AADE-13-FTCE-08

Innovative Rolling PDC Cutter Increases Drilling Efficiency Improving Bit Performance in Challenging Applications

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This paper was prepared for presentation at the 2013 AADE National Technical Conference and Exhibition held at the Cox Convention Center, Oklahoma City, OK, February 26-27, 2013. This conference was sponsored by the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individual(s) listed as author(s) of this work.

Abstract

Extended footage capabilities and high rate of penetration give PDC bits a distinct advantage over rollercone bits in many applications. However, the fixed PDC element creates an inherent limitation because only a small portion of the cutter contacts the formation, and as the cutters wear/chip drilling efficiency declines. The industry requires new technology that can effectively utilize the entire 360° diamond cutting edge to increase drilling efficiency and bit life. Numerous research studies indicate wear flats generate a high degree of frictional heat which breaks the diamond/diamond bond or can even convert diamond back to graphite in extreme cases.

A plan was initiated to rotate the cutter while drilling and engineers investigated different retention methods and cutting structure designs to create the optimal driving force to accomplish the objective. Several designs were implemented that hold the cutter securely in place and allow full cutter rotation. These assemblies were extensively modeled using FEA and laboratory tested to evaluate function and strength. In a test apparatus, the new shearing element (rolling cutter/RC) was able to cut an extended section of rock with a consistent force level (lbs).

Conversely, the traditional fixed-cutter assembly required steadily increased force to drive the cutter the same distance. Examination of the rolling cutter's dull condition clearly indicated significantly improved durability and cutting efficiency.

Initial field testing targeted the highly abrasive Granite Wash formation in Western Oklahoma/Texas Panhandle where cutter wear is the predominant failure mechanism. Application challenges include slow ROP and premature tripping for a new bit. A six-bladed prototype PDC bit was manufactured with three rolling cutters positioned in the shoulder area. The bit was run on a steerable motor through the horizontal interval with good results.

The next prototype was equipped with additional RCs and drilled more footage compared to offset average. Additional experiments are being conducted with RCs which will continue to increase performance. The authors will present several case studies which will document performance improvement in challenging drilling environments.

Introduction

Drilling with PDC bits in hard and abrasive formations has always been challenging, specifically for the shearing elements. An industry-wide effort to improve PDC bit performance has resulted in more efficient drilling in terms of reduced bit usage per hole interval while shortening time to production.[1-6] A survey that includes data through the end of 2011 indicates that over 70% of worldwide drilling is done with PDC bits.

The PDC bit encroachment into traditional rollercone applications began because of a PDC bit's ability to drill longer intervals at higher penetration rates. However, efficiently drilling with PDC bits in very hard and highly abrasive formations remained challenging. In 2003, a leaching process was introduced to enhance thermal stability which led to improved abrasion resistance of PDC cutters.[7] The challenge still exists to further improve PDC drilling efficiency and lower overall project costs in hard and highly abrasive formations.

Fixed Cutter Wear Mechanism

When a PDC cutter is shearing the rock, the cutting tip in contact with formation will gradually dull due to abrasive wear while severe frictional heating is building at the contact point leading to elevated temperature. This extreme temperature causes accelerated cutter wear, especially in non-leached cutters. More wear generates more heating. More heating induces more wear. Therefore, PDC cutters have limited life when drilling hard and abrasive formations. To break this cycle, it is critical to keep the cutting tip sharp and cool.

When grading dull PDC bits, most of the wear is observed on a small portion of the cutting edge, while a larger portion is still sharp. If a mechanism could be implemented to evenly spread wear over the full cutting edge bit life would be significantly increased. Such a device would allow the cutting edge to stay sharp for an extended period of time. This could be achieved if the cutters are rotating while shearing formation. Rotation will evenly distribute wear and also effectively cool the cutter thus increasing service life. An R&D effort was initiated to explore this concept.

Functional Rolling Cutter Design

The initial rolling cutter design component utilized a standard fixed PDC cutter inserted into a tungsten carbide sleeve (**Figure 1**). A tungsten carbide cover was then brazed onto the bottom of the sleeve to enclose the cutter. The gap between the cutter and the sleeve is controlled so the cutter is free to rotate. The cutter is mounted with a side rake and when the cutter is shearing rock, the side rake will create a side force to efficiently rotate the cutter. Proper side rake is critical to achieve rotation and minimize the loss of cutting efficiency.

Laboratory Experiments (Single Cutter Test Apparatus)

A vertical turret lathe (VTL) wear test was conducted to determine the effectiveness of the rolling cutter concept. A rolling cutter with grooves pre-fabricated in the cutting edge to promote rotation was clamped into a holder and then fixed to the VTL (**Figure 2**). The cutter then shears a granite cylinder across the sample face. The test can be done with different vertical and horizontal feed rates and under dry or water jet cooling conditions. Vertical, tangential and radial forces are recorded during each test. Wear flat sizes are measured at certain intervals to compare the wear resistance of different cutters.

Results against both standard and premium fixed shearing elements are shown in **Figure 3**. All cutters were mounted with the same back/side rakes and traveled at 70ft per minute and were conducted with water cooling to mimic downhole environment. After cutting initial 10 passes the experiments were stopped for cutter evaluation. The rolling cutter had no wear flat but the edge was honed to a slightly rounded shape. However a wear flat of 0.12-in had already developed on the fixed cutter elements.

Subsequent passes were then performed with the vertical force necessary for indentation recorded for all three cutters. Initially, all cutters required about 120lb vertical force to shear the rock. On the fixed cutters, the required force increased at a much faster pace, whereas on the rolling cutter, the vertical force increased more gradually.

After cutting only 60 passes, a standard cutter had developed a fairly large wearflat. It took more than 120 passes on the granite block to develop a similar wearflat on a premium cutter (**Figure 4**). By contrast the rolling cutter performed 320 passes and developed an even wear around the periphery of the diamond table. Yet the width of the developed wearflat was still considerably smaller compared to the fixed cutters. The test clearly demonstrated the rolling cutter shears rock more efficiently with less wear than fixed elements due to its capability to remain sharp and dissipate frictional heat. Based on the test results, it was expected that a bit that was equipped with rolling cutter technology would drill more footage at higher ROP than a bit equipped with conventional fixed shearing elements.

Field Testing

The Granite Wash formation being developed in the Texas panhandle and Western Oklahoma (**Figure 5**) is encountered at depths ranging between 11,000-12,500 ft. In this area, the term Granite Wash (GW) is the nomenclature applied to the extremely abrasive sandstone formation created by rocks eroded from the ancestral Wichita/Amarillo Uplift. The GW, which produces both crude oil and natural gas, is being developed in many cases with a steerable motor BHA to drill a long lateral borehole to increase reservoir exposure. A petrologic evaluation revealed GW is composed of quartz, feldspar with quartz/calcite cementation and is ideal for testing the rolling cutter's resistance to abrasive wear.

Prototype Field Test

A baseline 6 1/8-in MSi613 was modified to incorporate three rolling cutters (**Figure 6**) in the shoulder area where most wear is expected. They were placed on the three secondary blades.The bit was tested in a Washita County, Oklahoma application and went in the hole at the measured depth of 14,700ft and was pulled at 15,506ft due to downhole motor failure. Penetration rate was 20.5ft/hr, which was above average compared to offset wells. The grooved edges on the RCs were strategically angled to enhance cutter rotation. All three rolling cutters came out of the hole in very good dull condition. The cutters all rotated during drilling as witnessed by the slightly rounded cutting edge evenly distributed around the elements' circumference (**Figure 7**).

During field analysis, engineers observed wearflats formed on the fixed cutters located adjacent to the rolling cutters. The field test thus confirmed the rolling cutter concept can be applied to decrease cutter dulling compared to fixed cutter elements in challenging hard and abrasive formations. The cutting component has sufficient robustness to sustain the applied drilling load. Additional testing with the same configuration yielded similar results.

Prototype Field Test

To improve performance a second prototype was produced that included six rolling cutters positioned on each of the six blades in the shoulder area (**Figure 8**) to maximize the potential of the rolling cutters. The bit was run in Wheeler County, Texas and went in the hole at a measured depth of 17,140ft and reached TD at 19,230ft. A footage comparison to offsets drilled with fixed cutter PDC bits within a one mile radius documented the

test bit performed much better than the median average (**Figure 9)**. The rolling cutter bit generated an ROP of 15ft/hr which is average for the area.

Dull grade analysis showed the fixed cutters adjacent to the rolling cutters were worn to T1 stage, while the wear on rolling cutters was negligible and spread equally around the full 360° cutting edge. All five rolling cutters were in good condition with only one broken cutter whereas several broken fixed cutting elements were observed. Overall, the RCs displayed better resistance to abrasive wear and good overall strength characteristics.

The bit was repaired and sent back to Wheeler County, Texas for rerun. On its second pass the bit drilled 425ft of hole section from 15,891ft to 16,316ft at an average ROP of 10.5ft/hr. The bit equipped with the six rolling cutters drilled 67% more footage at 38% faster ROP than the median offset footage of 255ft and ROP of 7.6ft/hr. The bit came out of the hole in excellent dull condition with only one small chip (**Figure 10**).

The other five rolling cutters were still in good working condition. The cutting edges were rounded slightly due to wear. Most fixed cutters adjacent to the RCs were either chipped or broken. The good dull condition indicates that the rolling cutters have better impact resistance than fixed cutters, because they can stay sharp and shear formation with less force/WOB. When a cutter dulls it increases breakage potential because it requires a larger force to shear the formation. The field test results confirm that the ability of a cutter to retain a sharp edge reduces occurrence of chipping/breakage when drilling hard and abrasive formations.

Flexible Chassis Development

The initial rolling cutter and retaining sleeve assembly is relatively large and may have limited the number of shearing elements that could be placed on a single blade. To alleviate the problem, engineers proposed a new design that would be easier to manufacture and reduce overall cutter size allowing for more design variables to be implemented (**Figure 11**). The newer rolling cutter design is essentially the same size as a standard cylindrical fixed cutter. This design change has multiple advantages over the earlier design in terms of cutting structure design as well as manufacturing feasibility.

Generation-3 chassis development provides for flexibility and gives operators in Western Oklahoma the best chance for benchmark performance runs. In the next test bit 12 rolling cutter locations were established at the highest possible work rate locations. However these locations would now be interchangeable to allow both rolling and fixed cutters to be installed in any location, to have maximum flexibility with fixture evaluation. Additionally, backup cutters were installed behind every rolling cutter location, as with commercial fixed cutter products to enable sustained performance as primary cutting elements wear.

Stage 1 – Prototype Field Testing

The first stage in evaluating the new rolling cutter chassis would compare two bits equipped with three rolling cutters versus three fixed cutters in a radial pattern on the same bit chassis (**Figure 12**). Testing in a Granite Wash (Colony Wash B) horizontal application with a PDM drive system was the selected opportunity for field testing once again.

Performance showed a gain of 28% in footage drilled when comparing the average footage of the bits equipped with three rolling cutters compared to the average of the three fixed cutter bits used in the same interval in the Washita County well (**Figures 13a** & **13b**).

Dull Cutter/Bit Comparison

Observation of dull conditions was instrumental in this paired comparison. After field analysis it became apparent the rolling cutters needed to be placed further across the nose/shoulder transition to validate the wear model in these high work-rate areas. In the number two rolling cutter bit, wear in the nose area on the fixed cutters led to performance degradation (**Figure 14**). Reduction in wear in this area would give the PDC chassis more longevity. Also noted were the larger wear flats incurred all of the way down the profile, with respect to the rolling cutters on positions just inside and outside of that radial location (**Figure 15**).

Stage 2 – Prototype Field Testing

The next step was to test the affects of increasing rolling cutter count to see if additional footage gains were possible. In the next test bit seven rolling cutters were added in different locations across the shoulder area to improve the durability. Field tests on the initial runs show promise with footage improvements evident on early tests and no fixture reliability issues. Performance on a Colony Wash B well drilled in Q4 2012 realized footage gains compared to heavier set fixed cutter designs in offset runs in the same horizontal interval, Washita County, Oklahoma were favorable (**Figure 16**).

Run analysis by footage drilled shows the full rolling cutter run compares favorability against the heaver-set seven and eight bladed designs with over 50% more footage drilled than the average of the bit before and after in the same lateral (**Figure 17**). All bits were pulled for low penetration rate unless otherwise marked.

The sequential configured rolling cutter prototype PDC bit came out of the hole in good dull condition with no wear experienced on the seven rolling cutters installed (**Figure 18**). Only the fixed cutters radially inward from the rolling cutter positions experienced wear or chipping that led to the bit being pulled for PR. Rolling cutters are identified with red dots.

Starting in Q4 2012, the total RC count per bit was progressively increased on five/six bladed designs from 3, 5, 7, 10 and then 12. The 13mm designs are consistently exceeding footage totals compared to offsets drilled with standard fixed cutter PDC bits in central USA, Williston and Canadian applications.

In the central USA, which contains the largest data set (13 RC runs) the rolling cutter has increased average footage totals by 34.4% with equivalent or better ROP compared to median of offsets drilled with conventional fixed cutter PDCs from various manufacturers (**Figure 19**).

Conclusions

The initial hypothesis of the rolling cutter concept was that a PDC cutter which was allowed to rotate around its axis would demonstrate lower wear and retain sharpness as a result of its ability to utilize the entire circumference of the diamond table. Initial modeling confirmed the concept and laboratory testing validated the benefits.

Field tests in abrasive formations have demonstrated the capability to increase the cutter's resistance to wear significantly enhancing overall bit life. The rolling cutter also improves drilling efficiency and ROP by keeping the cutting edge sharper for a longer period of time.

Dull grading confirms that full rotation of the cutters is taking place. Further testing is currently underway with progressively more cutters on the bit being converted from fixed to rolling versions. The resulting bit technology will have the ability to further expand the operating envelope of PDC bits into harder, more abrasive formations leading to reduced cost of drilling operations.

Acknowledgements

The authors wish to express their gratitude to Smith Bits, a Schlumberger Company for permission to release the results of laboratory testing and field performance data. The support from MegaDiamond, Kennametal for supplying prototype components for initial laboratory testing is also acknowledged. Finally, thanks to Craig Fleming, Smith Bits for his editing and technical writing contributions.

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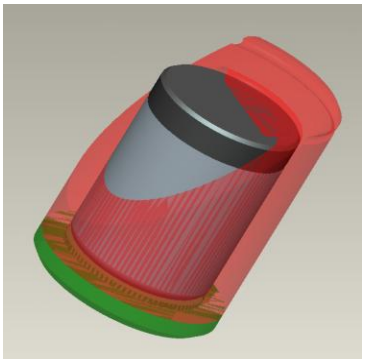


Figure 1 - Initial sleeved roller cutter design concept



Figure 2 – Vertical turret lathe test apparatus with placement jig

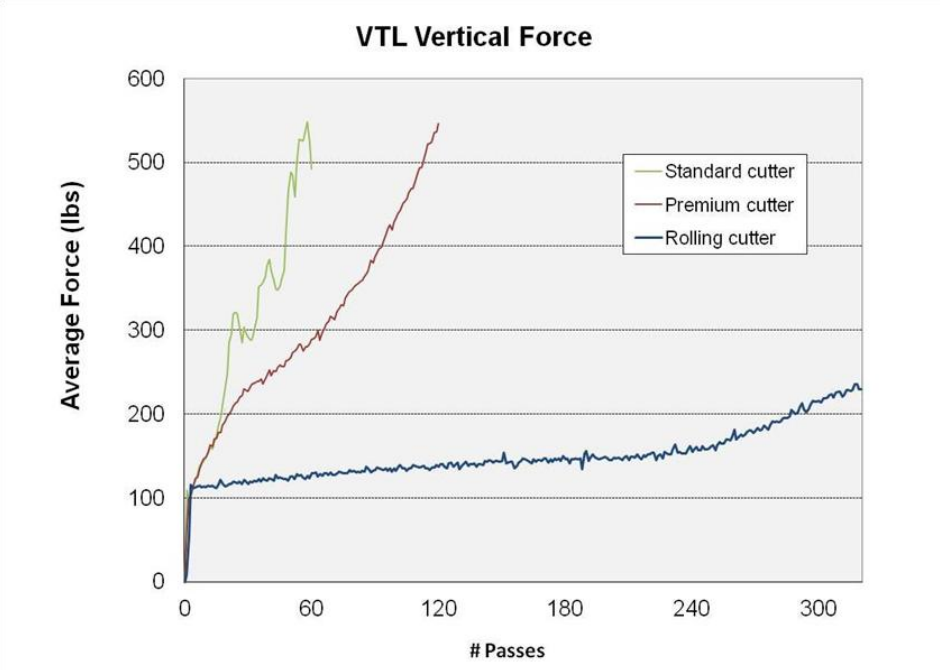


Figure 3 - VTL test results showing increase force required to drive fixed cutters vs low/consistent force for rolling cutter

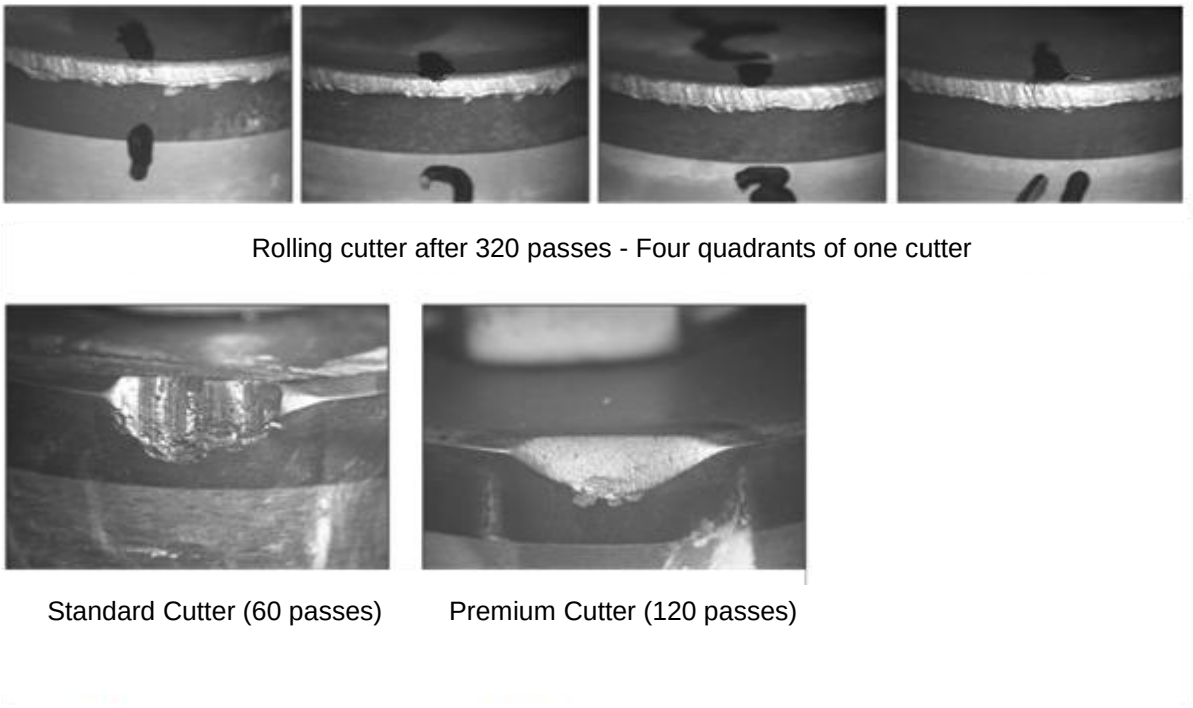


Figure 4 – Smaller wearflats developed on rolling cutters (upper grouping) compared to fixed standard and premium cutters



Figure 5 – General outline of Granite Wash play, mid-continent USA



Figure 6 – Schematic of prototype bit with three generation-1 rolling cutters in critical shoulder area before RIH



Figure 7 - Dull of the prototype bit with three generation-1 rolling cutters



Figure 8 – Dull of second prototype bit with six generation-1 rolling cutters in shoulder area
Note good dull condition of rolling cutter (red dot) compared to standard fixed cutting elements on either side

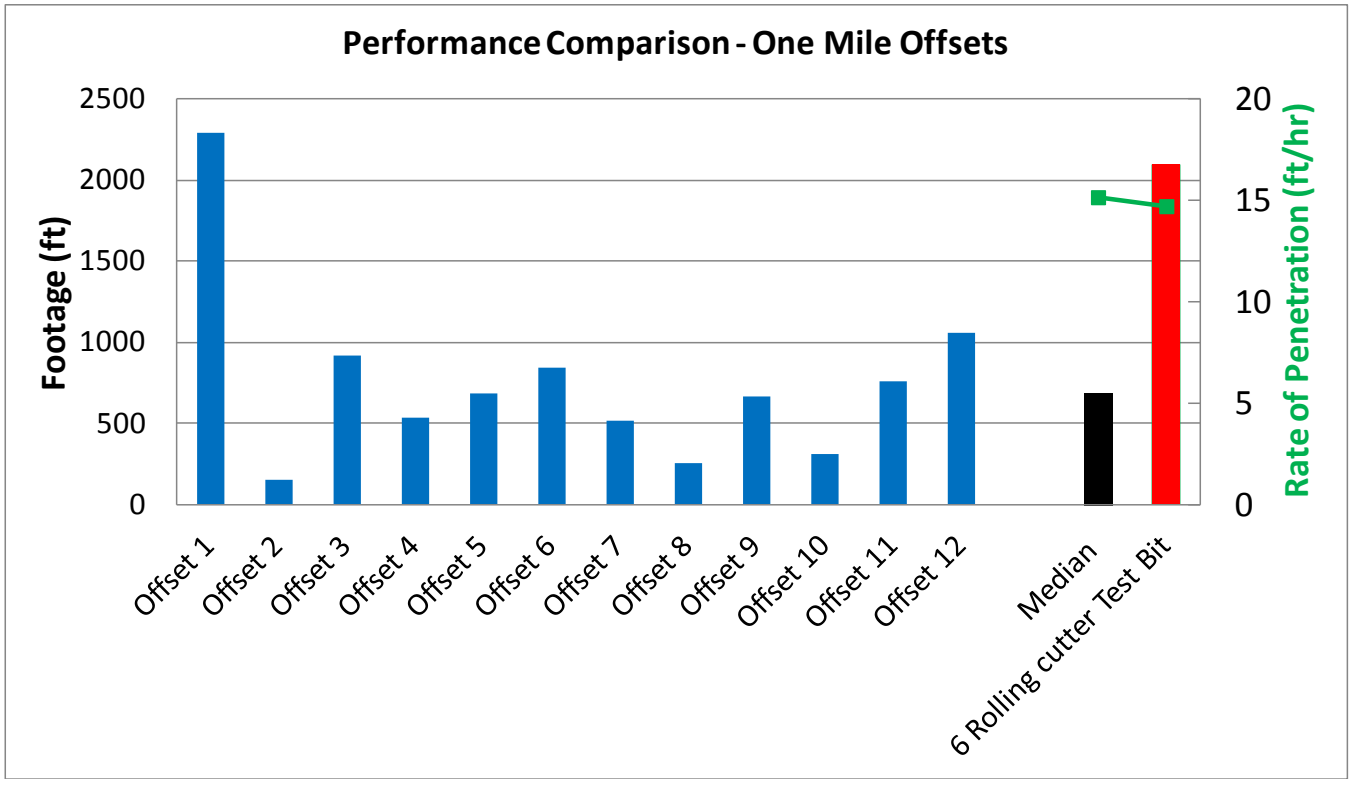


Figure 9 – Total footage drilled with the second prototype bit with six generation-1 rolling cutters



Figure 10 – Six RC's in prototype bit-2 in excellent condition after drilling 425ft of abrasive GW at a high ROP of 10.5 ft/hr



Figure 11 - Updated rolling cutter retaining device

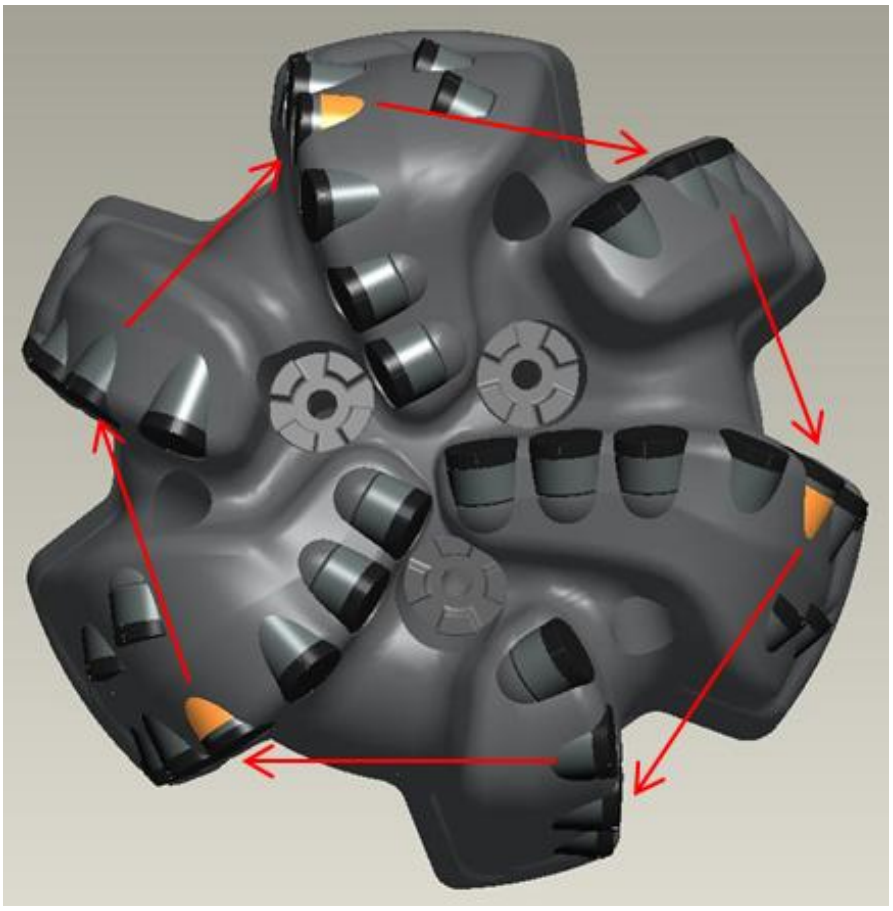
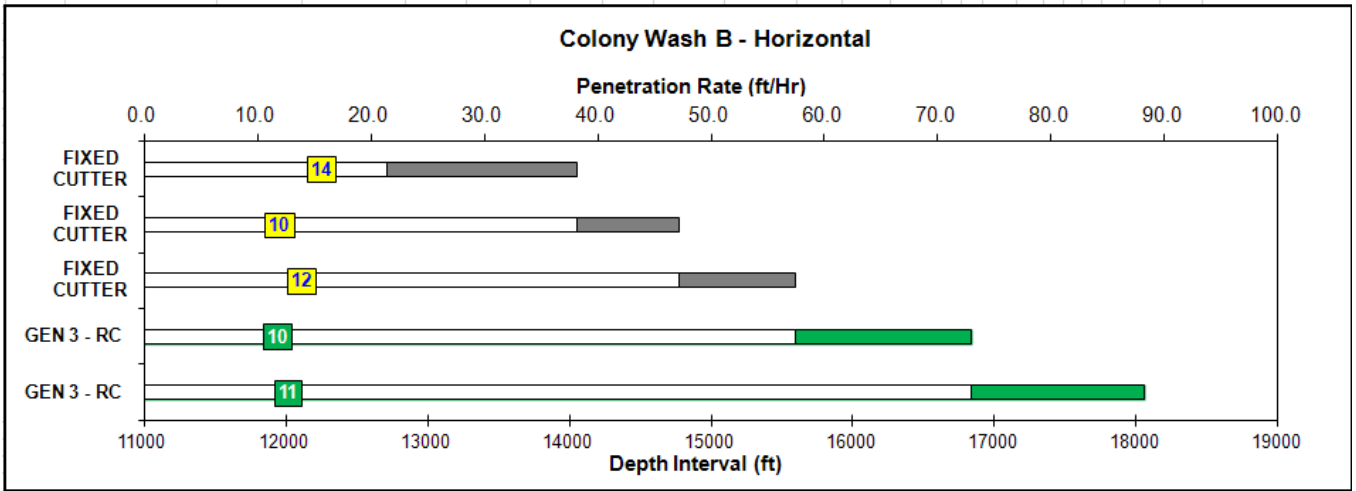


Figure 12 - Rolling cutter bit with three rolling cutters (orange) paired with three fixed cutters in alternating radial locations



Size	Type	Serial No.	County	DI	DO	Footage	Hours	Lo RPM	Hi RPM	GPM	WOB	ROP	Dull Condition										Well Type
6 1/8	FIXED CUTTER	7129316	WASHITA	12711	14057	1346	96	62	132	254	20	14.0	4	4	WT	A	X	X	X	IN	CT	PR	COLONY WASH B
6 1/8	FIXED CUTTER	7031458	WASHITA	14057	14773	716	69.5	57	138	254	25	10.3	2	4	WT	NS	X	X	X	IN	CT	PR	COLONY WASH B
6 1/8	FIXED CUTTER	7023538	WASHITA	14773	15594	821	67	136	136	264	25	12.3	2	3	WT	NS	X	X	X	IN	CT	PR	COLONY WASH B
6 1/8	GEN 3 - RC	JG0108	WASHITA	15594	16834	1240	122.5	57	132	264	25	10.1	0	1	WT	NS	X	X	X	IN	CT	PR	COLONY WASH B
6 1/8	GEN 3 - RC	JG1606	WASHITA	16834	18061	1227	110.5	52	132	229	25	11.1	1	3	BT	N	X	X	X	IN	LT	TD	COLONY WASH B

Figure 13a - Horizontal bit runs plotted by interval drilled with footage, ROP and operating parameters

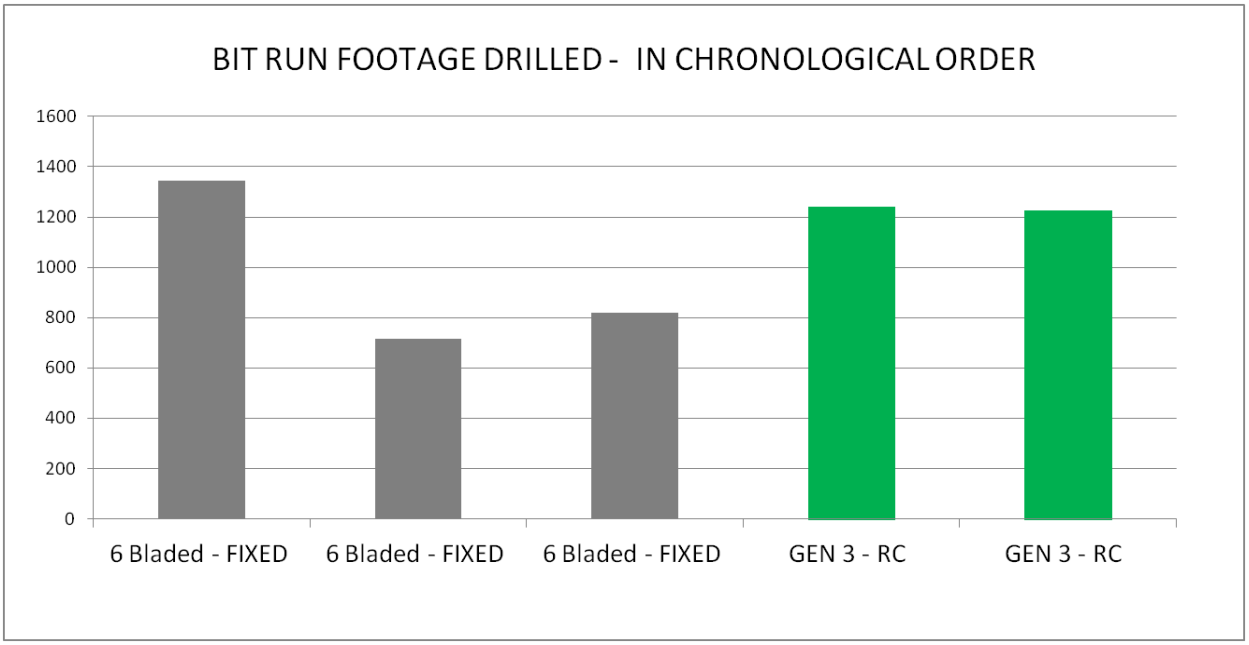


Figure 13b - Footage chart of the runs from the paired comparison tests. Average of the two rolling cutter runs drilled 28% more footage than the average of the three fixed cutter offsets in that same lateral.

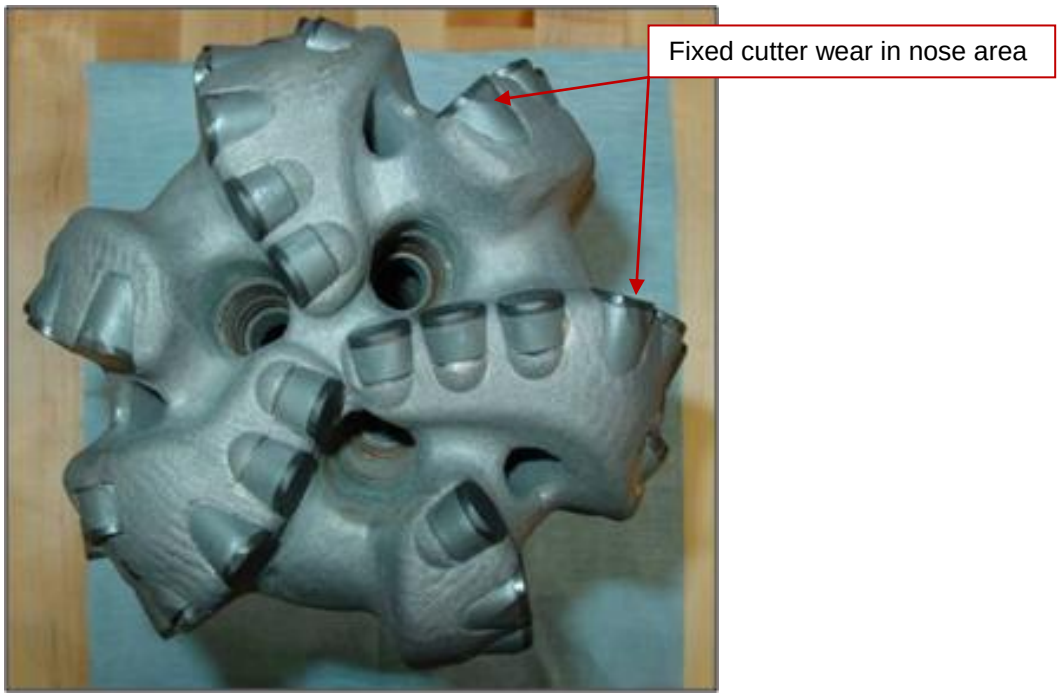
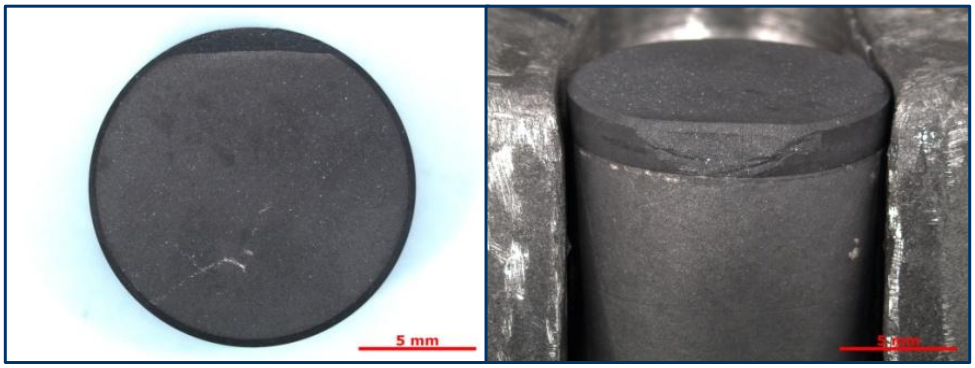
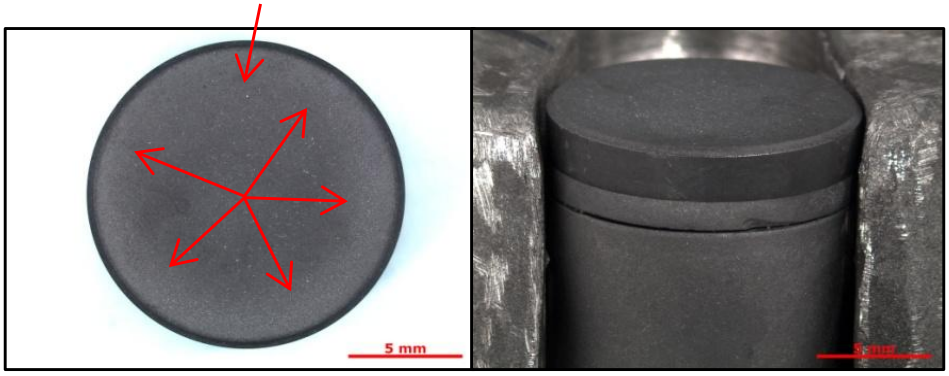


Figure 14 - Wear of standard fixed cutters illustrated need for more durability in nose area

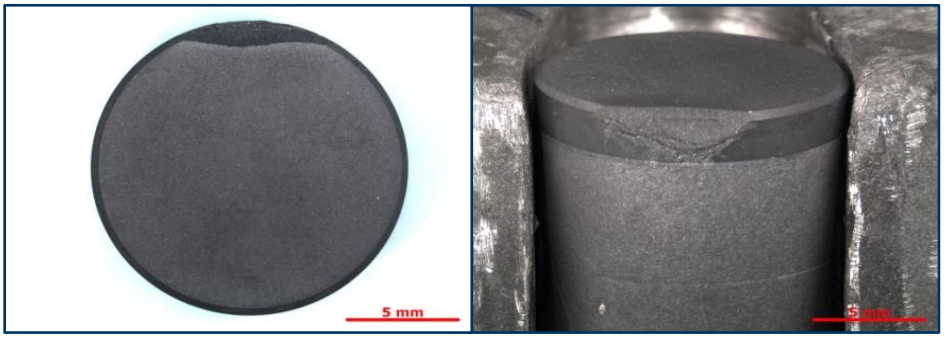


Fixed cutter #18, leading rolling cutter

Evidence of rotation



Rolling cutter #19



Fixed cutter #20, trailing rolling cutter

Figure 15 - Dull condition/analysis of cutters 18-20 alternating from fixed to rolling cutters

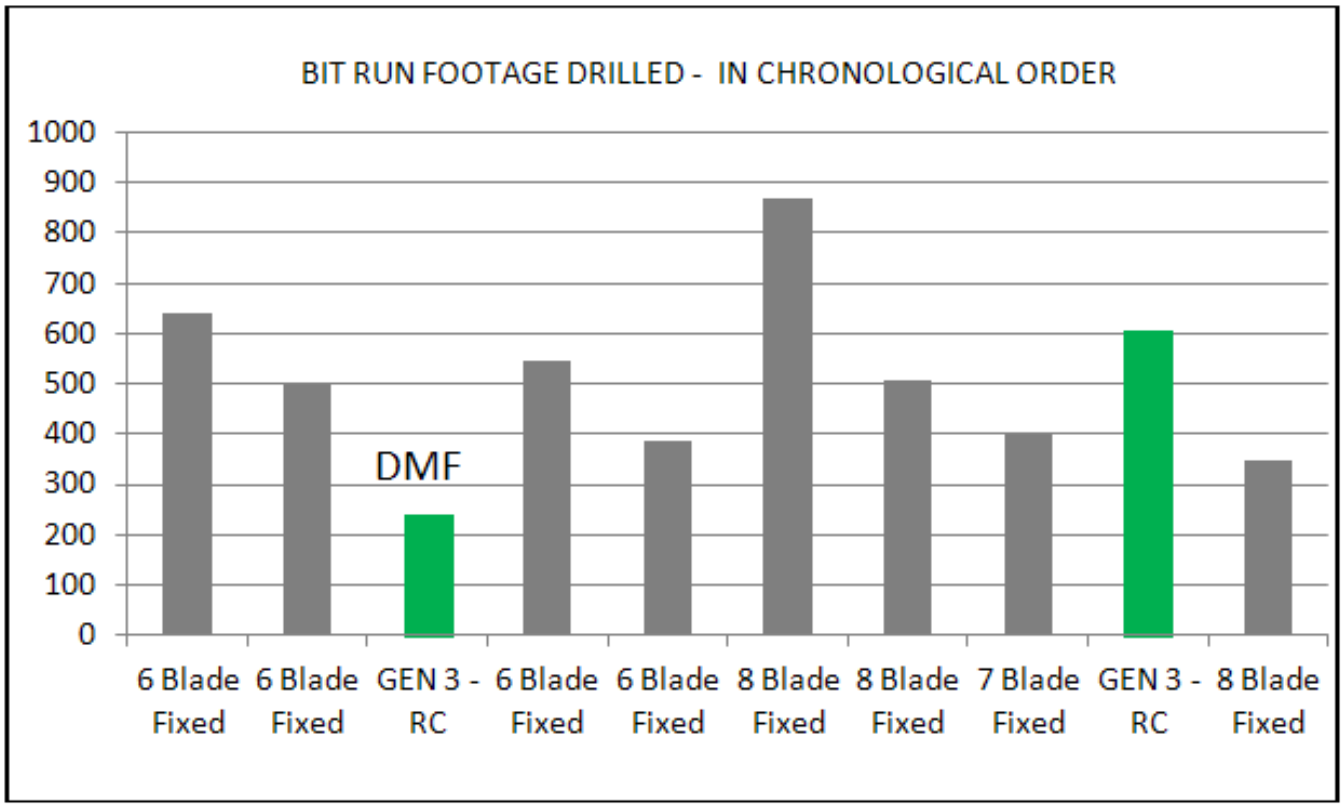
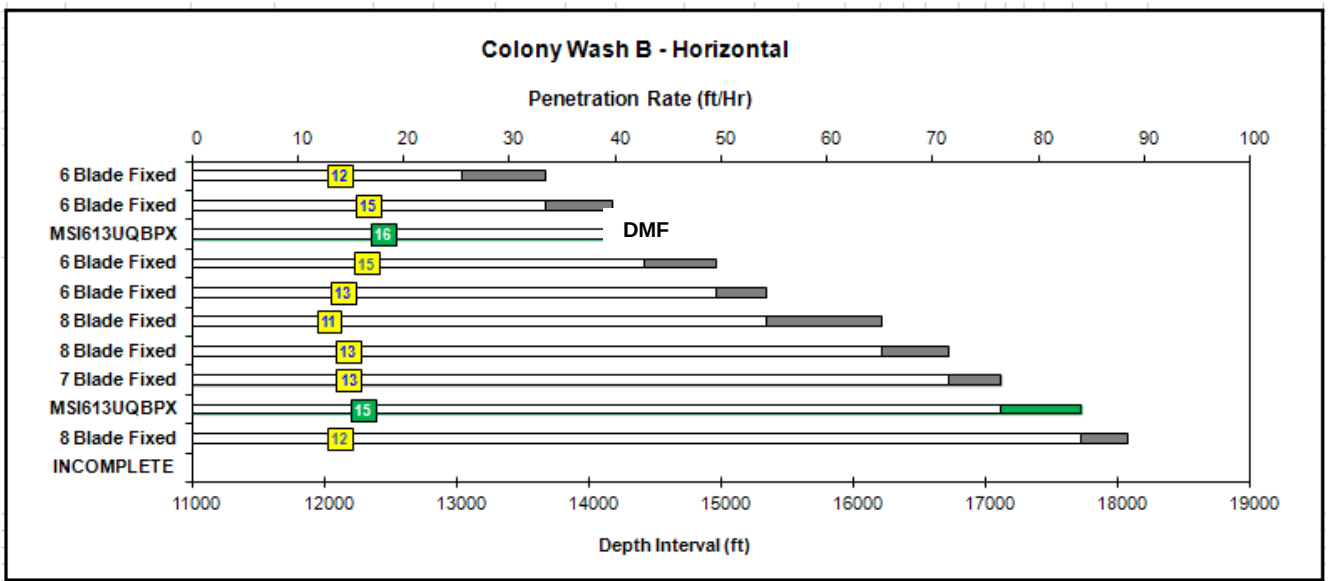


Figure 16 – Footage of light set rolling cutter bit outperformed majority of heavy-set fixed cutter bits



Size	Type	Serial No.	County	DI	DO	Footage	Hours	Lo RPM	Hi RPM	GPM	WOB	ROP			Dull Condition							Well Type
6 1/8	6 Blade Fixed	7138627	WASHITA	13035	13677	642	52	118	275	235	18	12	1	4	WT	NS	X	X	X	IN	RG	PR	COLONY WASH B
6 1/8	6 Blade Fixed	7022539	WASHITA	13677	14175	498	33	119	184	235	25	15	1	3	WT	NS	X	X	X	IN	RG	PR	COLONY WASH B
6 1/8	MSI613UQBPX	JG3260	WASHITA	14175	14414	239	14.5	140	210	250	15	16	0	1	WT	S	X	X	X	IN	NO	DMF	COLONY WASH B
6 1/8	6 Blade Fixed	M9834	WASHITA	14414	14959	545	36.5	123	210	250	18	15	1	3	WT	NS	X	X	X	IN	RG	PR	COLONY WASH B
6 1/8	6 Blade Fixed	12286	WASHITA	14959	15346	387	30.5	70	202	235	18	13	1	3	WT	NS	X	X	X	IN	RG	PR	COLONY WASH B
6 1/8	8 Blade Fixed	7141801	WASHITA	15346	16214	868	76	60	228	273	15	11	3	5	WT	A	X	X	X	IN	RG	PR	COLONY WASH B
6 1/8	8 Blade Fixed	7141800	WASHITA	16214	16720	506	38.5	130	196	235	10	13	3	4	WT	A	X	X	X	IN	RG	PR	COLONY WASH B
6 1/8	7 Blade Fixed	11977304	WASHITA	16720	17118	398	30	131	210	236		13	4	2	WT	N	X	X	X	IN	CT	PR	COLONY WASH B
6 1/8	MSI613UQBPX	JG3260	WASHITA	17118	17725	607	41.5	131	208	236		15	1	1	WT	NS	X	X	X	IN	NO	PR	COLONY WASH B
6 1/8	8 Blade Fixed	7142085	WASHITA	17725	18071	346	28	131	212	236		12	4	8	WT	SH	X	X	X	IN	CT	PR	COLONY WASH B
	INCOMPLETE																						

Figure 17 - Performance plot of run footage, ROP and operating parameters show encouraging results

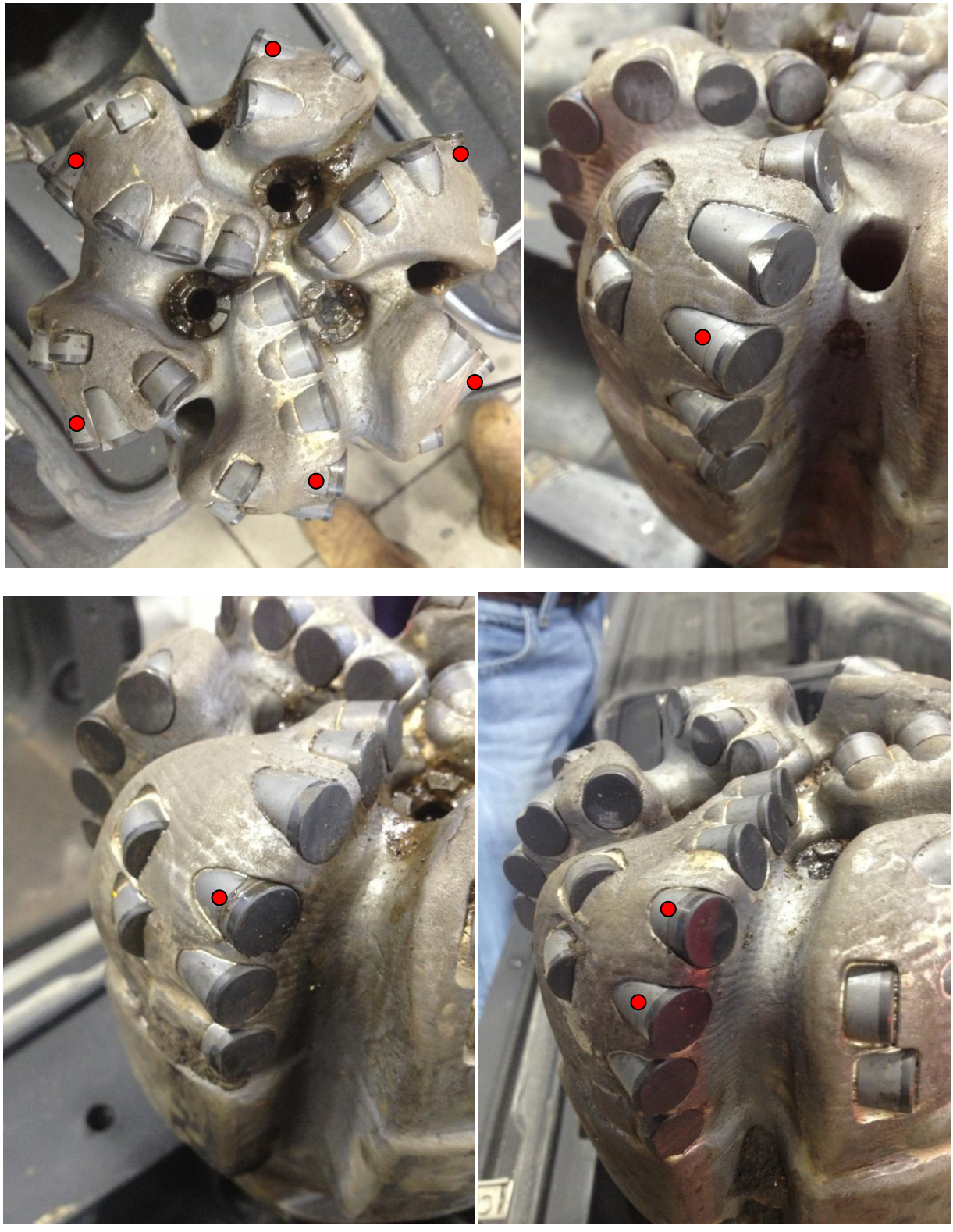


Figure 18 – Test bit pulled in good dull condition with limited wear on any of the rolling cutters (red dots)

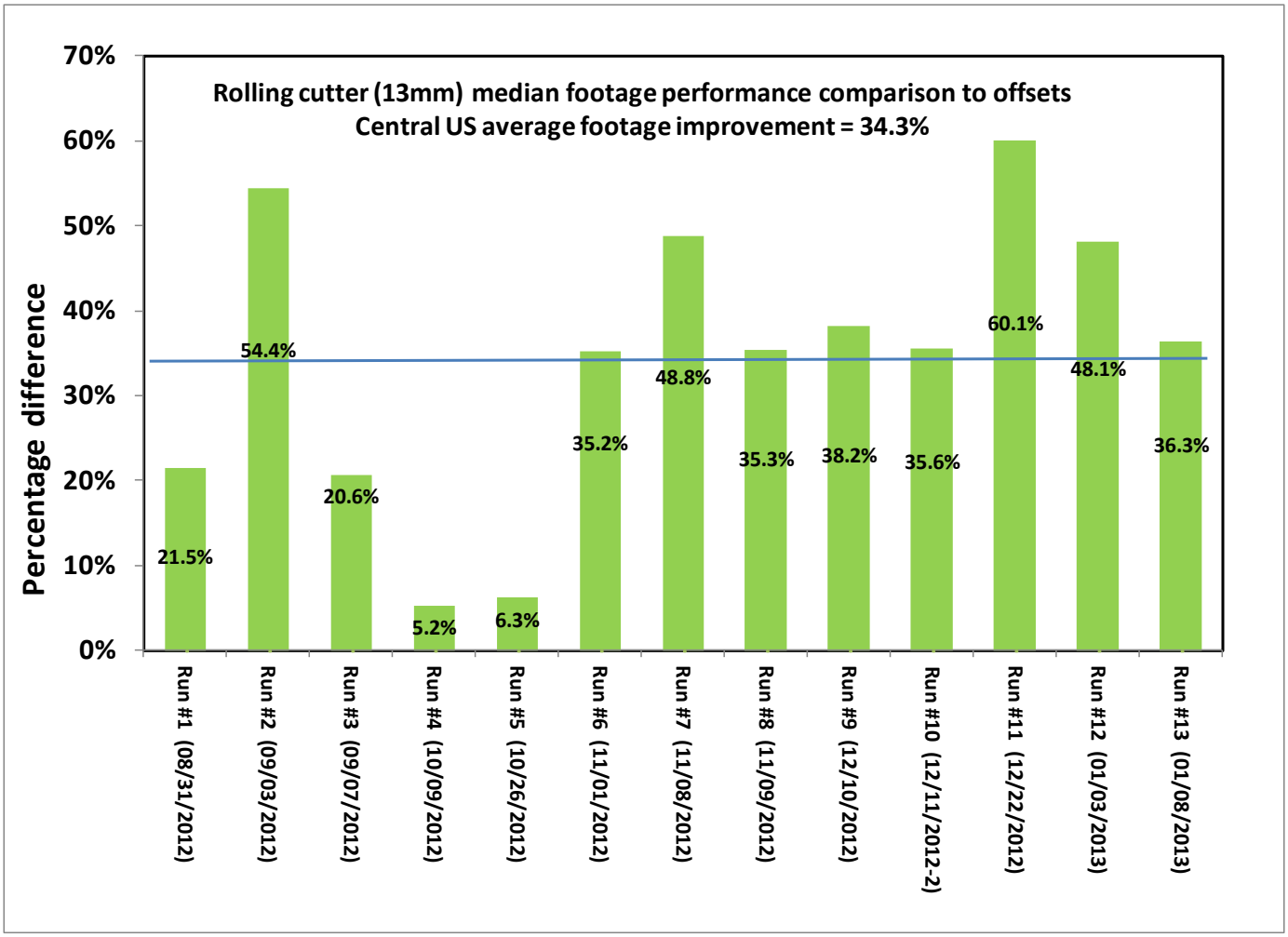


Figure 19 – Multiple rolling cutter designs have increased average footage totals by 34.4% compared to offsets drilled with conventional fixed cutter PDC bits from various manufacturers