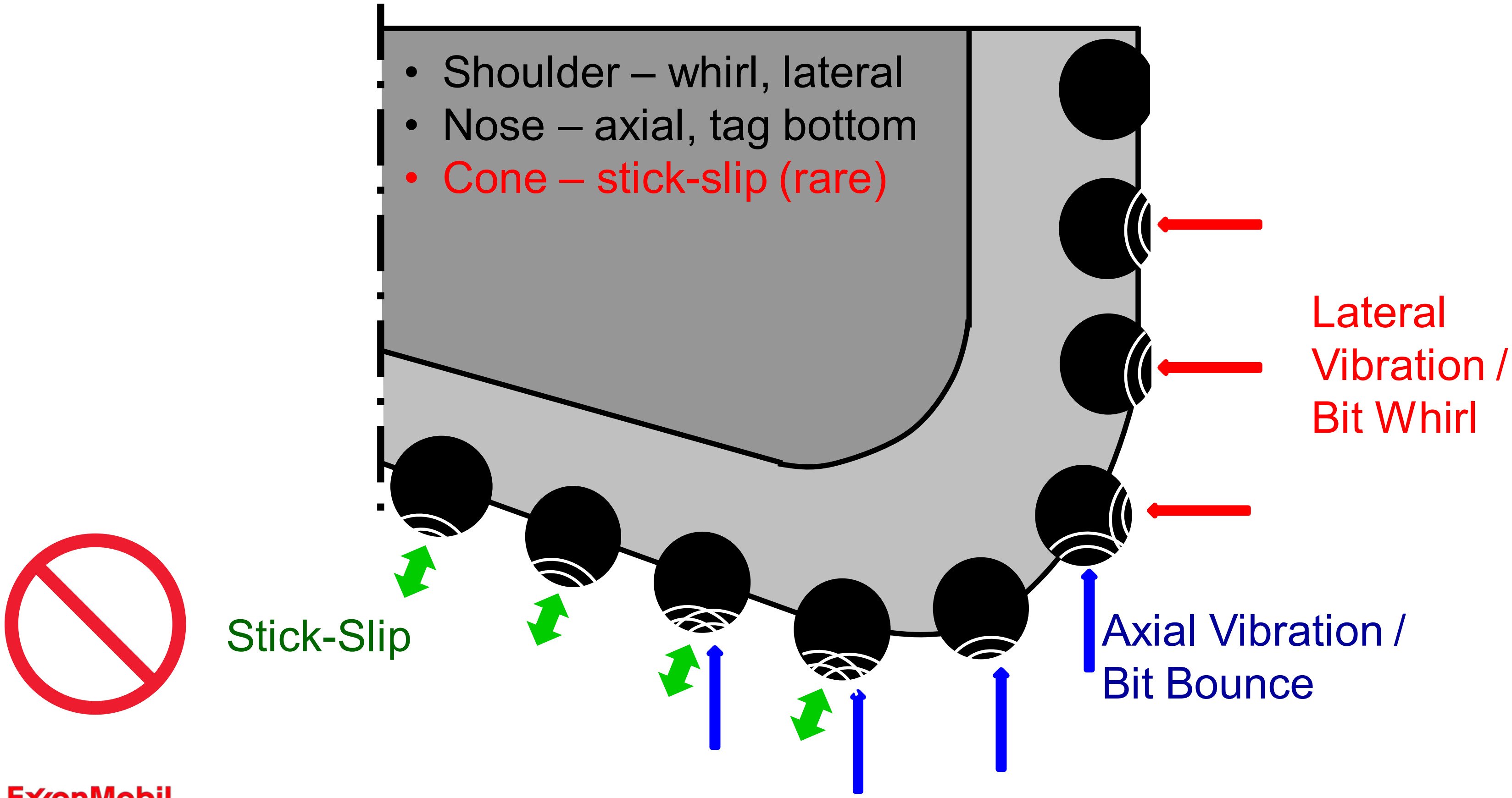
No uniform wear on outside cutters

Right Image Provided by Smith

Torsional Vibration and Stick-slip

- This slide is from around 2008
- Cutter spalling in the cone is very rare today even with severe stick slip due to cutter improvements
- I have dropped this slide from ExxonMobil training as cone spalling is no longer a good diagnostic for stick slip

Beach Marks Due to Edge Load ~Normal to Profile



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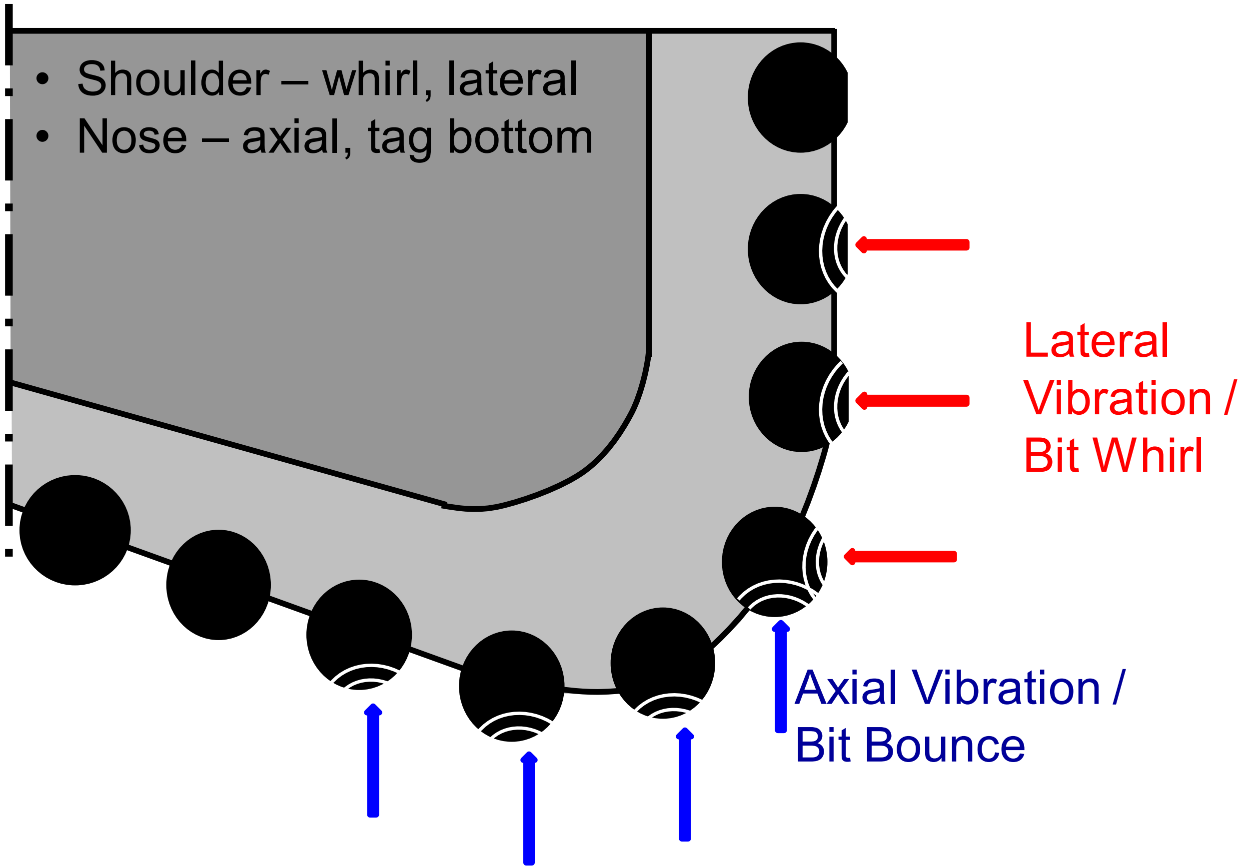
Beach Marks Due to Edge Load ~Normal to Profile



Questions

Learnings Check

- What documentation do you need for a case study?
  - Photos of the bit and all BHA components
  - BHA Information
  - Daily Reports
  - Digitial Surface (1 sample/sec)
  - Downhole Data (telemetry and memory)
  - Formation information

- What is the effect of load direction on failure load?
  - Diamond table is strongest in compression
  - Failure is more likely if the table is put in tension

Learnings Check

- What indicates the fracture initiation site for beach marks?
  - Center of the elipse
- What is the general direction of motion for beach marks?
  - Cutter edge loading
  - Normal to the profile
- On what area of the bit will I see beech marks for

  a) whirl, b) stick-slip, c) axial vibration?

  shoulder cone nose

Plastic Hinge

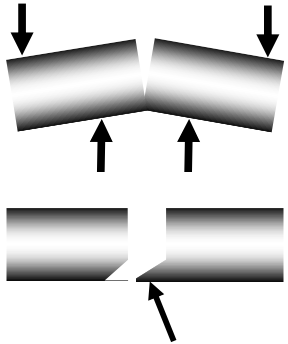
Hands on demonstration

Trial One

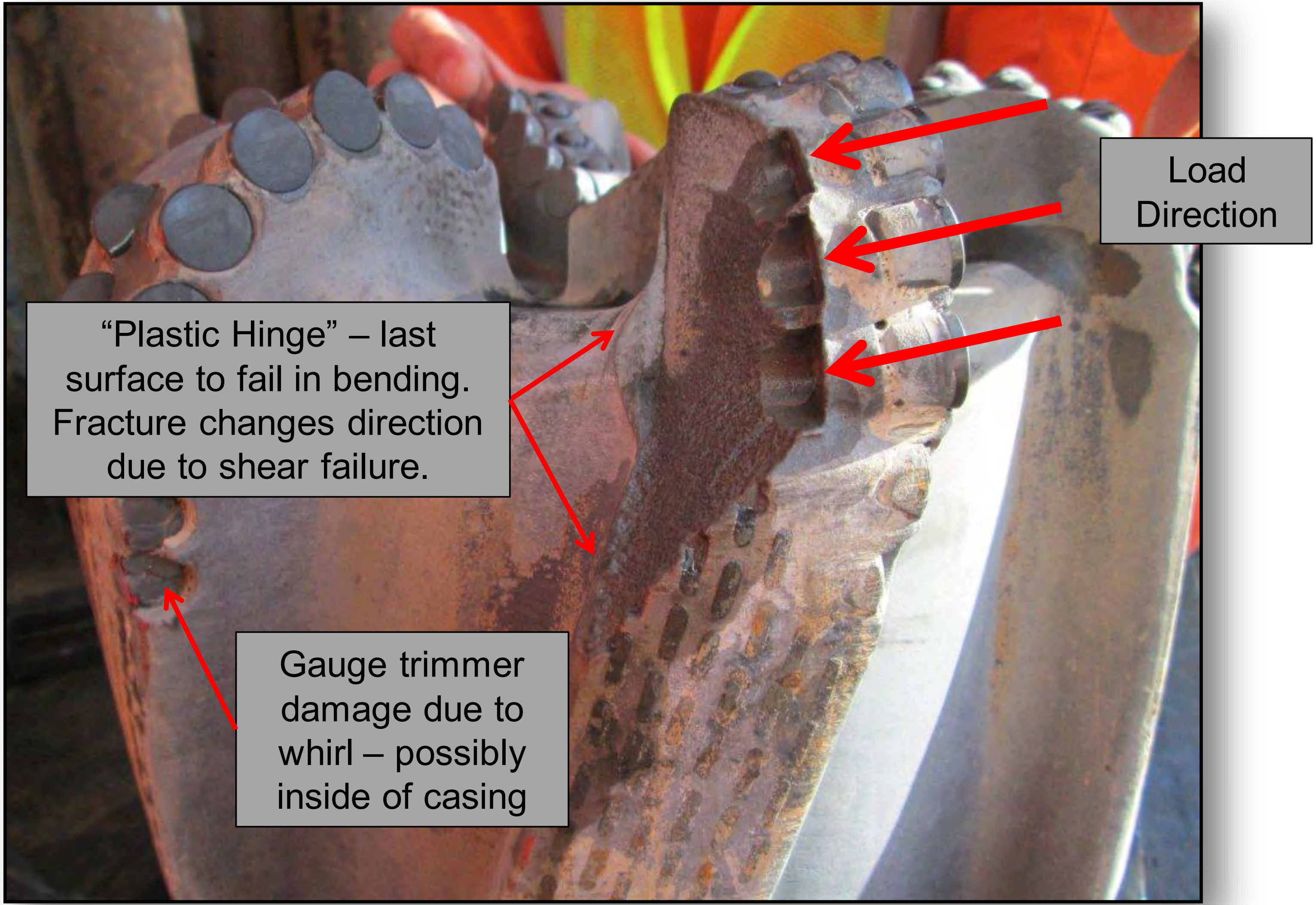
- Apply 1-2 lbs of compression along the axis
- Break chalk in bending

Trial Two

- Apply 1-2 lbs of tension
- Break chalk in bending



Plastic Hinge in compression
(last material to break)


Load Direction
“Plastic Hinge” – last surface to fail in bending. Fracture changes direction due to shear failure.
Gauge trimmer damage due to whirl – possibly inside of casing

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Plastic Hinge

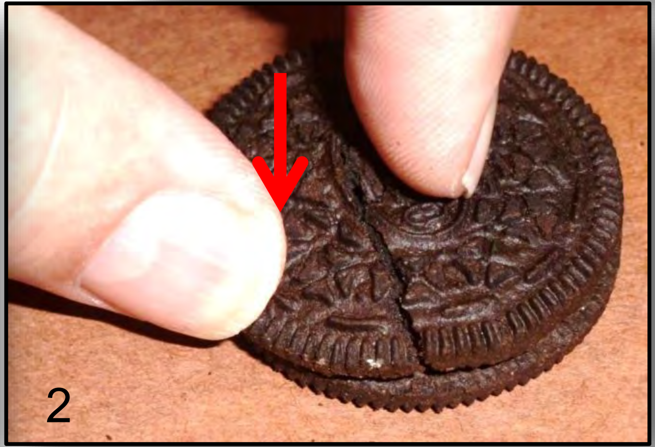
- When a plastic hinge is present it can be used to indicate the load direction.
- Indicates compression, the last material to break.

Blade Breakage Direction – Where is the Plastic Hinge?

Oreo Cookie – Cutter Tangential Fracture Toughness

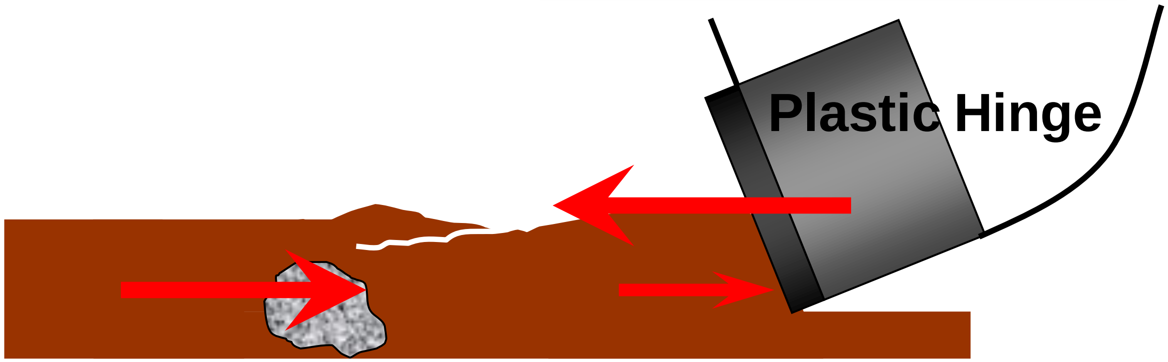
Hands on demonstration

- Trial
- Place the cookie on the table
- Hold it down in the middle
- Apply load to one edge until it fractures

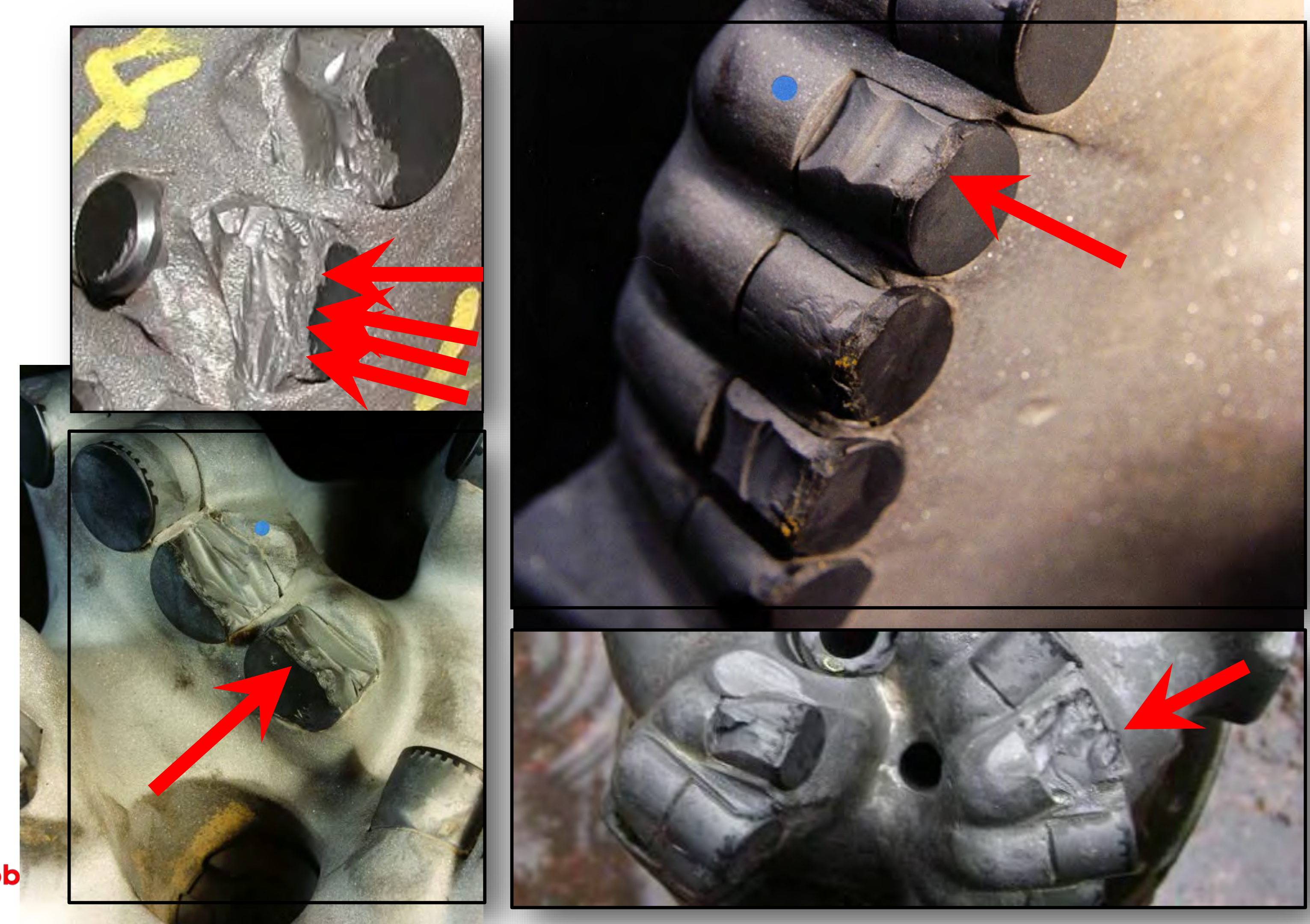


Tangential Cutter Fracture

- Over stressed in tangential cutting direction
- Fracture is back through diamond and into carbide substrate
- Stiffness Difference - Young's Modulus
  - PDC Diamond 140 x 10^6 psi
  - WC Substrate 90 x 10^6 psi
  - Steel 30 x 10^6 psi



Load F_t Tangential to Edge



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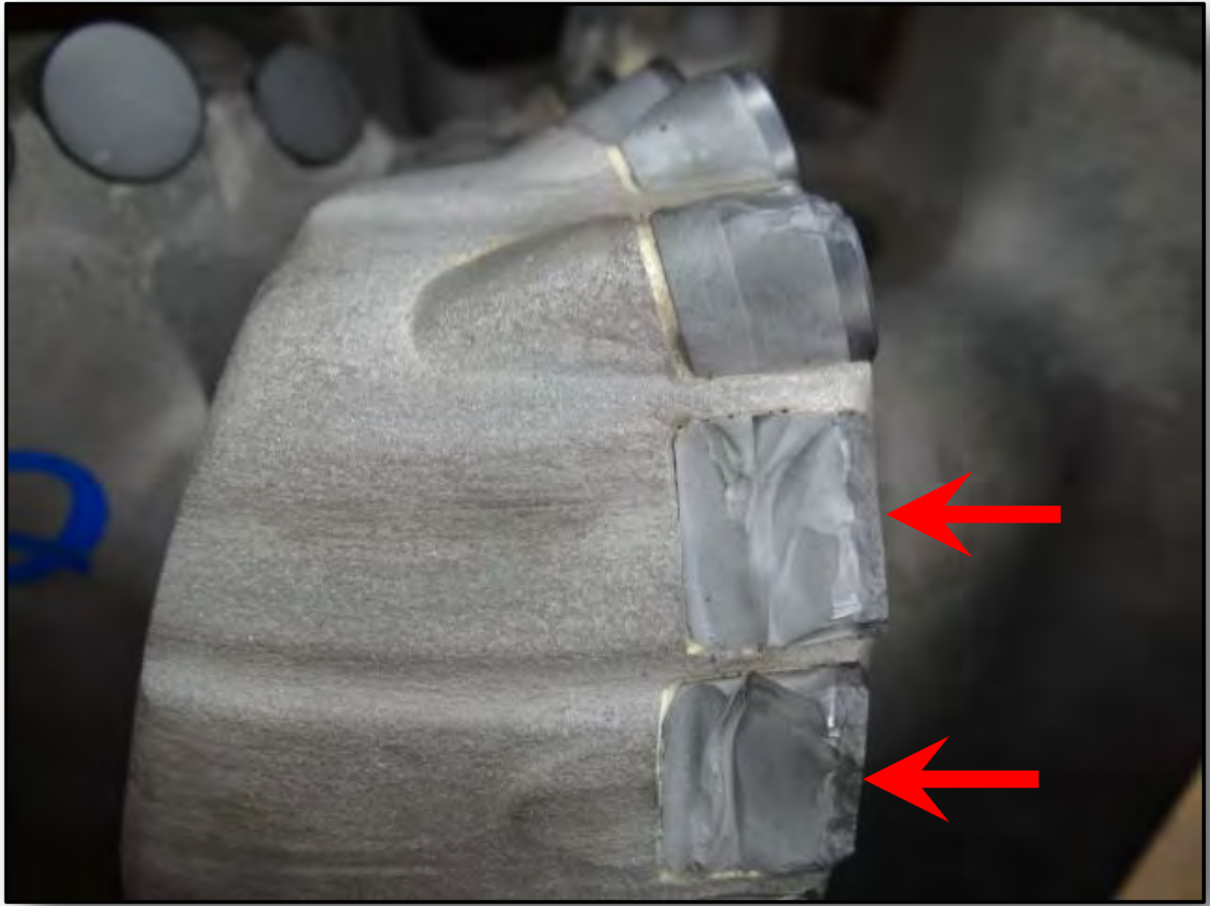
Tangential Cutter Fracture



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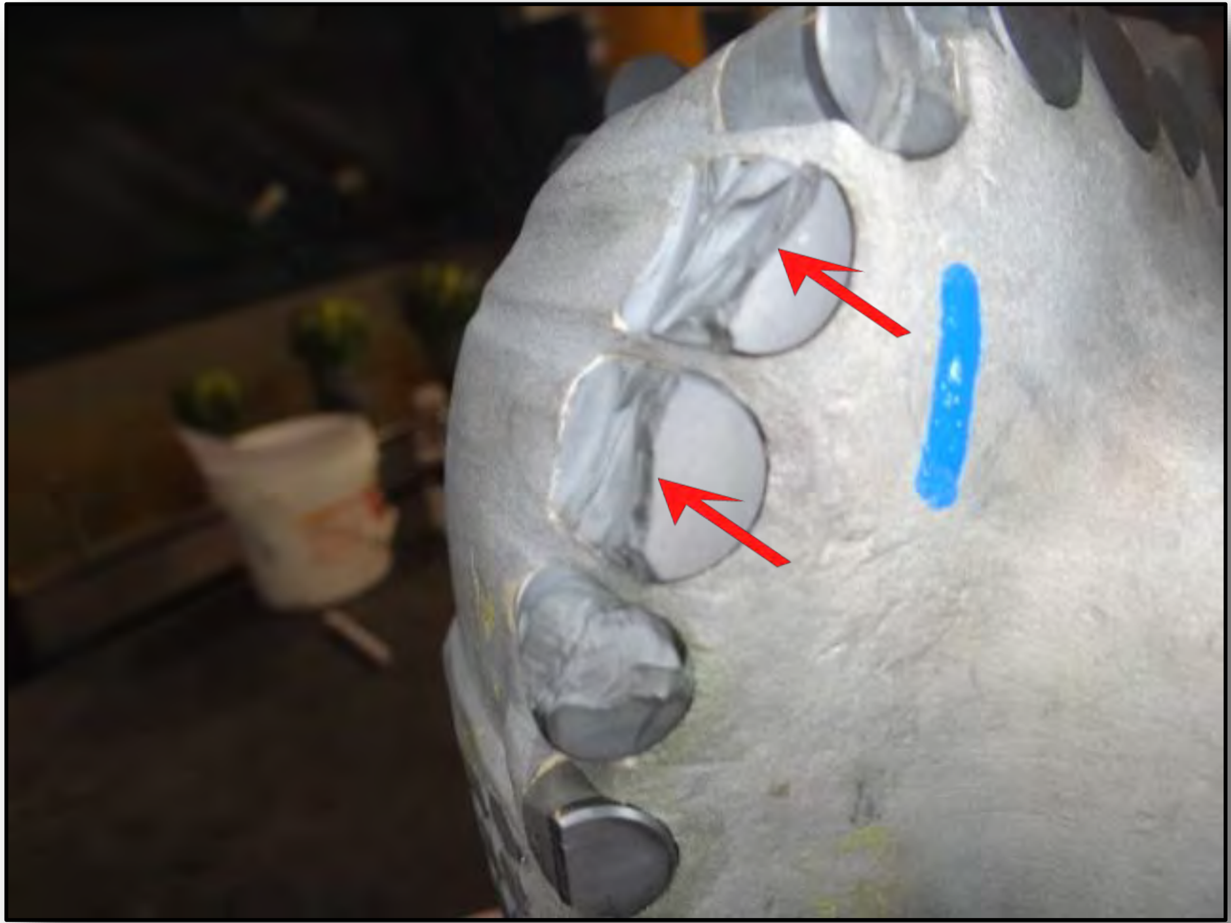
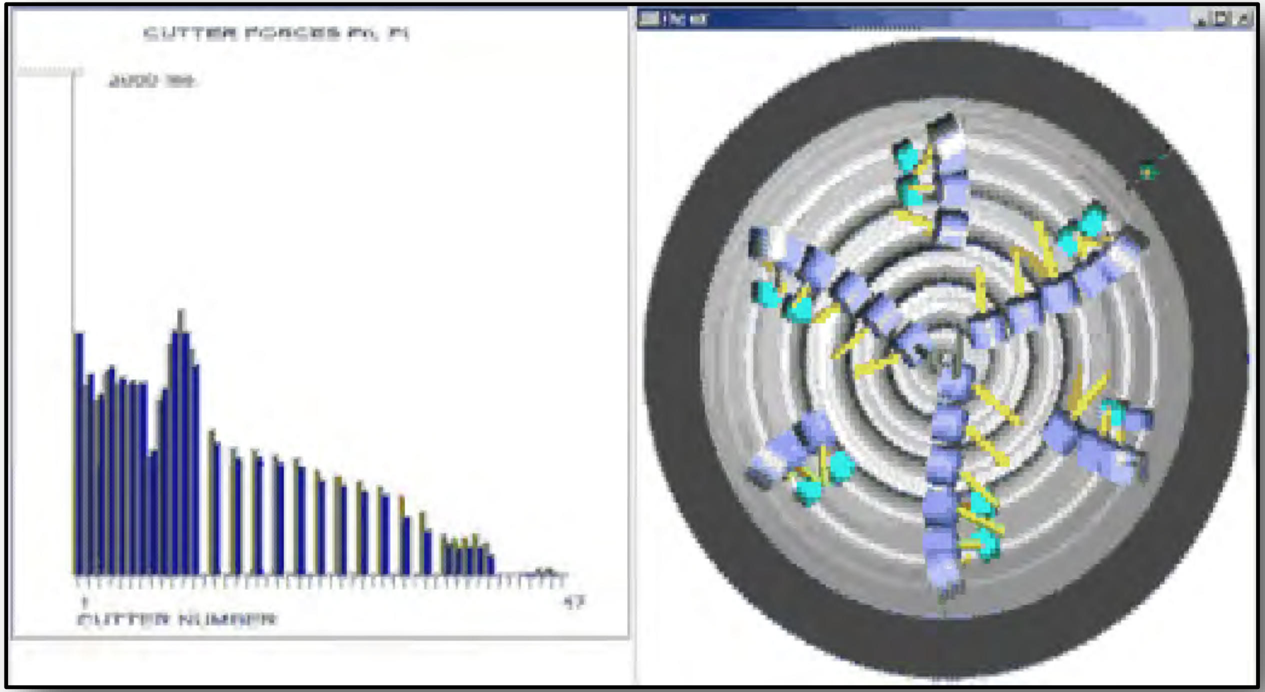
Tangential Cutter Fracture



Structural Limit - Interbedded Formation



Highest load per cutter inside cone until…

- Soft to Hard formation transition
- Highest load per cutter on the nose

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Animation courtesy Baker Hughes

For interbedded formations select cutters for fracture toughness in tangential direction

Structural Limits

- Core Out
  - Highest load per cutter in the center
  - Least overlap, yet least wear due to least sliding
  - In uniform rock – bit will core out due to excess WOB
- Tangential cutter fracture on the nose
  - Look for interfacial severity
  - Also look for potential of drill out damage
- What do you do when you reach the Structural Limit?
  - Redesign the limiter

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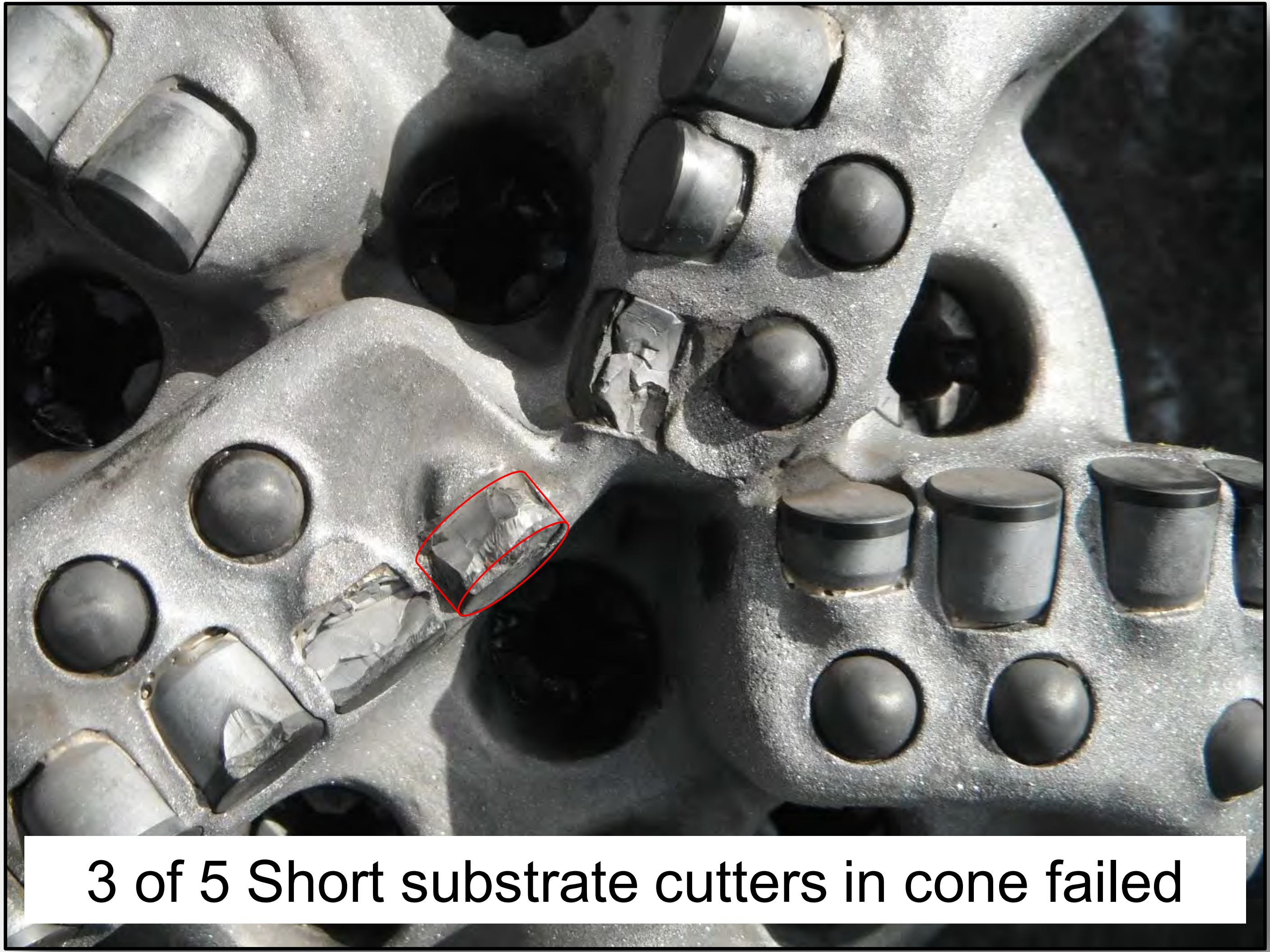

3 of 5 Short substrate cutters in cone failed

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Structural Integrity

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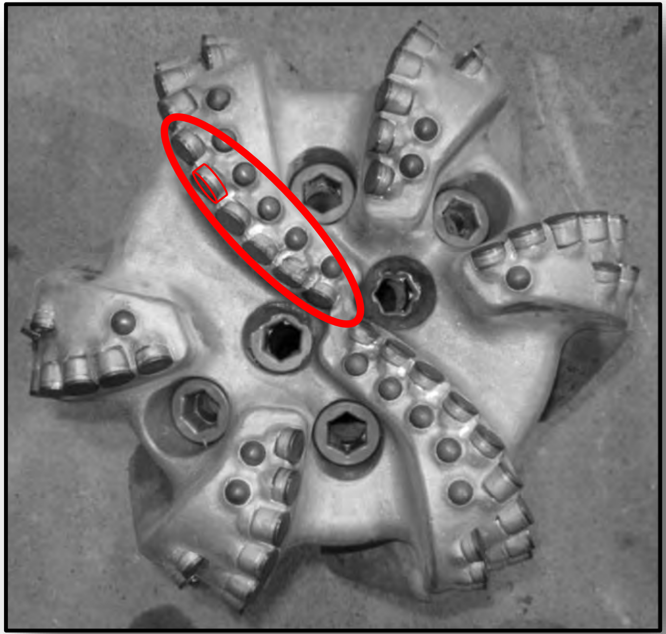
Core Out – What can we do about it?



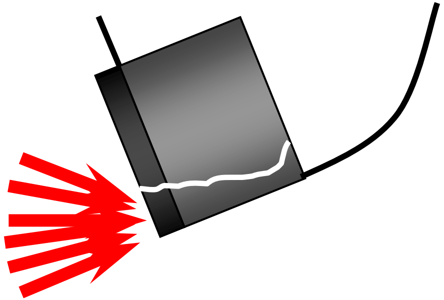
Recommended Design Changes

1. Put long Substrate cutters in center
2. Three-blades-to-center

Improving Structural Integrity - Recommendations

- Select bits with three blades to center
- Avoid short substrate PDC cutters everywhere
- Avoid bits with smaller cutters inside the cone
- Work with vendors to select cutters based on tangential fracture toughness (Engage Drilling Technical for help)

- Push for more fracture resistant cutters
- Current 8 ½ WOB Limit - 77klb (50klb downhole)
  - 3 blades to center, long substrates, 16mm



- Vendor Challenge: Develop models and lab tests to measure and improve structural integrity

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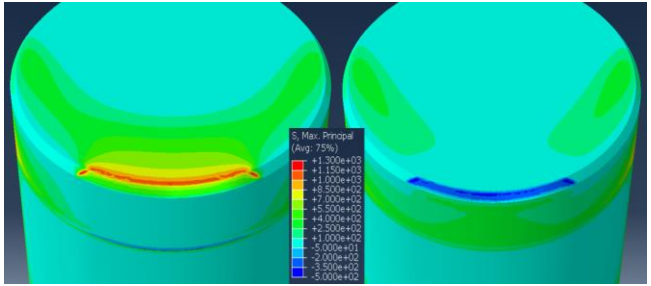
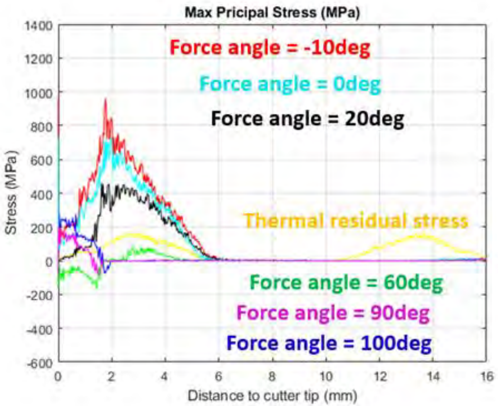
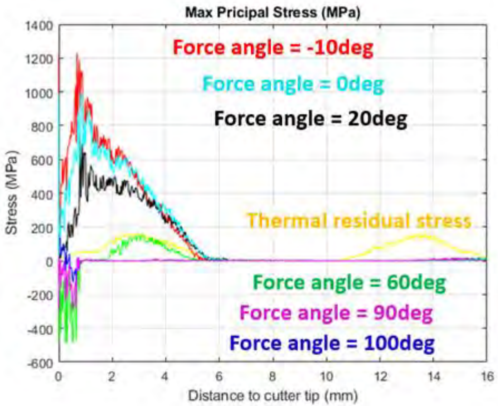
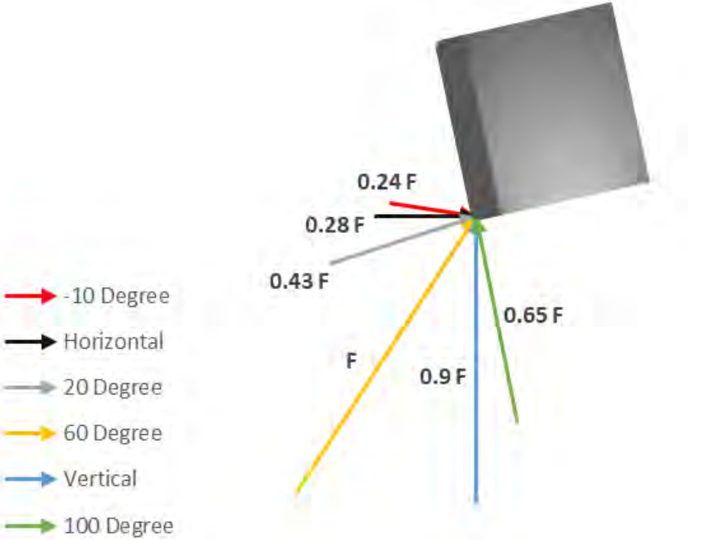
Load to Failure vs Load Direction

- Concentrated load to edge chamfer only
- Compute the stress level in the cutter vs direction
- Relate load direction to the load to failure









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Ref: SPE 199598-MS

Summary: Tangential Fracture Toughness – Oreo Cookie Break

- Inside Cone – Drill-out damage, Excessive WOB, Stick-Slip
- Trimmers Only - Whirl in casing
- On Nose – Hard formation transition, Junk damage
- Just Outside Nose – Hard formation transition with bedding angle
- Random - Interfacial Severity
  - Chert, Pyrite, Conglomerates, Inclusions, Junk
- First Cutter of Secondary Blades - Substrate erosion

Questions

Learnings Check

- What is the general load direction for the Oreo-cookie break?
  - Tangential – in the cutting direction
- When am I likely to see tangential cutter fracture?
  - Formations with interfacial severity, junk damage, excess WOB (core out), drill out damage
- On what area of the bit will I see tangential fracture for

  a) excess WOB, b) drill out damage, c) interbedded formations?

  Cone Gauge trimmers Nose
- What design features should be checked if tangential cutter fracture is occurring?
  - No small cutters, Long substrate cutters, Three blades to center, Cutter selection

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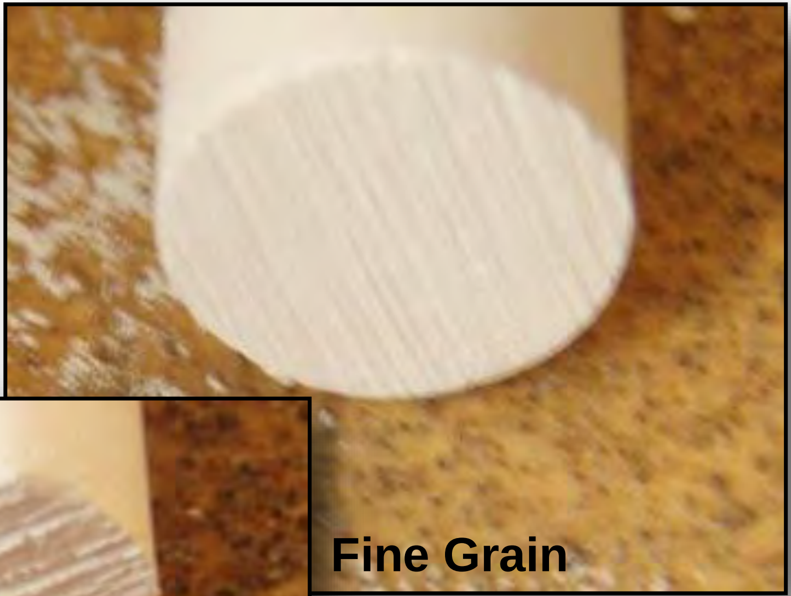
Reading Wear Scars

Hands on demonstration

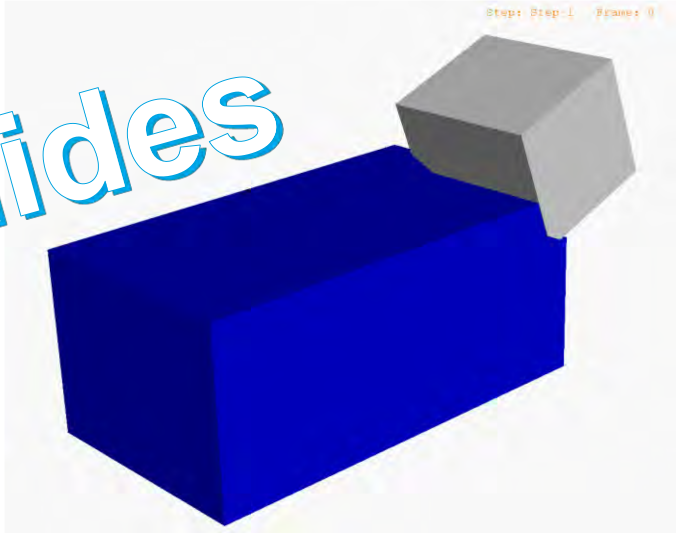
- Determine
- Surfaces in Contact
- Direction of Motion
- Wear Particle Sizes
- Heat Generation vs. Wear



Smooth Cutter Wear

With no vibration or overload, cutters will wear smoo
Smooth Wear is function of:

- material flow below the cutter (sliding distance)
- contact pressure, remember this equals rock stren independent of depth of cut
- abrasiveness (quartz content, size, and shape) – a



Animation courtesy Baker Hughes

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Smooth Cutter Wear

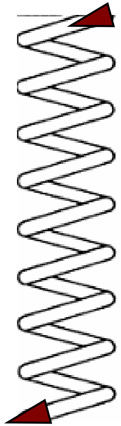
Smooth Wear = f (sliding distance, the only thing you can control)

Increasing WOB

- increases depth of cut (DOC - in/rev) → reduces revolutions required to drill a given distance → reduces sliding distance (rev/ft) → reduces wear

Example: To drill 100 feet at 120 RPM the outside cutter of an 8-1/2” bit slides:

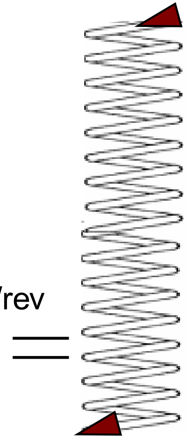
16,000 ft @ 100 fph



0.16 inch/rev

32,000 ft @ 50 fph

0.08 inch/rev



ExxonMobil

Smooth Cutter Wear

When do I stop adding WOB?

Smooth Wear = f (sliding distance, th

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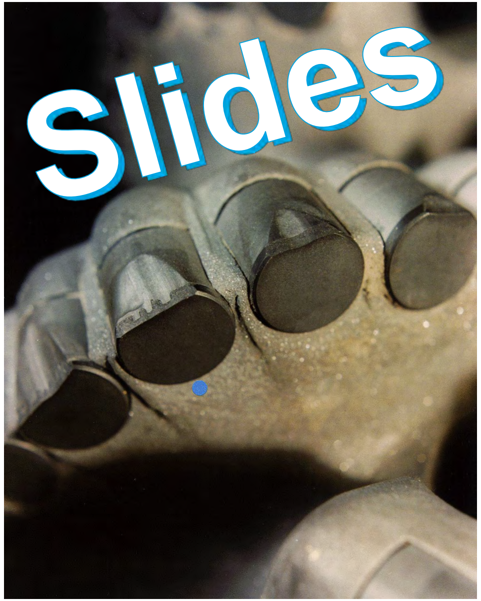

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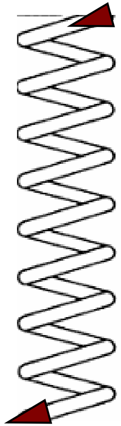

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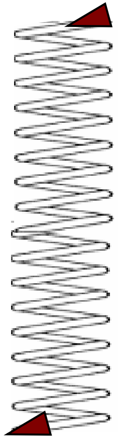

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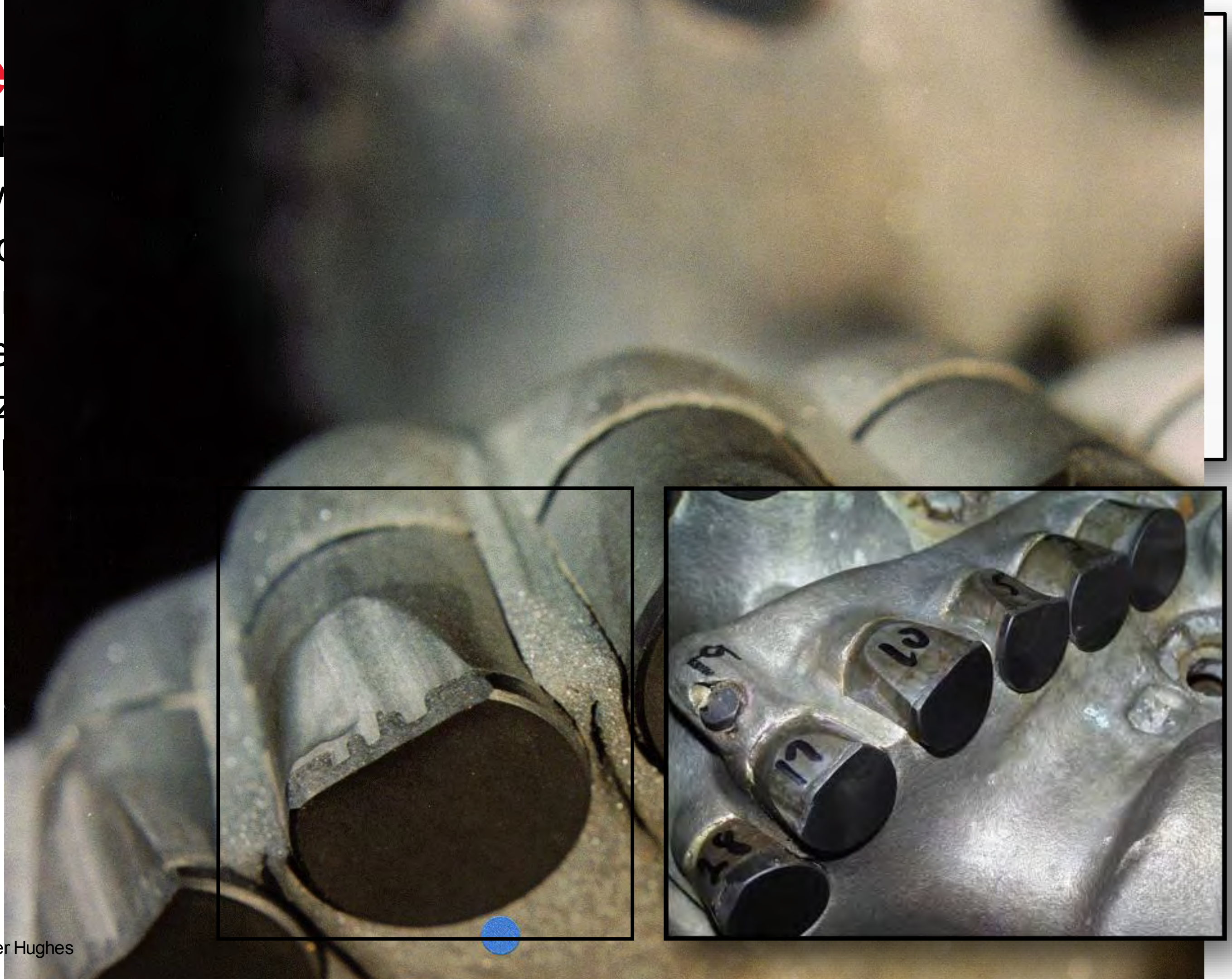
Smooth Cutte

Without vibration, mec
overload, cutters will w
Smooth Wear is functio

- Contact pressure, re
  strength, it is indepe
- Abrasiveness (quartz
- Material flow below t
- Cutter temperature



Animation courtesy Baker Hughes

Smooth Cutter Wear

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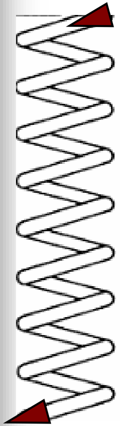

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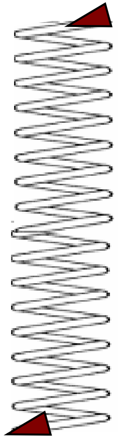


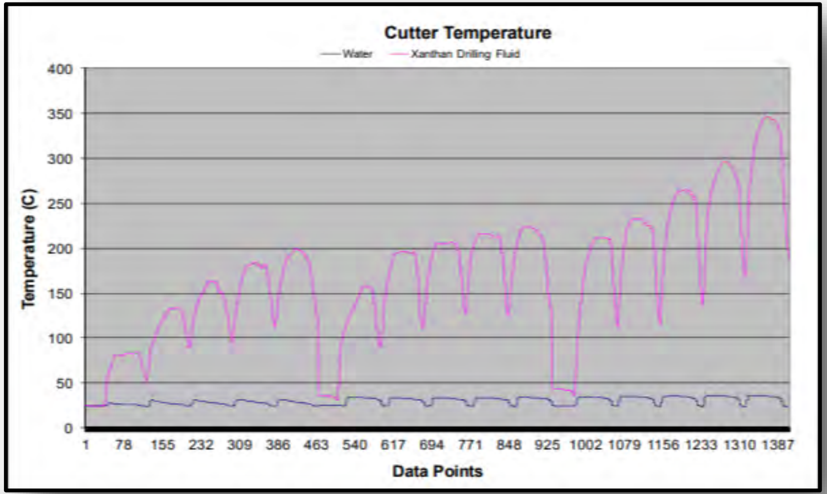
Smooth Cutter Wear

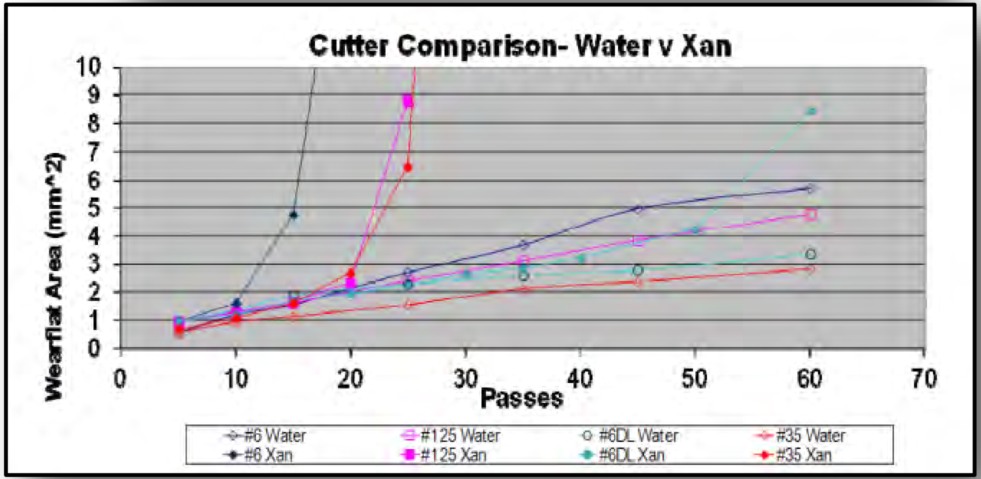
Smooth Wear = f (sliding distance, and temperature)

Cutter temperature is a function of:

- Mud heat capacity, surface film – water is best
- Wear flat area – wear can go non-linear
- Sliding speed – Radius and RPM
- Local mud velocity (CFD, 2nd nozzles)
- Rock strength
- Abrasiveness (abrasive formations carry heat away from wear flat, non-abrasive heat cutters)
- Depth of cut – temperature increases only slightly, the ribbon carries away most of the energy & heat

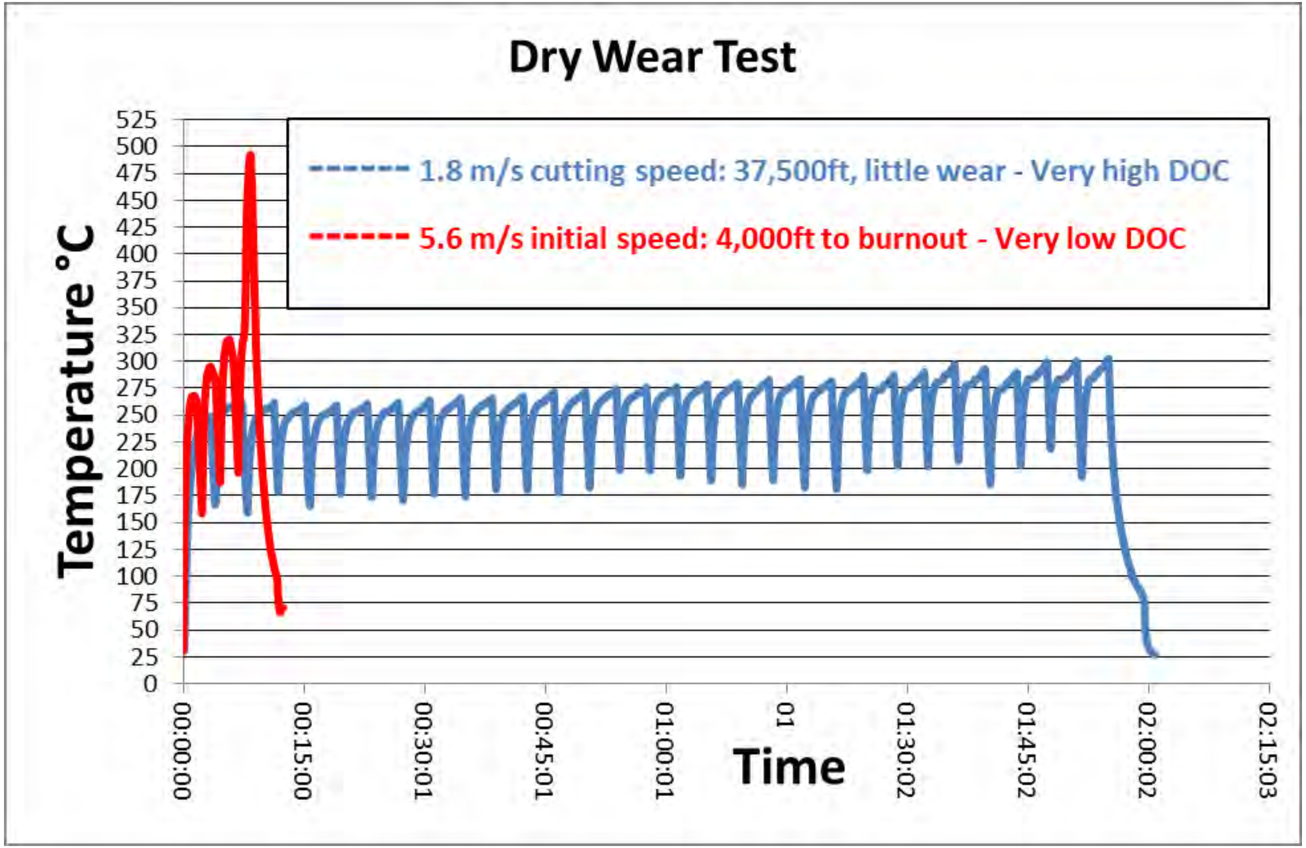
- Cutter thermal stability





Ref: AADE12-FTCE-38 Freeman 2012

Damage vs Temperature



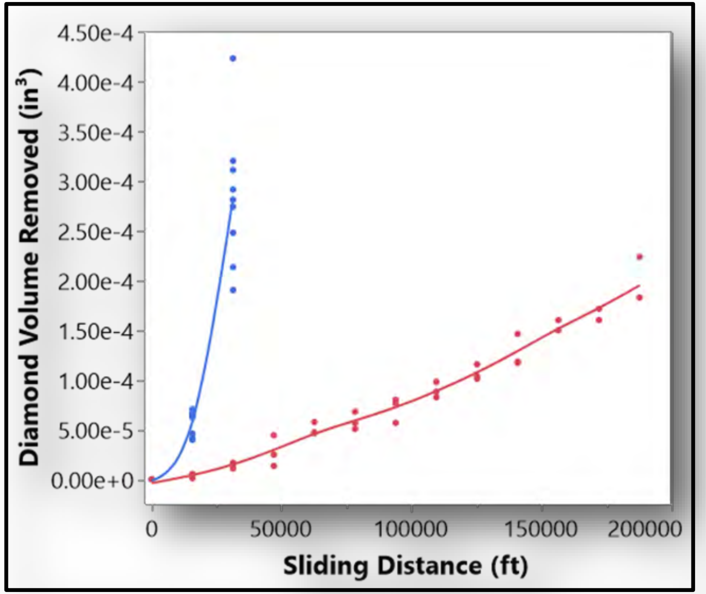
Note that damage is a strong function of temperature.

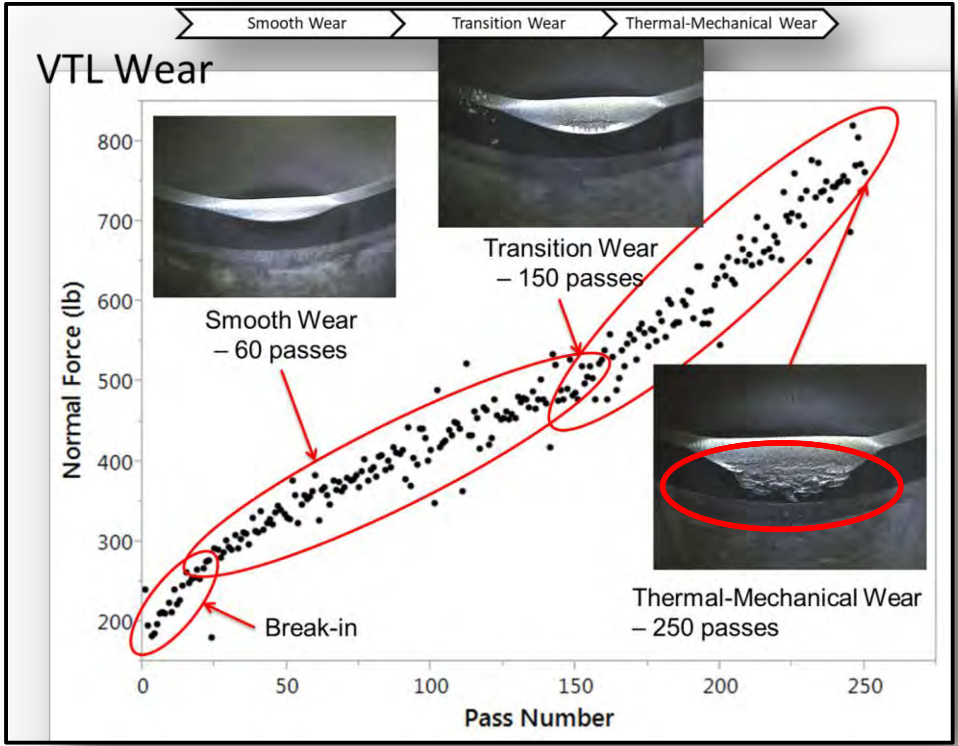
Temperature is affected by RPM and wear flat size.

Below the thermal limit, the wear is linear with sliding distance.

Graphic courtesy of NOV

Smooth Wear to Thermal-Mechanical Damage





The "red" cutter is more thermally stable and therefore has a more linear wear progression than the "blue" cutter. Once the blue cutter starts wearing it heats up and the heat rapidly degrades the cutter.

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Charts courtesy of US Synthetic

Spalling Can Be Due to Combined Thermo-Mechanical Effects

(a)Micro-spalls along wear flats - thermal; (b) Spalling of thermo-mechanical origin

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REF: *Classification of Polycrystalline Diamond Compact (PDC) Cutter Damage* Witt-Doerring 2021

Mechanical, Then Wear, Then Thermal Damage

- Localized shoulder damage
- Smooth wear should be more uniform
- This suggests fracture, followed by wear, followed by thermal spalls

Heat Checking in Non-abrasive Hard Formations

Smooth Cutter Wear

Smooth Wear = f (sliding distance, and temperature)

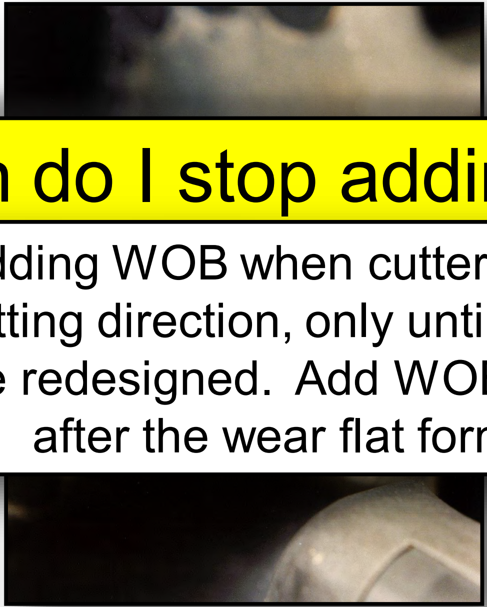
Increasing WOB

- increases depth of cut (DOC - in/re
  distance → reduces sliding distance (re

Example: To drill 100 feet at 120 RPM ... s:

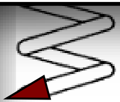
When do I reduce RPM?

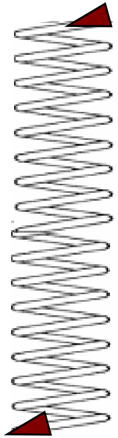
Lower RPM when you see thermal damage, only until the limiter can be redesigned.



16,00
@ 100 fph

32,000 ft @
50 fph





When do I stop adding WOB?

Stop adding WOB when cutters fracture in the cutting direction, only until the limiter can be redesigned. Add WOB early, not after the wear flat forms.

/rev

08 inch/rev

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Questions

Learnings Check

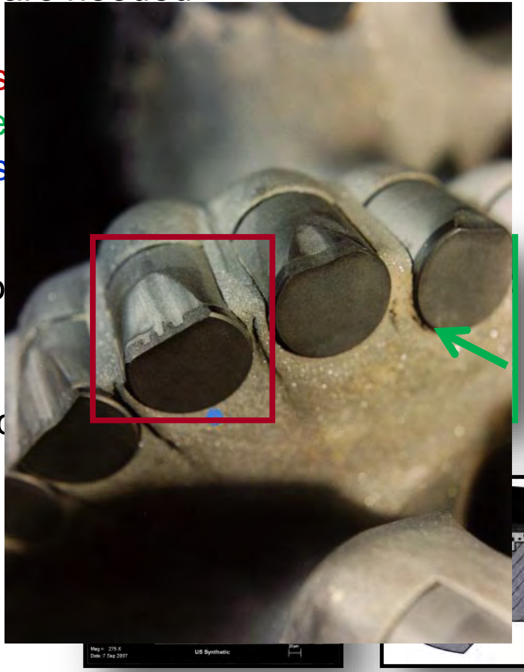
- We drill into a formation that has 2X compressive strength and we double the WOB, what happens to the ROP? What happens to wear?
  - ROP is the same.
  - Wear goes up 2X: same sliding and 2X the strength
- We drill into a formation that has 3X higher compressive strength with the same parameters, what happens to the ROP? What about wear?
  - ROP drops to one third. Wear goes up **9X**
  - 3X the sliding distance and 3X the strength
- If we drop WOB in half and double the RPM, what will the ROP do? What will the wear do?
  - ROP is unchanged. The bit will turn 2X revolutions thus 2X wear…if we don't vibrate or thermally overload the cutters.

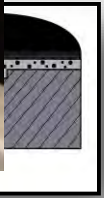
Cutter Material Selection and Types

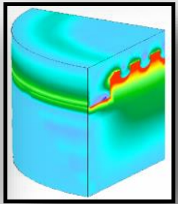
- There continue to be major improvements in PDC cutter technology
- Work with vendors to pick cutters based on the specific application and damage
- Pick a bit service company that has an active well documented lab and field trial process with low latency
- Service companies should provide test data on both tangential and axial fracture toughness – both are needed
- Insure they select

❑ smooth wear resis
❑ tangential fracture
❑ axial fracture resis
❑ thermal stability

Vendor Design Optio
- Grain size
- Layered material
- Treated – leachec
- Thermal stability
- Residual stress
- Interface design







Graphics courtesy of US Synthetic

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Erosion and Wear - markers of time and flow direction

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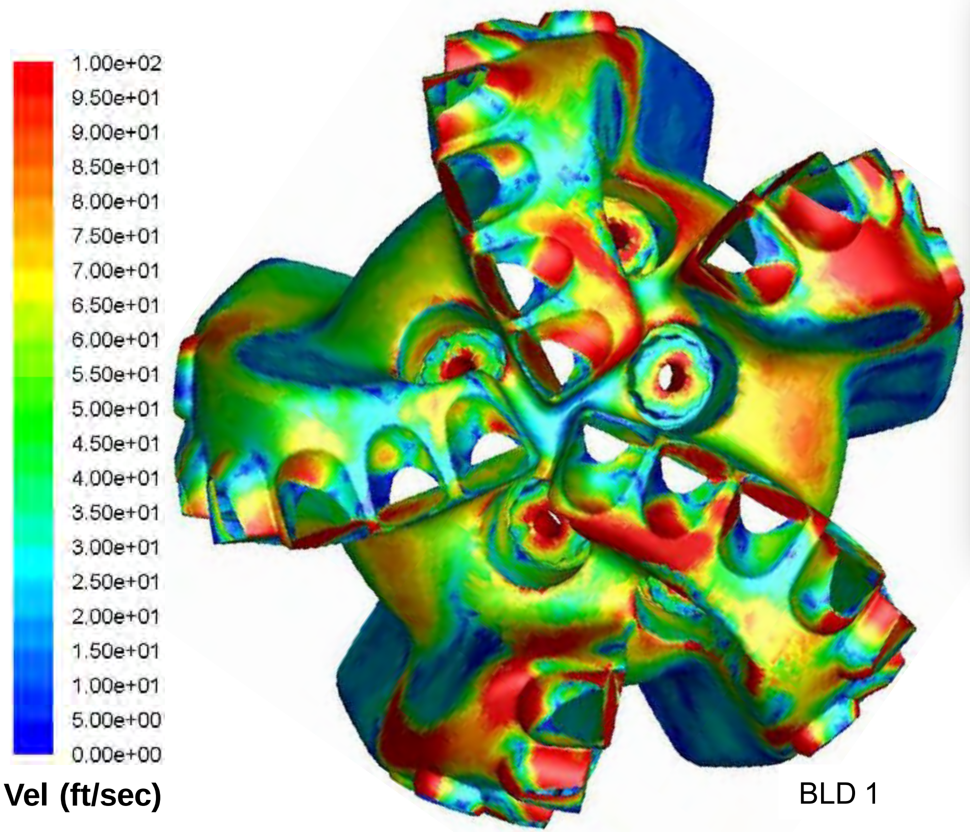
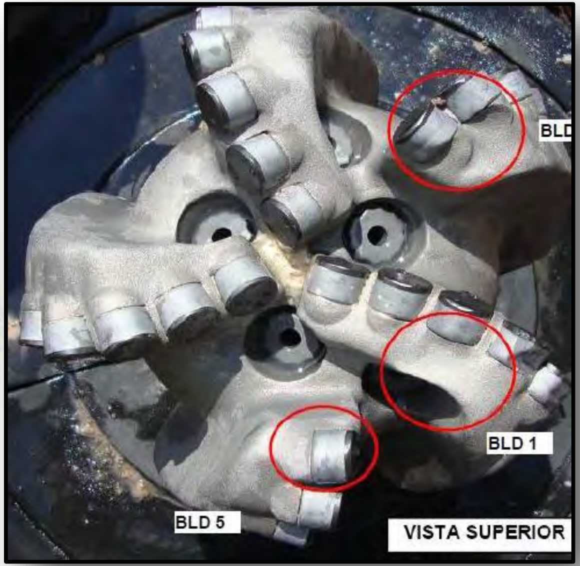
Nozzle Orientation and Erosion



Vel (ft/sec)

BLD 1

BLD 5



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Graphics courtesy of Halliburton

Cutter Corrosion – Diagnostic for other BHA damage

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Pitting Corrosion in High Stress Areas

Graphics courtesy of PV Fluids

BHA Forensics

Reverse Bit Whirl

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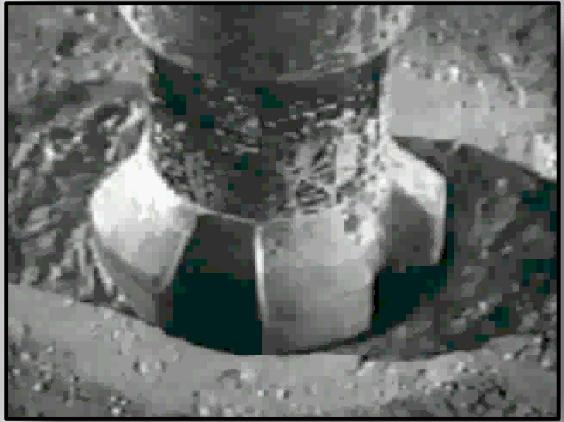
Forward Bit Whirl



Video courtesy of Baker Hughes

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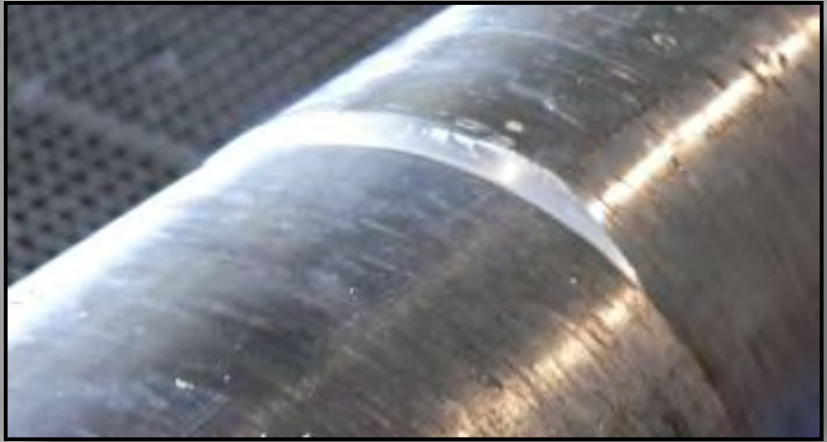
Forward Bit Whirl – uneven wear per side

Forward BHA Whirl

- Diagnostics
- BHA bending
- Eccentric BHA wear scars



Photos courtesy of Baker Hughes
Video courtesy of Schlumberger

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Forward BHA Whirl

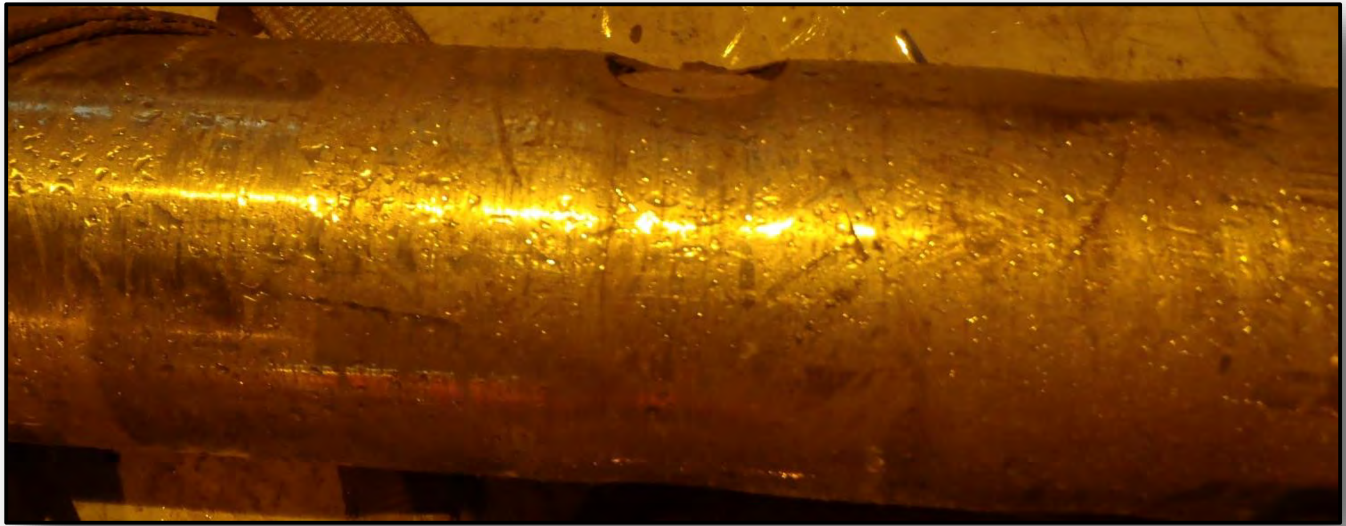
Forward BHA Whirl

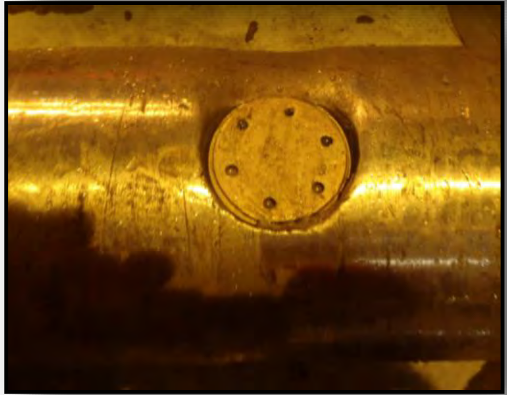
Forward Whirl – How bad can it get?

Drill Pipe / Tool Joint

In Line Stabilizer

Reverse BHA Whirl





Video courtesy of Schlumberger

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Reverse BHA Whirl

Reverse Bit whirl and Reverse BHA whirl
Severe nicks and dents on MWD are due to embedded broken inserts

Graphics used with permission of Baker Hughes

Mitigation

Increase WOB to suppress bit whirl

Change the RPM away from the natural excitation frequency

Change the natural frequency away from the required RPM

- Change mass
- Change stabilizer spacing
- Improve damping

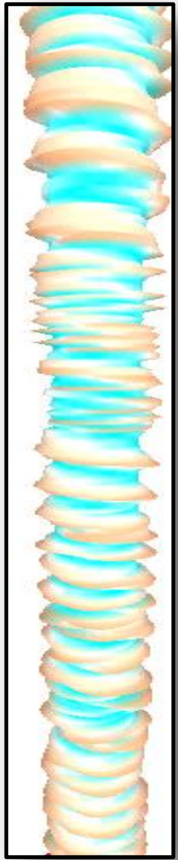
Reduce friction forces

- Improve borehole quality
- Replace stabilizers with roller reamers
- Add mud lubricants
- Trial low friction stabilizers

Reduce WOB if buckling or redesign BHA

Bulged pipe from compression fatigue with reverse whirl

Spiral Patterns Induce Stabilizer End Wear



Borehole pattern
from Piceance
Creek, CO

Photos courtesy NOV

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Stabilizer End Wear is Diagnostic for Patterns

The formation is abrasive, but this wear is due to the stabilizer drilling on a pattern or multiple ledges.

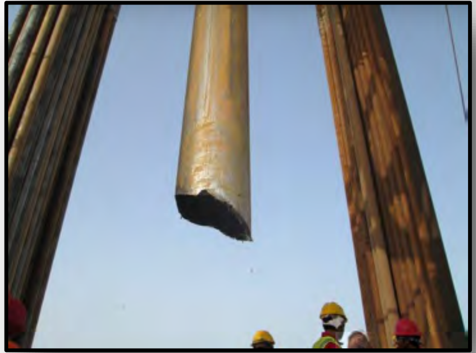

6 ¾ PD Xceed
8-1/8" Top Stabilizer

Spiral Patterns How bad can it get?

Graphics courtesy Halliburton

Graphics courtesy Halliburton

Torsional Failure and HFTO Damage – 45° Cracks



High Frequency Torsional Oscillation (HFTO) results in X shaped fractures due to stress reversals

Fracture perpendicular to the axis of the tool is due to bending fatigue.
Angle of fracture ø = 0°
This is not due to torsion.

DC image courtesy of Halliburton MWD image courtesy of Baker Hughes API Pin image courtesy of NOV

Questions

Learnings Check

- If you observe preferential wear on one end of a stabilizer (from the bottom up), what should you suspect? From the top down? How can you be sure?
  - Borehole patterns. Backreaming with Borehole patterns.
  - Review ADN and Photo electric Image logs. Look for pattern in near bit inclination data.
  - Run a caliper.
- What type of BHA damage should you see with forward whirl?
  - Smooth wear on one side of the tool. (Jump rope motion)
- You observe rounded gauge pads on a string stabilizer, what do you suspect?
  - Reverse whirl of the BHA, gearing motion
- When will you likely see heat checking?
  - High normal load in a formation with low abrasiveness

Learnings Check

- We raise our WOB from 25 to 50 klb and the ROP doubles. What happens to smooth cutter wear?
  - Sliding distance is cut in half, and wear is cut in half.
- What direction do cracks form for bending fatigue?
  - Perpendicular to the bending, typically perpendicular to the axis of the tool.
- What directions do cracks form for torsion?
  - 45° to the axis of torsion
- What cracks can form with high frequency torsional oscillation (HFTO)?
  - X shaped cracks – forward and reverse torsional loading

Bit Balling and Ribbon Flow

Bit Balling

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Bit Balling

Note cuttings on top of gauge pads. Did this occur on the trip out or while drilling?

Balling below the pads suggest it occurred while drilling.

Balling – Limestone with 20% clay

Bit Balling – NAF Mud

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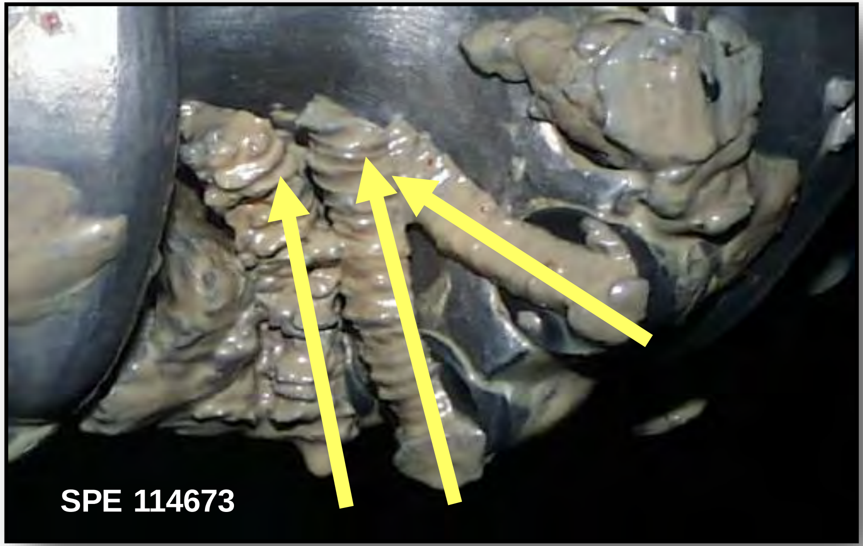
Ribbon Flow Affects Balling

- Check vendor's computational fluid dynamics (CFD) results
- Review vendor's cuttings trajectory model (and knowledge)
- Increase blade standoff inside cone (2-3 cutter diameters)
    - Look for and avoid choke points
    - Rule of thumb for blade clearance – 3/4 inch width
    - Deflect cuttings toward the bit OD and junk slots - Avoid convergence



Graphics used with permission Baker Hughes

12 ¼ Hibernia

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Balling – Laying Bricks

Ribbon Flow Problems

Where are the ribbons going to flow?
First 7 cutters have no clearance.

Cutters are recessed from front of blade, interfere with ribbon flow.

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Ribbon Flow Problems

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Ribbon Flow Problems – Body Erosion and Pack Off

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Questions

Learnings Check

- How much material accumulation is required to call it balling?
  - Any accumulation of cuttings that affect the bit loads.
- How hard are the ribbons when first formed?
  - Equal to or above rock strength if fine grained and low permeability
  - May be zero in high permeability sands
- Can the bit ball up with oil based mud? Can the bit ball in a limestone?

  Yes No & Yes – make sure it is a limestone and not marl
- How can we detect ribbon flow issues?
  - Ask vendors to show their ribbon flow model results
  - Look for insufficient chip flow clearance in front of cutters
  - Look for particle flow erosion surrounding the cutter

Summary

- Forensics Analysis Learning Objectives
- Observations and Documentation
- Bit Forensics
  - Reading Fracture Initiation and Direction of Loading
  - Bit Wear Scars – Mechanical and Thermal
  - Erosion and Corrosion
- BHA Forensics
  - BHA Wear Scars and Direction of Motion
  - Torsion and HFTO Loads
- Bit Balling and Ribbon Flow

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