SPE-179088-MS

Optimizing Bridge Plug Milling Efficiency Utilizing Weight-On-Bit to Control Debris Size: A Comparative Study of the Debris Size vs Weight-On-Bit Utilizing Five Bladed Carbide Mill, Tri-Cone and PDC Bits

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This paper was prepared for presentation at the SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition held in Houston, Texas, USA, 22–23 March 2016.

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Abstract

Weight-on-bit can be challenging to calculate at surface as downhole motor performance is generally observed from differential pressure and rate of penetration (ROP). If an accurate weight-on-bit (WOB) is maintained, motor performance and ROP can be maximized while controlling debris size. This will increase the efficiency of the entire millout operation. The weight-on-bit can be monitored and manipulated live via new software (Yeung, J. et al. 2015).

The objective of this research paper is to conduct a comparative study that analyzes the performance of the five bladed carbide mill, tri-cone and PDC bits in terms of debris size vs weight-on-bit. Two main criteria will be used for the analysis. Firstly, a test will be carried out in order to determine how the set down force affects the drilling tool in terms of generating smaller debris size. This knowledge intends to improve wellbore clean outs and reduce the number of wiper trips. Secondly, the test will analyze how set down force of the drilling tool affects the ROP on the bridge plug. One specific type of 4-1/2'' bridge plug with a combination of selected mills and bits will be studied in this paper to control the experiment. However, the overall milling parameters may vary greatly depending on the manufacturers, plug, mill, and bit types.

A series of bridge plugs will be milled out in a controlled environment using the five bladed carbide mill and tri-cone and PDC bits. Each bridge plug will be milled out using a different weight-on-bit. After the bridge plug is milled out, all the plug debris is collected, and sorted based on a debris size distribution graph. The ROP will also be measured during the milling process to determine milling efficiency.

In summary, this paper will compare the performance executed by the five bladed carbide mill, tri-cone, and PDC bits. This paper will identify the optimal weight-on-bit to achieve the desired quantitative debris size with these plugs. More studies need to be conducted for different plug types to see how weight-on-bit affects debris size.

Experiment Setup

All milling was performed using a piece of 114.3mm x 22.47 Kg/m x J55 casing that was bolted down to an I-beam. Also bolted to the same I-beam was a hydraulic cylinder with a DAQ recorder tied into the main hydraulic circuit that fed the piston. Using a specific DAQ software that was configured for the piston size, the WOB was controlled and recorded from a central control station. Piston WOB was verified by using a load cell to ensure accuracy before testing began. A linear displacement transducer was installed on milling bench to measure and record ROP during milling operation.

Cuttings were collected by allowing the flow returns to pass through a mesh screen above a catch tank. After each test the cuttings were manually collected and sorted into the three main plug materials; metal, composite, and elastomer.

Controlled Variables

A number of variables were controlled throughout the experiment in order to evaluate the performance of each of the drilling assembly in a consistent manner and give accurate test results.

1. Composite Bridge Plug Selection:

To maintain the consistency of the test results, all the plugs used in the milling experiment were provided by the same plug manufacturer.

2. Motor selection:

For this particular paper, we decided to use 2-7/8” OD downhole motor. 2-7/8” OD downhole motor is a common selection in the Western Canada region to mill out composite bridge plugs inside of a 4-1/2” casing. The pump rate was set to 480 L/min (3 bbl/min) for all the drill outs. Based on the motor performance curve, the motor generated a torsional force of 1540 lbs/ft and an rpm of 520-560 revs/min.

3. Fluid Selection:

Lastly, the condition of the fluid used in the milling operation was also controlled. Chemical additives such as gel or friction reducer were not added to influence the overall performance of the motor. As we had low circulation pressure during the experiment, we were not required to pump friction reducer. The exact same setup for the fluid pumper unit, operator, and pump rate was used for the entire mill out experiment.

Manipulated Variables

1. Weight on Bit (WOB):

The first manipulated variable was the set down force. In order to test out the effect of the set down force, we used three different WOB settings; low, medium, and high. The range of low, medium, and high weight on bit was calculated based on the potential maximum set down force at various reached depths. This was acquired by running commercially available tubing force analysis software. Higher potential maximum set down force was observed closer to the heel section of the well as compare to the toe. (**See Appendix 1** for the maximum potential set down force vs reached depth graph).

2. Plug Drilling Assembly:

Five different types of drilling assembly were evaluated for the milling experiment. An under drift mill, a full drift mill, a Tri-cone, an offset mill and a PDC mill were used for the test as shown in **Figure 1 through 4**.

Figure 1: Plugs 1 – 3, 92.0mm/3.625" Crushed Carbide Insert Mill with carbide buttons with convex face profile (Under Drift Mill).

Similar to figure 1, Plugs 4 – 6 94.0mm/3.701" Crushed Carbide Insert Mill with carbide buttons with convex face profile (Full Drift Mill).



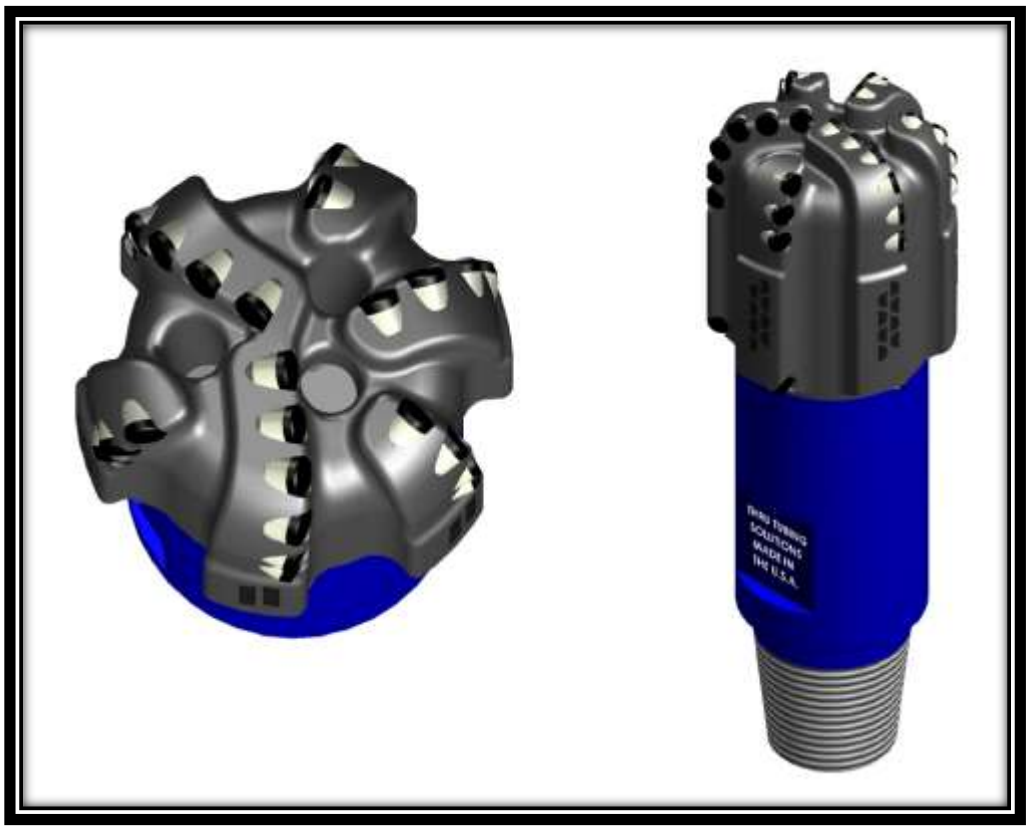
Figure 2: Plugs 7 – 9, 92.0mm/3.625" Sealed Bearing Tricone Tooth Bit, with 3 Nozzles



Figure 3: Plugs 10 – 12, 82.9mm/3.267” rotating out to 94.0mm/3.701” Bicentre/Eccentric Crushed Carbide Insert Mill with carbide buttons with convex face (Offset Mill).



Figure 4: Plugs 13 – 14, 92.0mm/3.625” PDC Bit with 34 9mm cutters and 3 nozzles



Milling Schedule

Table 1: Milling schedule for the experiment

Plug #	Mill/Bit Type	Set down Force (daN)
1	Underdrift Mill	low
2	Underdrift Mill	medium
3	Underdrift Mill	high
4	Full-drift Mill	low
5	Full-drift Mill	medium
6	Full-drift Mill	high
7	Tri-cone	low
8	Tri-cone	medium
9	Tri-cone	high
10	Offset Mill	low
11	Offset Mill	medium
12	Offset Mill	high
-	-	-
13	PDC	medium
14	PDC	high

A milling schedule was created using different values for the manipulated variable and the controlled variable set in the experiment parameters. Each of the drilling assemblies were subjected to the three set down force values during milling operation.

Sieve Analysis

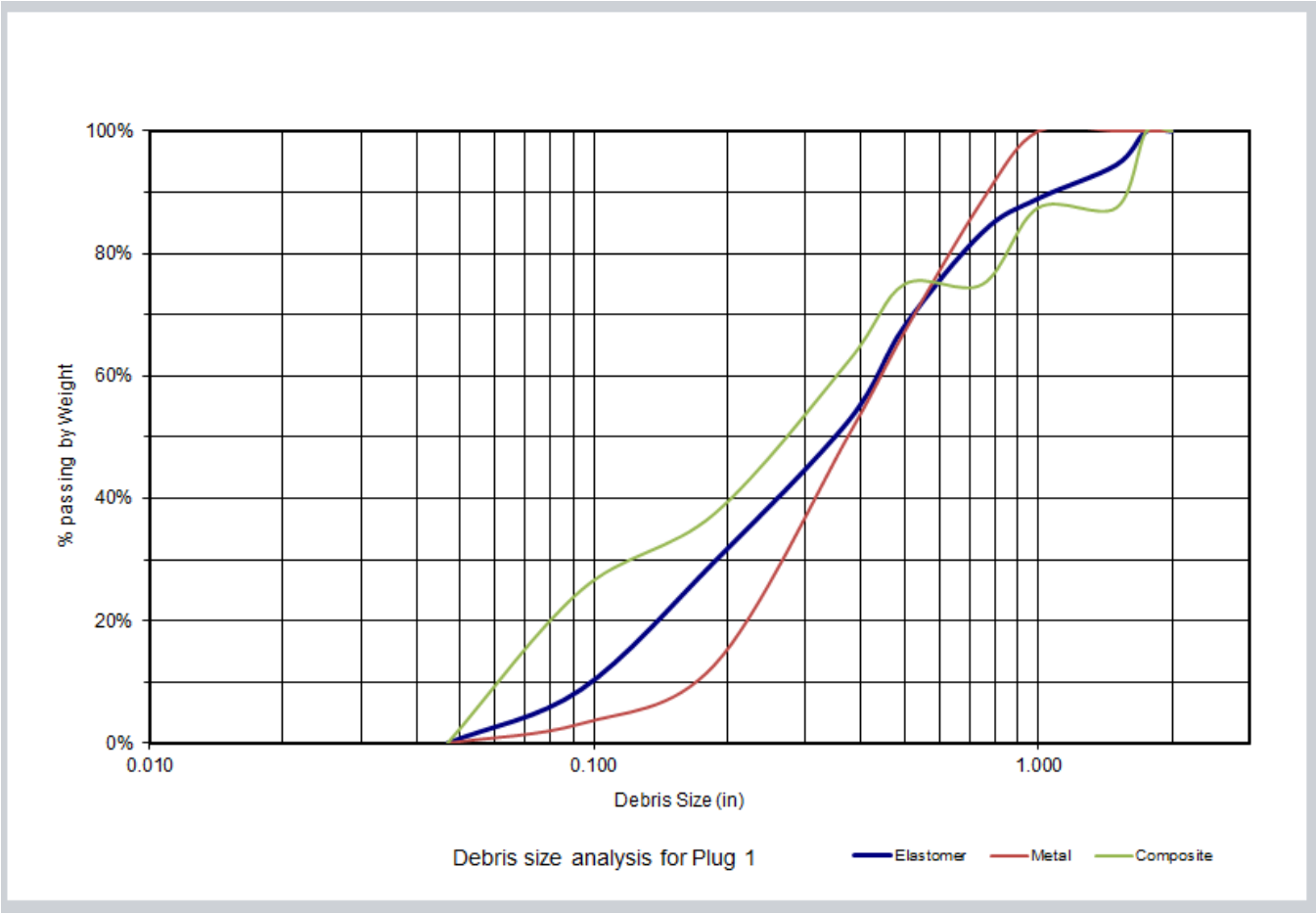
In order to quantify the size of bridge plug debris, a sieve analysis was conducted to obtain the particle distribution. This is a proven method that is commonly used to analyze the particle size of sand and gravel to show the size distribution. A sieve analysis graph was completed for each bridge plug by the material types which includes metal, composite and elastomer. The generated graphs were used to determine which combination of plug drilling assembly and weight on bit produced the smallest cuttings.

A total of 14 bridge plugs were milled out for the milling experiment. After each mill out, all the debris that was produced was collected separately. Then each pile of debris was sorted into three different groups based on the material type. The metal material was mostly from the slips or any other metallic components inside of the bridge plug. Composite material was from the body of the bridge plug while elastomer material was comprised of the packer element which sits in the middle of the bridge plug.

For the setup, a series of sieves with different screen sizes were stacked on top of one another to form a sieve assembly. The sieves with the bigger screen sizes were placed on the top while the sieves with the smaller screen sizes were placed on the bottom.

Before the debris was sorted through the sieves, the total weight of the debris was recorded. Next, the debris was fed through the sieve assembly. Then the debris was retained by the sieve based on its particle sizes. In order to prevent the debris from piling on top of each other, the entire sieve assembly was shaken for an extended period of time. After all the debris was sorted through the sieve assembly, the weight debris from each sieve was recorded. In order to obtain a percentage retained per each sieve size, the weight of debris per sieve was divided by the total weight. An example of a sieve analysis is shown in **Figure 5**.

Figure 5: Cumulative Percent Passing vs the Logarithmic Sieve Size (plug#1-Underdrift mill, low set down force)



The data collection was then analyzed in two different ways. First the data was analyzed by 20 % of weight retained in sieves (80% passing by weight) to determine the largest potential particle size. The same analysis was repeated with 80% of weight retained in sieves (20% passing by weight) to determine the smallest potential particle size.

Once sieve analysis was done to all 14 bridge plugs by its material types for both analyses, a ranking system was developed to quantify the data **(Table 2 and Table 4)**. A score of 1 was assigned to the data point that yield the smallest cutting size and a score of 14 was given to the largest cutting size for each material type. All the scores for the three material types were added up to generate an overall performance score. The lower the overall score indicates the smaller cutting size.

Then the overall score for each bridge plug was categorized and ranked again based on the three different weights on bit that were used. Using the two ranking systems, correlations between the drilling assembly, WOB, and the debris sizes was determined in **Table 3 and Table 5**.

Result of Sieve Analysis

1. 20 % of weight retained in sieves (80% passing by weight)

For this specific analysis, observing the data from **Table 3**, the drilling assembly ranking was almost identical across the board regardless of the weight on bit. The weight on bit does not appear to affect the overall performance of the drilling assembly in terms of generating smaller cuttings. A higher weight on bit did not necessarily improve or decrease the performance of any particular type drilling assembly.

However, this particular data set appeared to have a stronger correlation between the type of drilling assembly and the overall size of the debris. Tri-cone assembly generated the smallest cuttings compared to its peers regardless of the weight on bit. This is due to the fact that Tri-cones create an additional grinding motion which further break down the larger pieces of debris.

The full drift mill and the under drift mill are ranged in the middle of the ranking system. These mills are designed to cut but not grind up the debris. PDC mill and the offset mill created larger debris sizes. The reason why the offset mill performed worse is due to the smaller outer diameter of the mill. This causes a gap between the outer diameter of the mill and the inner diameter of the casing allowing the larger debris to escape the milling face during milling operation.

Table 2: 80% passing by weight (20% weight retained in sieves) Ranking based on size. Note: Ranked from #1 to #14 (Smallest debris size to the largest debris size)

		Under Drift Mill			Full Drift Mill			Tri-cone			Offset Mill			PDC Mill		
Description	Debris Type	Plug #1	Plug #2	Plug #3	Plug #4	Plug #5	Plug #6	Plug #7	Plug #8	Plug #9	Plug #10	Plug #11	Plug #12	-	Plug #13	Plug #14
80% passing by weight	Elastomer	6	3	7	8	4	9	1	2	5	14	13	12	-	10	11
80% passing by weight	Metal	8	11	2	4	6	7	3	1	5	14	10	12	-	13	9
80% passing by weight	Composite	8	12	7	9	4	3	6	1	2	13	14	10	-	11	5
	Total	22	26	16	21	14	19	10	4	12	41	37	34	n/a	34	25
	Weight on Bit	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH

Table 3: Weight on bit vs Plug Drilling Assembly 80% passing by weight (20% weight retained in sieves). Ranking based on debris size.

Overall Ranking (smallest to largest)	Low WOB (Overall)	Med WOB (Overall)	High WOB (Overall)
1	Tri-cone	Tri-cone	Tri-cone
2	Full Drift Mill	Full Drift Mill	Under Drift Mill
3	Under Drift Mill	Under Drift Mill	Full Drift Mill
4	Offset Mill	PDC Mill	PDC Mill
5	n/a	Offset Mill	Offset Mill

2. 80 % of weight retained in sieves (20% passing by weight)

In the second analysis, the focus was on the smaller pieces of debris retained by the sieves with smaller openings. 80% of the weight retained in sieve (20% passing by weight) was selected as the cut off point for the analysis summarized in **Table 4**. The bridge plug scores were sorted based on weight on bit and shown on **Table 5**.

The results from 80% retained by weight look slightly different from the first analysis. The performance of the tricone dropped from second place for the medium WOB and to fourth place for the high WOB. This means that the tricone produced larger particle sizes within the smaller particle group when compared to other drilling assembly.

The overall performances of under drift mill and the full drift mill were consistent for the three WOB values. Both of the mills produced the smallest particles within the group. Once again the PDC mill and the offset mill produced the largest cuttings compare to its peers regardless of the weight on bit.

Table 4: 20% passing by weight (80% weight retained in sieves) Ranking based on size. Note: Ranked from #1 to #14 (Smallest debris size to the largest debris size)

		Under Drift Mill			Full Drift Mill			Tri-cone			Offset Mill			PDC Mill		
Description	Debris Type	Plug #1	Plug #2	Plug #3	Plug #4	Plug #5	Plug #6	Plug #7	Plug #8	Plug #9	Plug #10	Plug #11	Plug #12	-	Plug #13	Plug #14
20% passing by weight	Elastomer	1	7	2	5	3	4	8	9	12	14	13	11	-	6	10
20% passing by weight	Metal	4	1	6	2	3	8	5	7	9	14	10	12	-	11	13
20% passing by weight	Composite	2	12	10	13	7	11	6	5	4	9	8	14	-	3	1
	Total	7	20	18	20	13	23	19	21	25	37	31	37	n/a	20	24
	Weight on Bit	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH

Table 5: Weight on bit vs Plug Drilling Assembly 20% passing by weight (80% weight retained in sieves) Ranking based on debris size.

Overall Ranking (Smallest to largest)	Low WOB (Overall)	Med WOB (Overall)	High WOB (Overall)
1	Under Drift Mill	Full Drift Mill	Under Drift Mill
2	Tricone	Under Drift Mill	Full Drift Mill
3	Full Drift Mill	PDC Mill	PDC Mill
4	PDC Mill	Tri-cone	Tri-cone
5	n/a	Offset Mill	Offset Mill

ROP (Rate of Penetration) vs WOB (Weight on Bit)

The ROP values were recorded during the experiment (**Table 6)** with the intention of determining whether WOB has a strong correlation with ROP or not. By analyzing the collected data, it was concluded that there is a correlation between the two for a few different milling assemblies but not for all. The higher weight on bit value did not necessary gave a faster ROP.

For example, there is a positive relationship between WOB and ROP for the under drift mill, and the full drift mill but not for the offset mill and the PDC mill. The reason why the offset mill and the PDC mill have slower ROP values at higher WOB value is because these mills are more aggressive and can chew through the plug. As a result, the higher weight on bit value does not equate to faster ROP for the offset mill and the PDC mill.

Tri-cone mill had a specific range for faster ROP at medium and high WOB while performing poor ROP at lower WOB.

However, looking **Table 6**, there is a strong correlation between ROP and the debris sizes. For instance, on **Table 3**, the drilling assembly that produced the smallest cutting sizes was with the tri-cone which happens to have the lowest ROP value. On the other hand, the plug milling assembly that produces the largest cutting size is the Offset Mill and the PDC and it is shown to have the fastest ROP value on **Table 6**. The under drift mill and the full drift mill are in the middle of the pack in terms in debris size and ROP.

Table 6: Mill/Bit ROP vs Weight on Bit

	Mill/Bit ROP (in/min)					
Weight on Bit	**Under Drift Mill**	**Full Drift Mill**	**Tri-cone**	**Offset Mill**	**PDC**	**Average ROP Speed based on WOB**
LOW	0.205	0.212	0.001	0.627	N/A	0.261
MEDIUM	0.464	0.428	0.544	1.097	0.948	0.633
HIGH	0.924	0.477	0.448	0.235	0.518	0.521
Average ROP Speed by BHA	0.531	0.372	0.331	0.653	0.733	-
Ranked based on Speed (slowest to Fastest)	3	2	1	4	5	

Conclusions

- The weight on bit does not appear to affect the performance of the drilling assembly in terms of creating smaller cutting sizes.

- The tri-cone produced smaller cutting sizes while the offset mill and the PDC mill produced larger cutting sizes. The under drift and the full drift mill are in the middle of the range.

- Under drift mill and the full drift mill generated smallest debris particles within the small particle group than Tri-cone, Offset mill and PDC mill.
- There is a positive correlation between WOB and ROP for underdrift mill and full drift mill.
- The ROP of Offset mill and the PDC dropped significant when the WOB is too high.
- There is a strong correlation between ROP and the debris sizes. Slower ROP generated smaller cuttings while faster ROP generate larger cuttings.

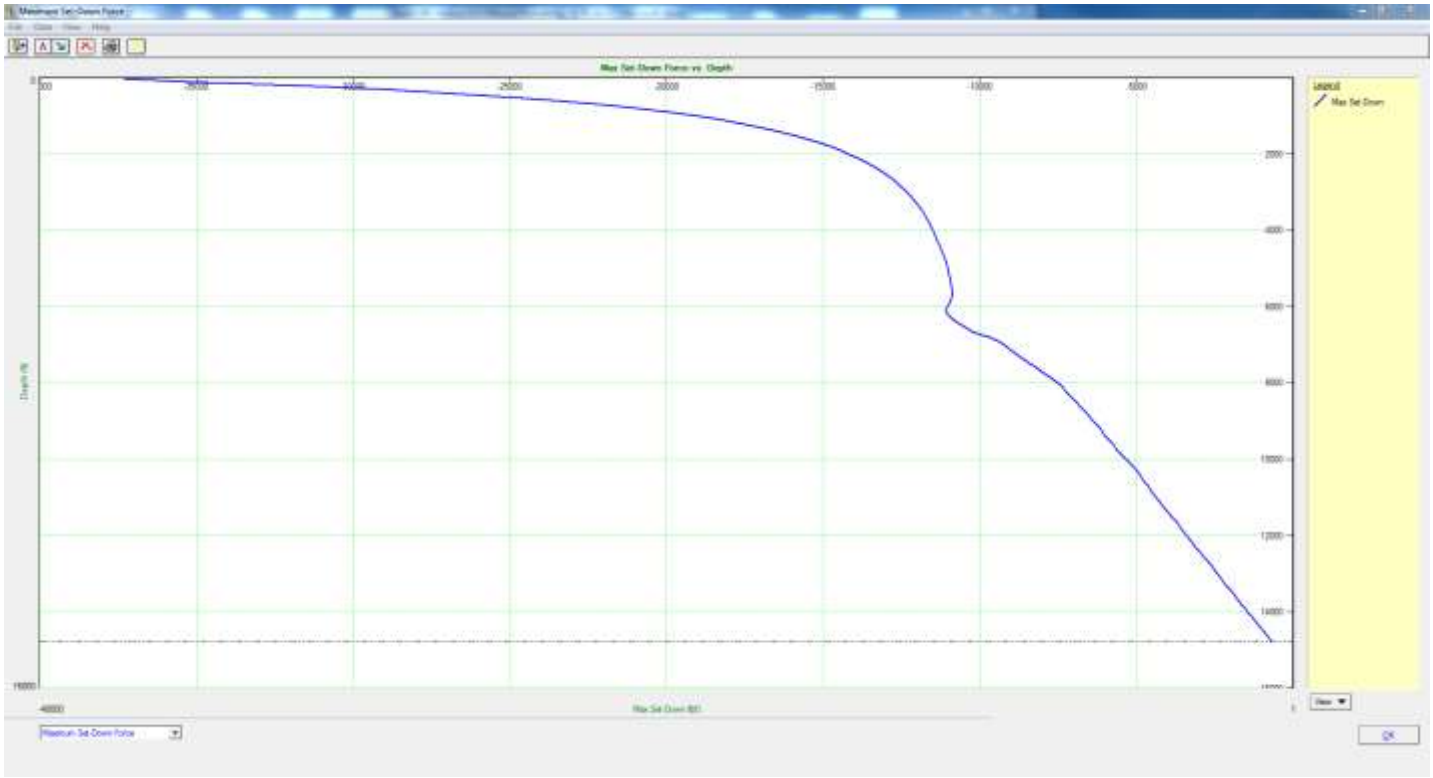
Acknowledgements

The authors will like to thank Jane Ga Lee, Essential Energy Services, Thru Tubing Solutions, Magnum Oil Tools and Shell Canada Ltd for their contribution and assistance in collecting and analysizing the data.

References

1. Yeung, J., Opel, S., Smalley, E. 2014. Optimizing CT Milling Efficiency with the Use of Real-Time CT Modeling Software. Paper SPE 173668 prepared for presentation at the SPE/ICoTA Coiled Tubing and Well Intervention Conference and Exhibition, 24-25 March 2015, The Woodlands, Texas.

Appendix 1: Tubing Force Analysis model (Maximum set down force vs Depth)



Appendix 2: Pictures of different sizes of metal debris (Sorted based on debris sizes)



Appendix 3: Pictures of different sizes of Composite Material (Sorted based on debris sizes)



Appendix 4: Pictures of different sizes of Elastomer Material (Sorted based on debris sizes)

