SAND2021-11677C

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Advanced Analytics of Rig Parameter Data Using Rock Reduction Model Constraints for Improved Drilling Performance

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Geothermal Rising Conference

San Diego, CA

October 3-6, 2021

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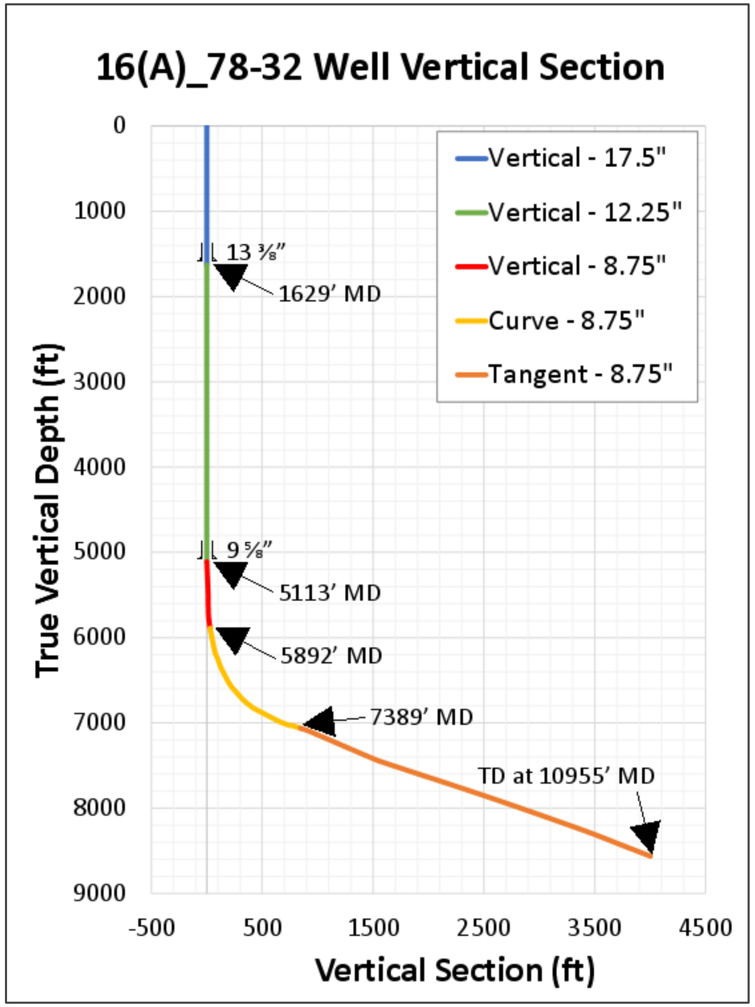
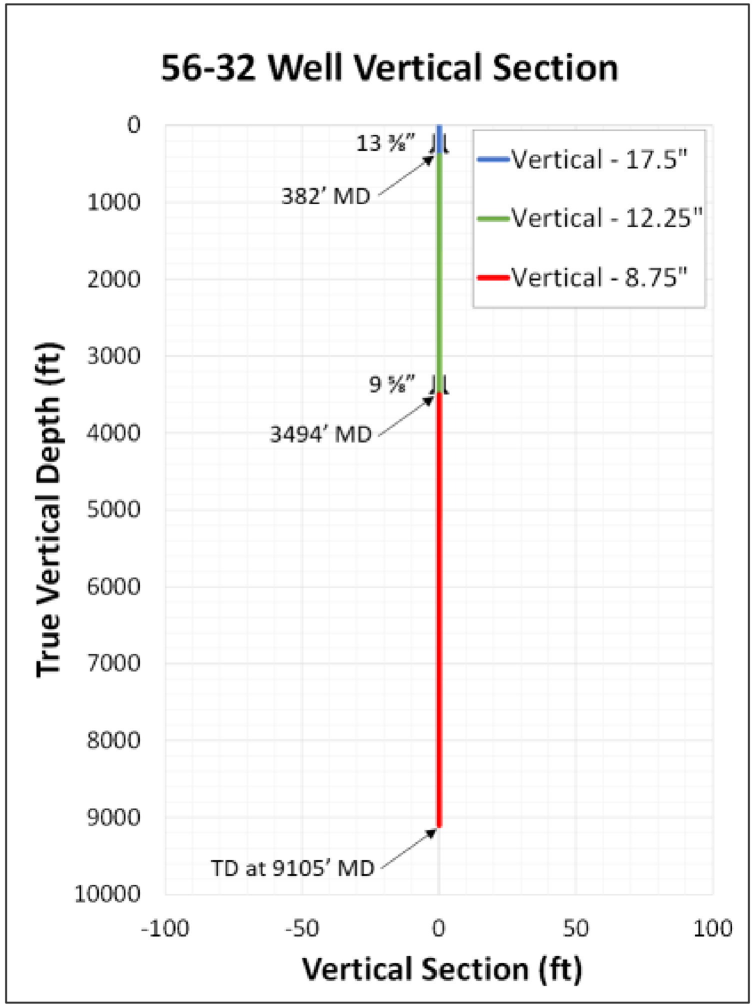
Introduction

- During drilling, monitoring and evaluation of multiple parameters ideally favor improved productivity and cost savings
- A method is needed to enable the intuitive interpretation of response parameters and is amenable to implementation in computational algorithms for real-time evaluation
- A method is demonstrated whereby drilling response parameters may be interpreted for improved drilling performance
- This analysis is not an exhaustive assessment but rather an overview of representative bit performance that demonstrates the application of the approach using rock reduction constraints
- Drilling data from the Utah FORGE site have been used for the analyses

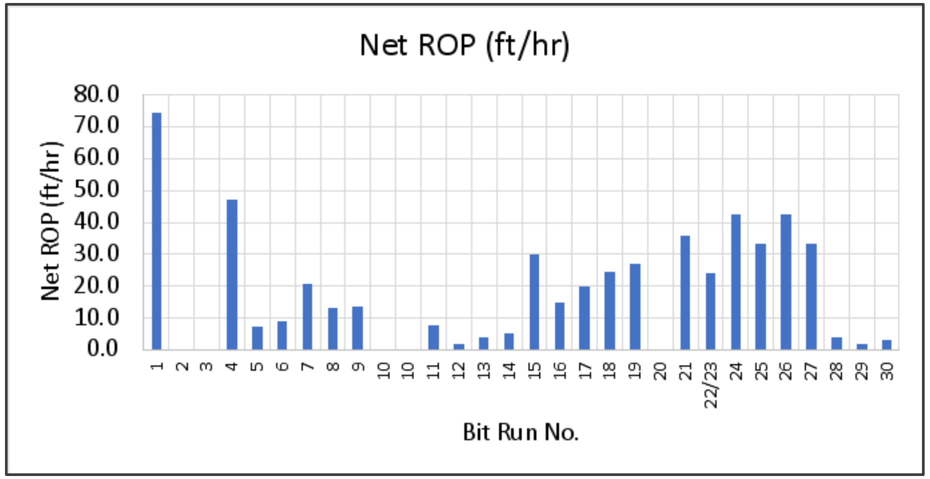
Utah FORGE Drilling Program

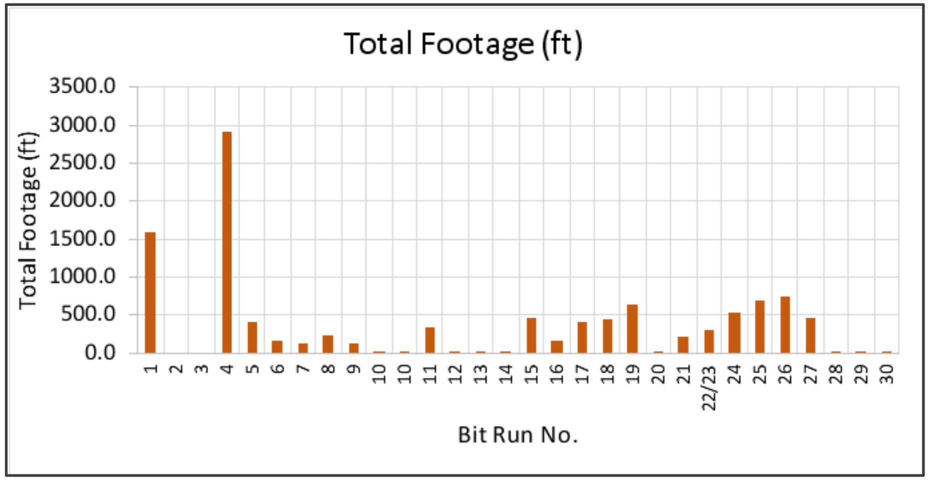




FORGE Well 16(A)_78-32

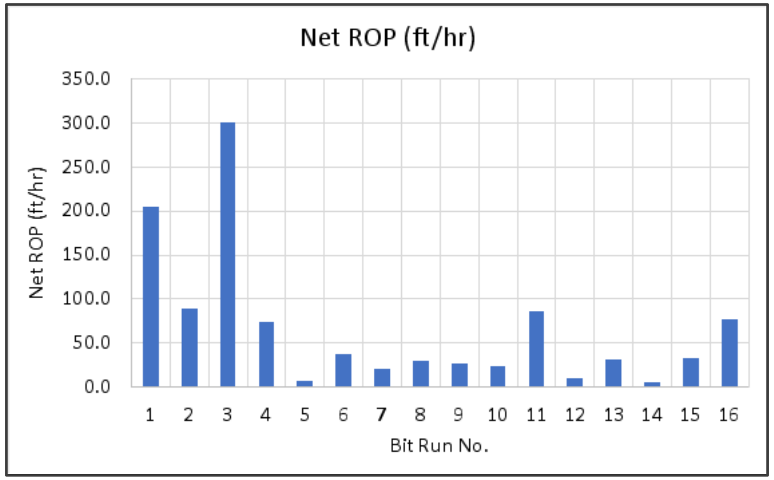
Bit Run No.	Manufacturer	Type	Serial No.	BHA	Bit Dia. (in)	Depth Start (ft)	Depth End (ft)	Total Footage (ft)	Time on Bottom (hrs)	Net ROP (ft/hr)
1	NOV ReedHycalog	TKC76-C5 PDC	A275580	Surface BHA	17.50	28.0	1629.0	1601.0	21.5	74.5
2	NOV ReedHycalog	TKC66-R1 PDC	E266453	2	12.25	-	-	-	3.0	-
3	Smith	GF 15BODJPS TRI-CONE	RK6139	3	12.25	1629.0	1644.0	-	0.5	-
4	NOV ReedHycalog	TKC66-R1 PDC	E266453	4	12.25	1644.0	4552.0	2908.0	61.5	47.3
5	Smith	MDSi616	JM 7398	5	12.25	4552.0	4964.0	412.0	55.0	7.5
6	Smith	Z713S	JP4755	6	12.25	4964.0	5113.0	149.0	16.5	9.0
7	Ulterra	GTX63	R28DF	-	8.75	4987.0	5112.0	125.0	6.0	20.8
8	Smith	XS616	JV2705	9	8.75	5113.0	5345.0	232.0	17.5	13.3
9	Ulterra	U616M PDC	54132	10	8.75	5345.0	5469.0	124.0	9.0	13.8
10	CCI - Canamera 713	Core	462-06	11	8.75	5469.0	5495.0	26.0	0.0	0.0
10	CCI - Canamera 713	Core	462-06	12	8.75	5495.0	5504.0	9.0	0.0	0.0
11	NOV ReedHycalog	TKC66-P3 PDC	A271699	14	8.75	5504.0	5846.0	342.0	43.5	7.9
12	nine blade core bit	Core	Core	15	8.75	5846.0	5856.0	10.0	5.0	2.0
13	Ulterra	U616M	54131	16	8.75	5856.0	5858.0	2.0	0.5	4.0
14	CCI - Canamera 713	Core	Core	17	8.75	5858.0	5892.0	34.0	6.5	5.2
15	NOV ReedHycalog	TKC63-C7	A255857	18	8.75	5892.0	6360.0	468.0	15.5	30.2
16	NOV ReedHycalog	SKC613M-O1C	A232400	20	8.75	6360.0	6526.0	166.0	11.0	15.1
17	NOV ReedHycalog	SKC513M-O1C	A276122	22	8.75	6526.0	6945.0	419.0	21.0	20.0
18	NOV ReedHycalog	FTKC63-O1	A276121	23	8.75	6945.0	7389.0	444.0	18.0	24.7
19	NOV ReedHycalog	TKC63-C7	A255857	30	8.75	7389.0	8024.0	635.0	23.5	27.0
20	OTHER	Mill	Mill	-	-	8024.0	8025.0	1.0	-	-
21	NOV ReedHycalog	SKC513M-O1C	A276122	34	8.75	8025.0	8241.0	216.0	6.0	36.0
22/23	NOV ReedHycalog	SKC613M-O1C	A230682	35	8.75	8241.0	8535.0	294.0	6.0	24.0
24	NOV Reed Hycalog	TKC63-O1	A270819	38	8.75	8535.0	9064.0	529.0	12.5	42.3
25	NOV Reed Hycalog	TKC63-O1	A270978	39	8.75	9064.0	9748.0	684.0	20.5	33.4
26	NOV Reed Hycalog	TKC63-P1	A271436	41	8.75	9748.0	10490.0	742.0	17.5	42.4
27	NOV Reed Hycalog	TKC63-P1	A271437	42	8.75	10490.0	10955.0	465.0	14.0	33.2
28	CCI - Canamera 713	Core 713	3409-01	47	8.75	10955.0	10971.0	16.0	4.0	4.0
29	Ulterra	PDC U613M	47954	48	8.75	10971.0	10973.0	2.0	1.0	2.0
30	CCI - Canamera 713	Core 713	77302	49	8.75	10973.0	10987.0	14.0	4.5	3.1

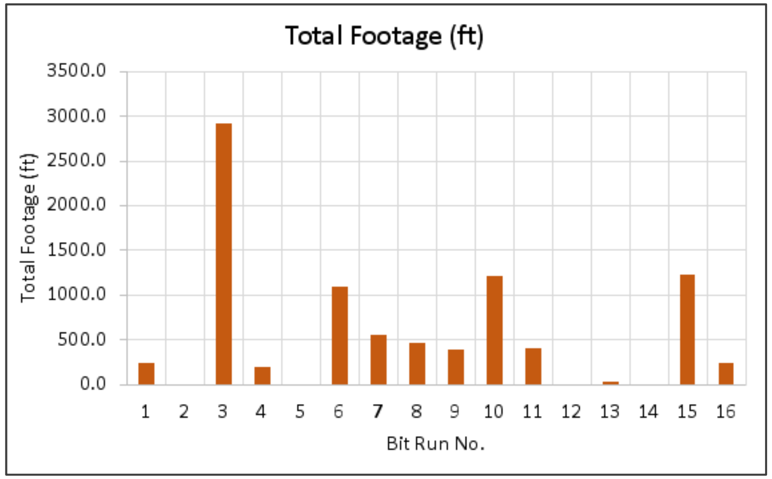




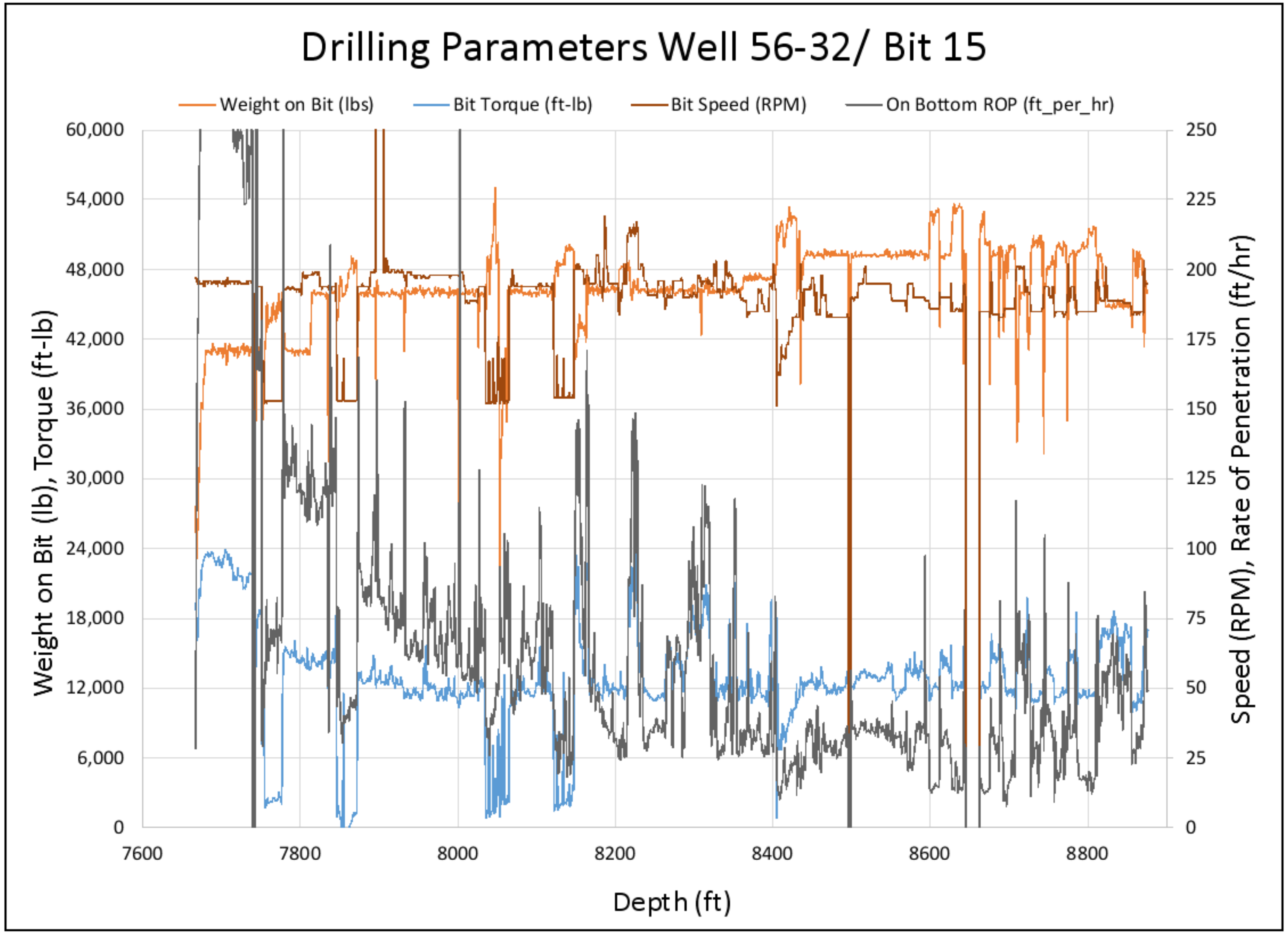
FORGE Well 56-32

Bit Run No.	Manufacturer	Type	Serial No.	BHA	Bit Dia. (in)	Depth Start (ft)	Depth End (ft)	Total Footage (ft)	Time on Bottom (hrs)	Net ROP (ft/hr)
1	ReedHycalog	TK59-B1	A252419	1	17.50	134.0	381.0	247.0	1.2	205.8
2	-	M-22	-	-	12.25	381.0	390.0	9.0	0.1	90.0
3	ReedHycalog	TKC66-R1	A266974	2	12.25	390.0	3309.0	2919.0	9.7	300.9
4	ReedHycalog	TK63-A1A	A268226	3	12.25	3309.0	3500.0	191.0	2.6	73.5
5	-	GX-177	-	4	8.75	3500.0	3506.0	6.0	0.8	7.5
6	ReedHycalog	TKC73-H1	A275660	4	8.75	3506.0	4595.0	1089.0	28.9	37.7
7	-	EP5475	5042714	5	8.75	4595.0	5143.0	548.0	26.2	20.9
8	ReedHycalog	TKC63-P1	A277166	6	8.75	5143.0	5610.0	467.0	15.5	30.1
9	ReedHycalog	TKC63-P1	A271436	7	8.75	5610.0	5999.0	389.0	14.8	26.3
10	ReedHycalog	FTKC73-A1	A275803	8	8.75	5999.0	7208.0	1209.0	52.1	23.2
11	ReedHycalog	FTKC73-A1	A276121	9	8.75	7208.0	7620.0	412.0	4.8	85.8
12	E6	Hammer	-	-	8.75	7620.0	7628.0	8.0	0.8	10.0
13	ReedHycalog	FTKC63-A1	A276121	-	8.75	7628.0	7663.0	35.0	1.1	31.8
14	E6	Hammer	-	-	8.75	7663.0	7667.0	4.0	0.8	5.0
15	ReedHycalog	TKC63-P1	A271437	10	8.75	7667.0	8900.0	1233.0	37.0	33.3
16	ReedHycalog	FTKC83-A3	A276071	11	8.75	8900.0	9145.0	245.0	3.2	76.6

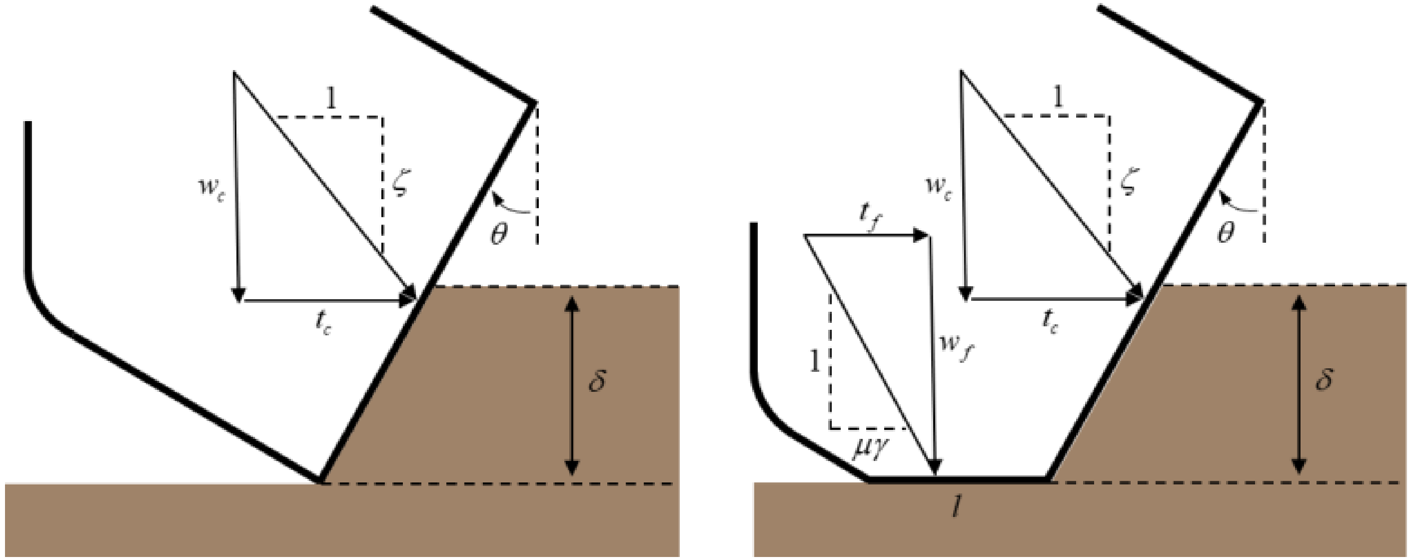




Typical Drilling Parameter Data



Rock Reduction Model Constraint (Detournay and Defourny, 1992)



ε intrinsic specific energy
ζ cutting force ratio
μ friction coefficient

F_n vertical cutter force
F_s horizontal cutter force
A frontal area of cut

$$E = \frac{F_S}{A}$$ (1) Specific Energy

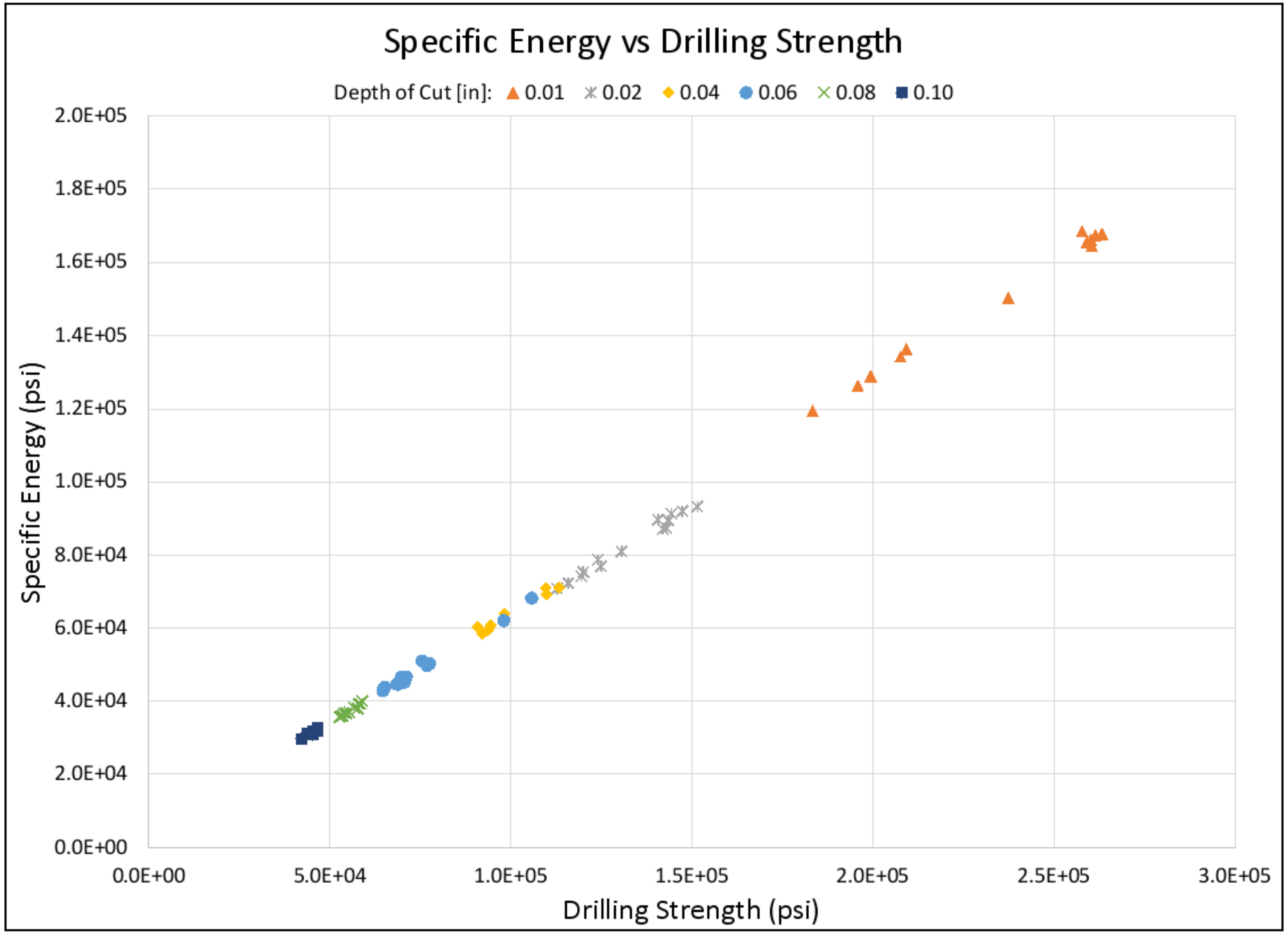
$$S = \frac{F_n}{A}$$ (2) Drilling Strength

$$E = \varepsilon \qquad S = \zeta\varepsilon$$ (3) Sharp Cutter

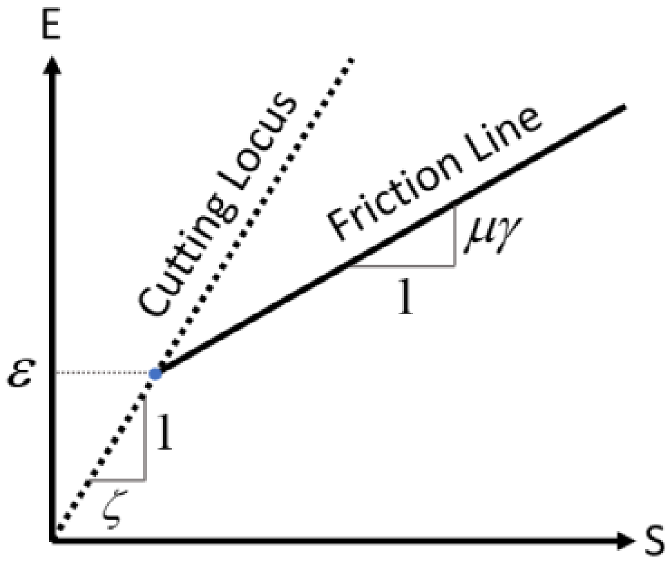
$$E = E_0 + \mu S$$ (4) Blunt Cutter

$$E_0 = (1 - \mu\zeta)\varepsilon$$ (5) Intercept

Single Cutter Data (Glowka, 1987)



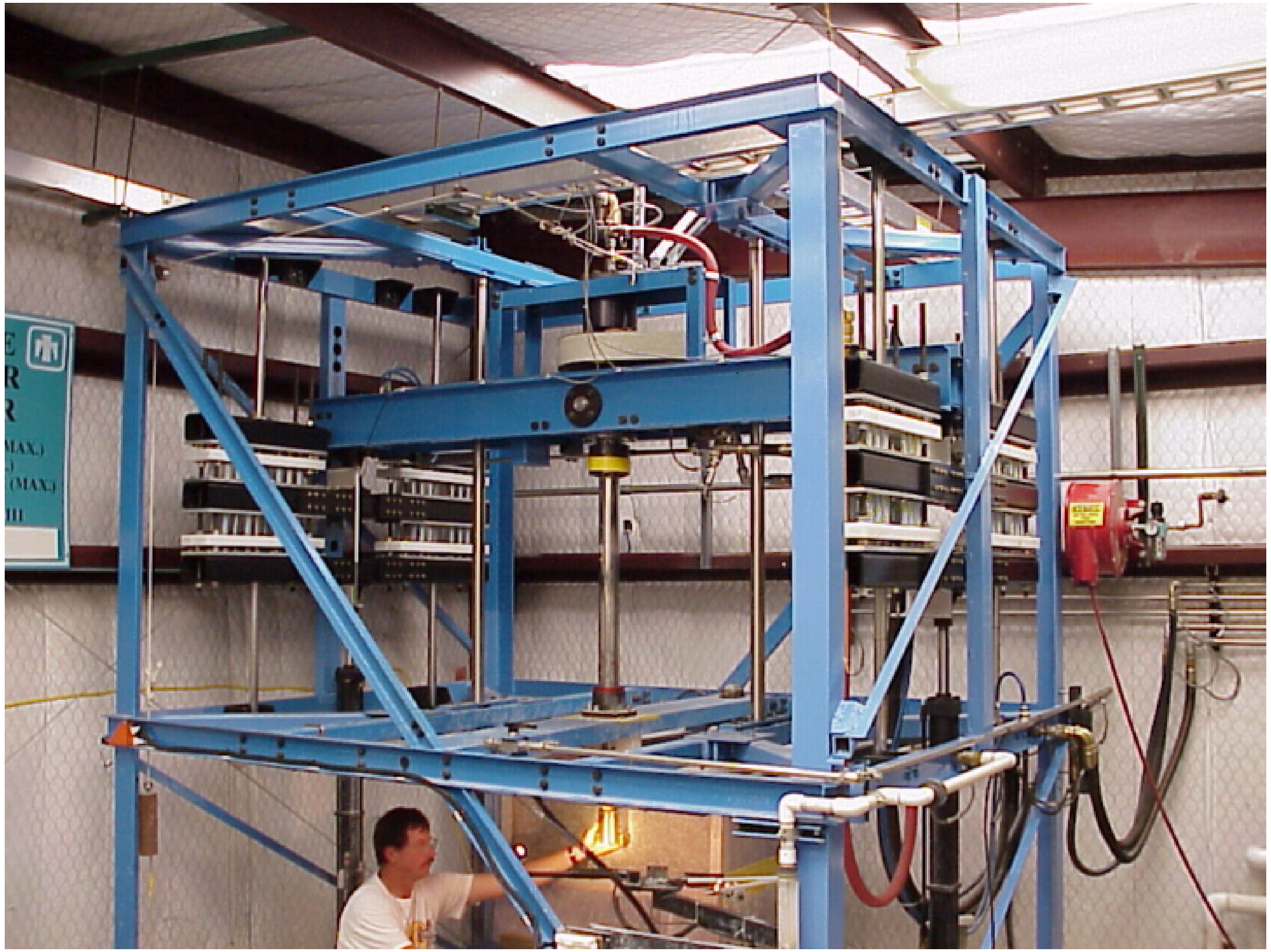
Full Bit Model (Detournay and Defourny, 1992)



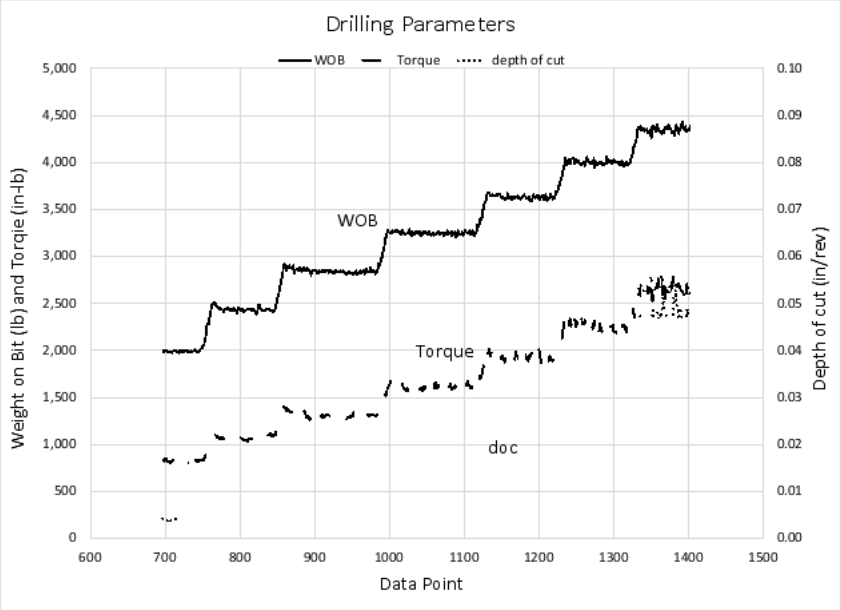
r bit radius
γ unitless bit constant
δ depth of cut per revolution

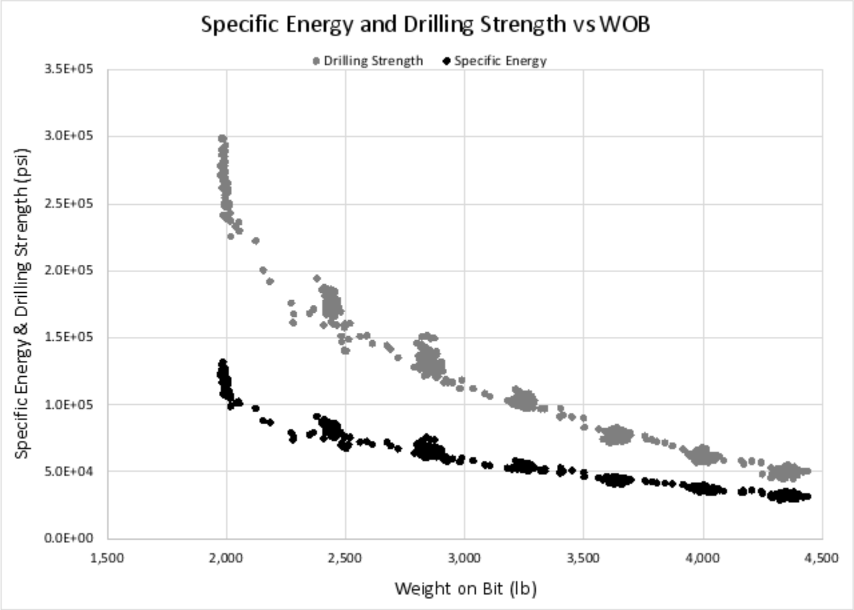
$\frac{2T}{r} = (1 - \mu\gamma\zeta)\varepsilon\delta r + \mu\gamma W$	(6) Torque constraint
$E = \frac{2T}{r^2\delta}$	(7) Bit Specific Energy
$S = \frac{W}{r\delta}$	(8) Bit Drilling Strength
$E = E_0 + \mu\gamma S$	(9) Friction Line
$E_0 = (1 - \beta)\varepsilon$	(10) Intercept
$\beta = \gamma\mu\zeta$	(11) $\mu\gamma$ Friction Line Slope

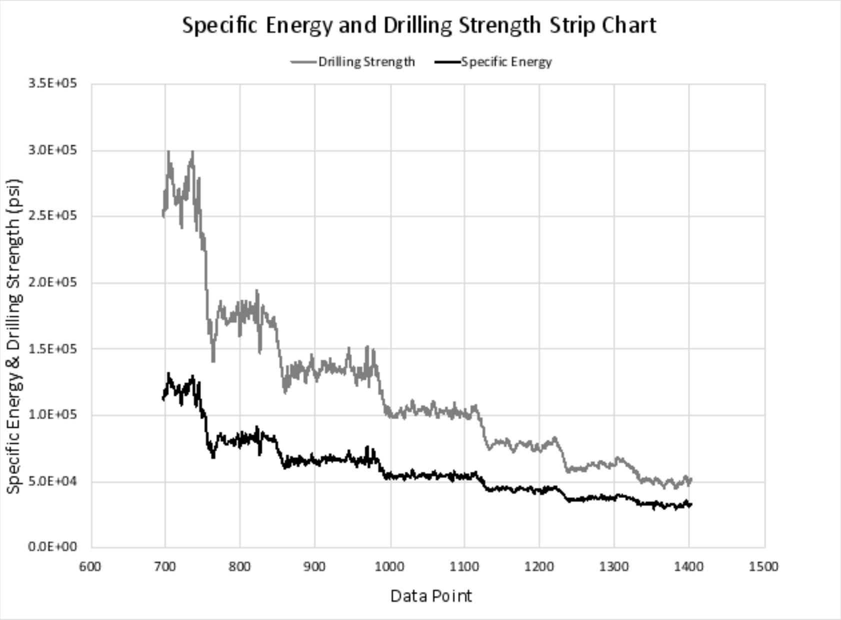
Laboratory Validation

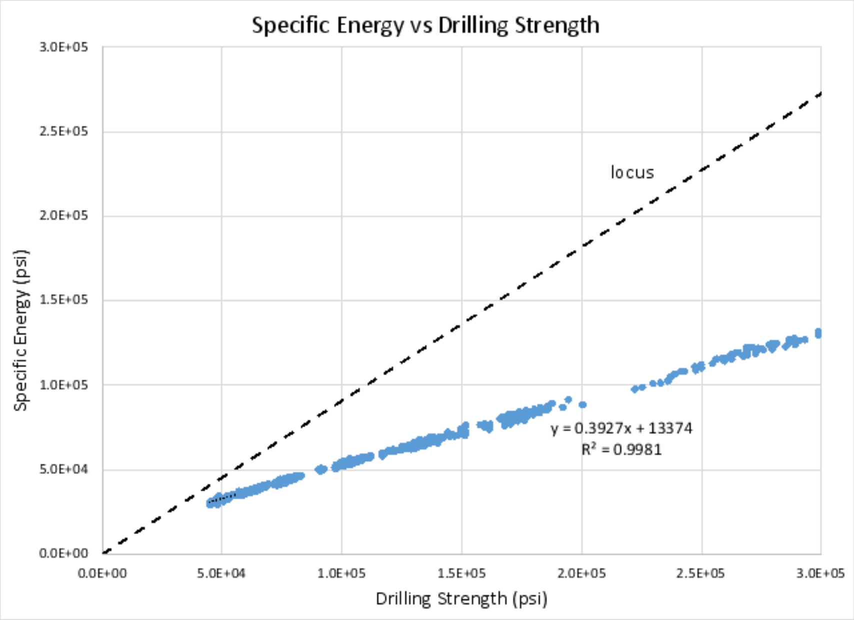


Laboratory Validation (cont.)

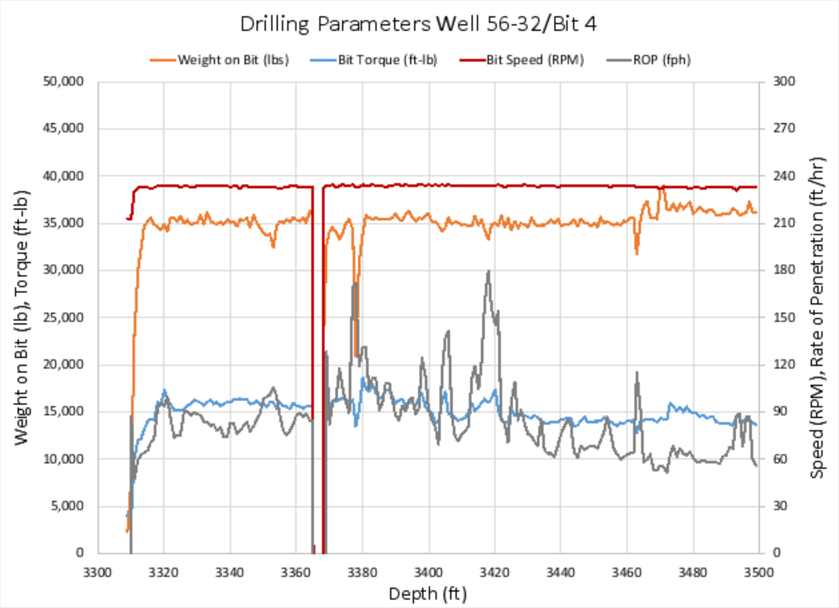


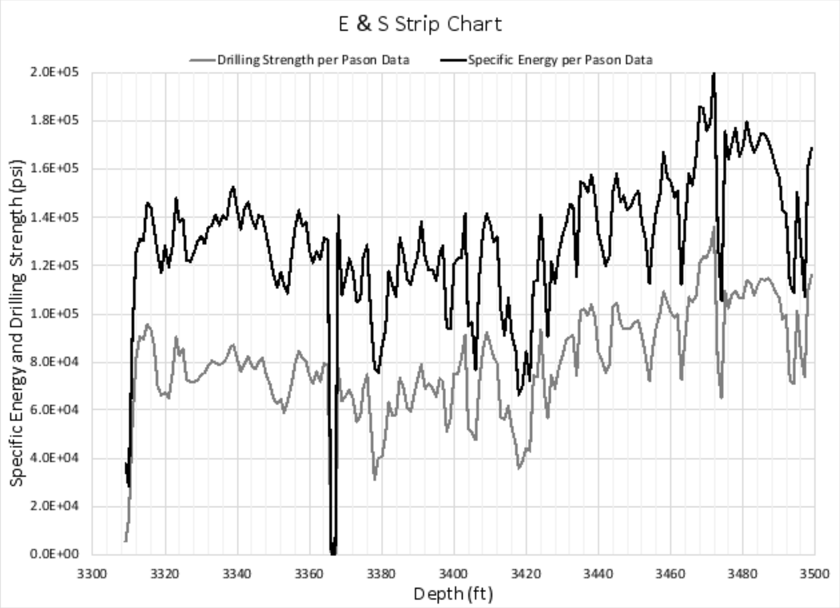


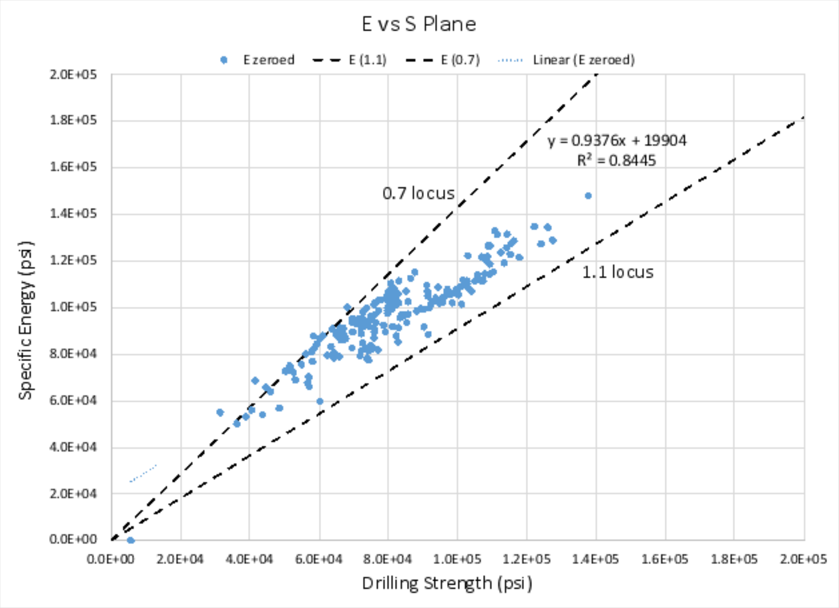




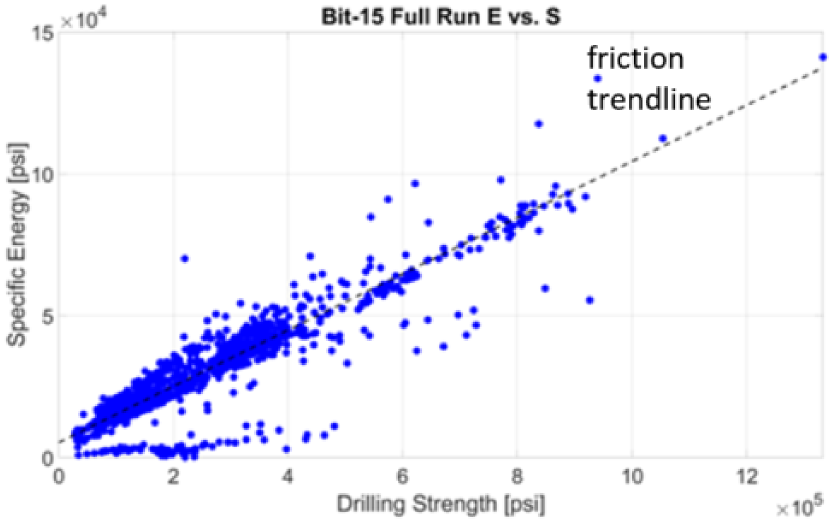
Utah FORGE Bit Evaluations - Formation intrinsic specific energy

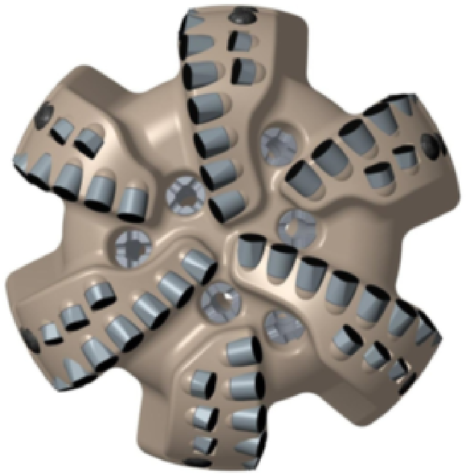


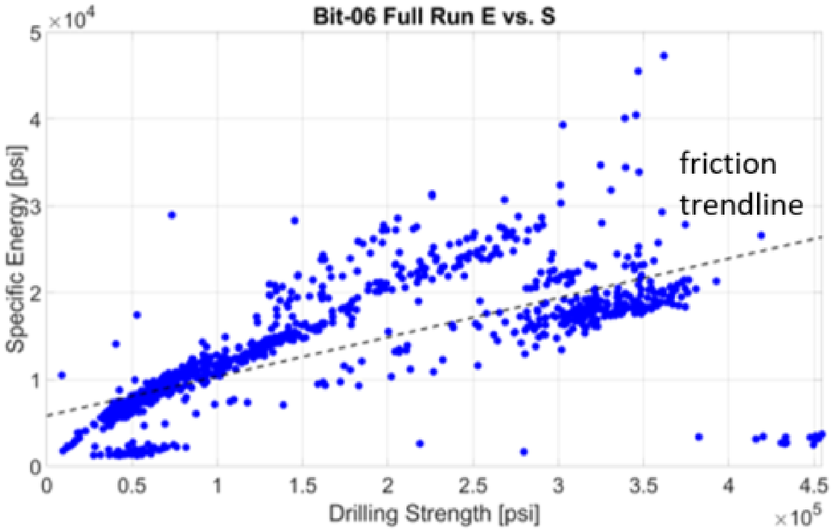




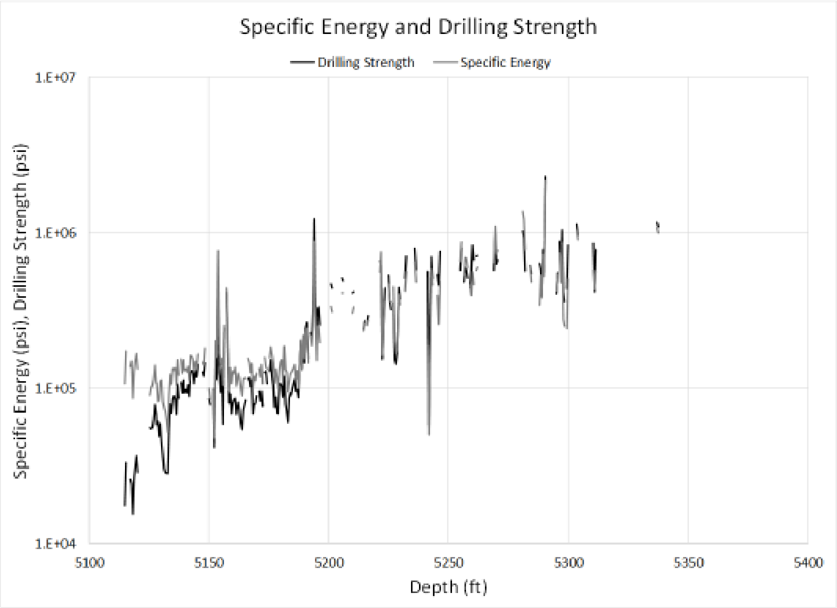
Utah FORGE Bit Evaluations – Bit Response

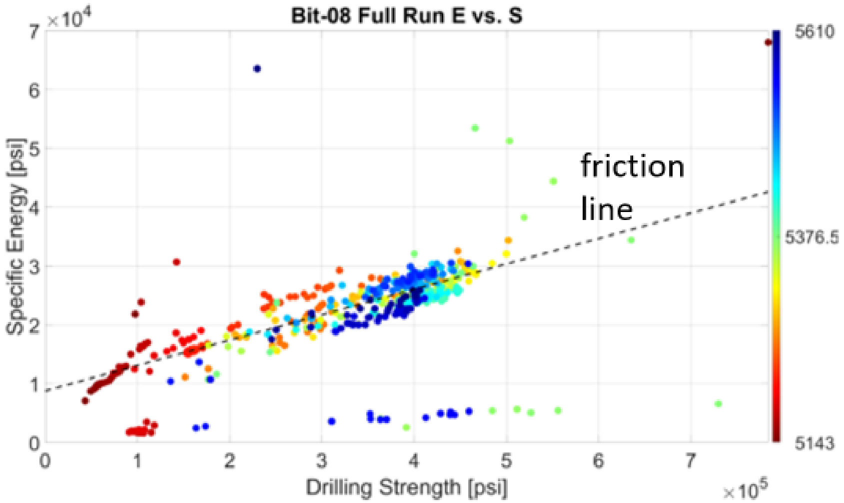


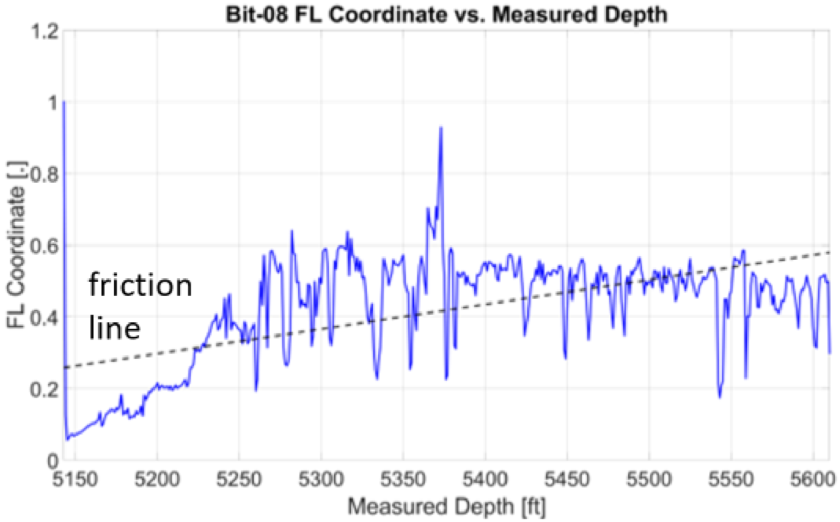




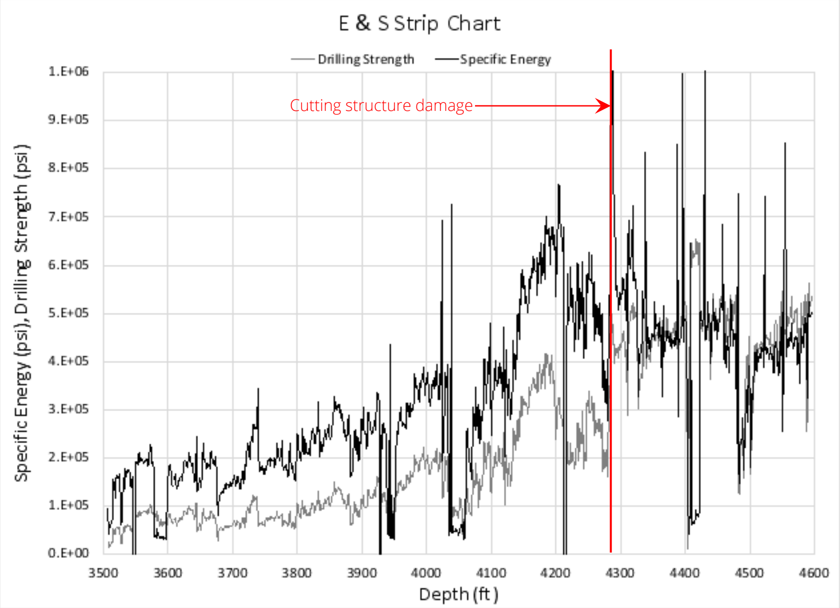
Utah FORGE Bit Evaluations – Bit Response (cont.)

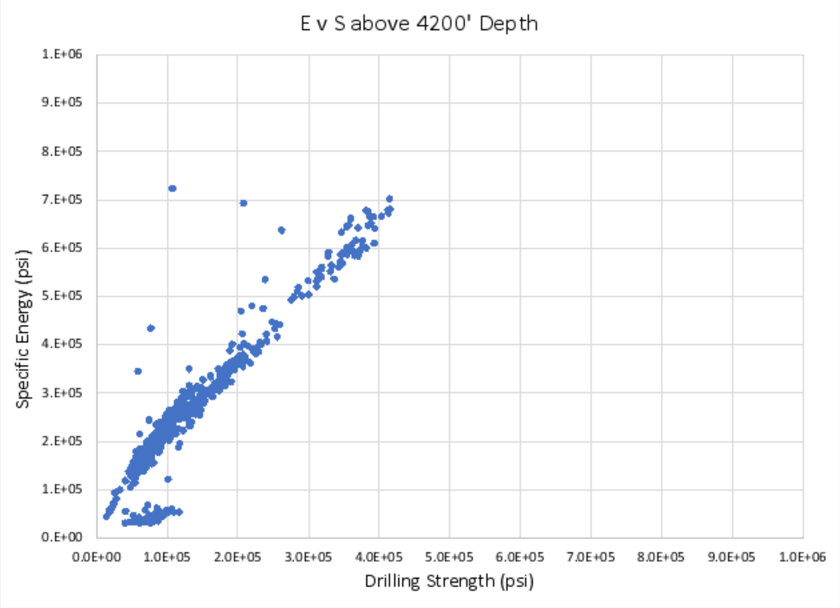


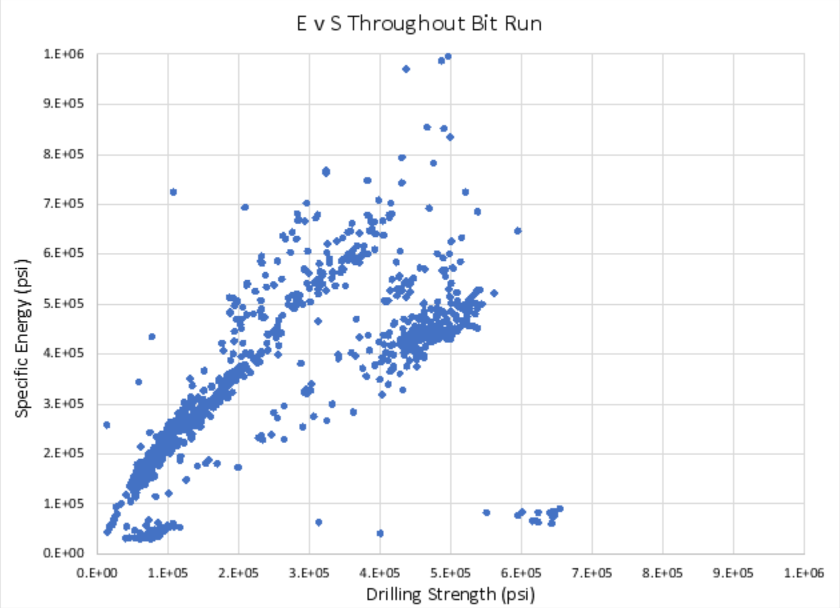




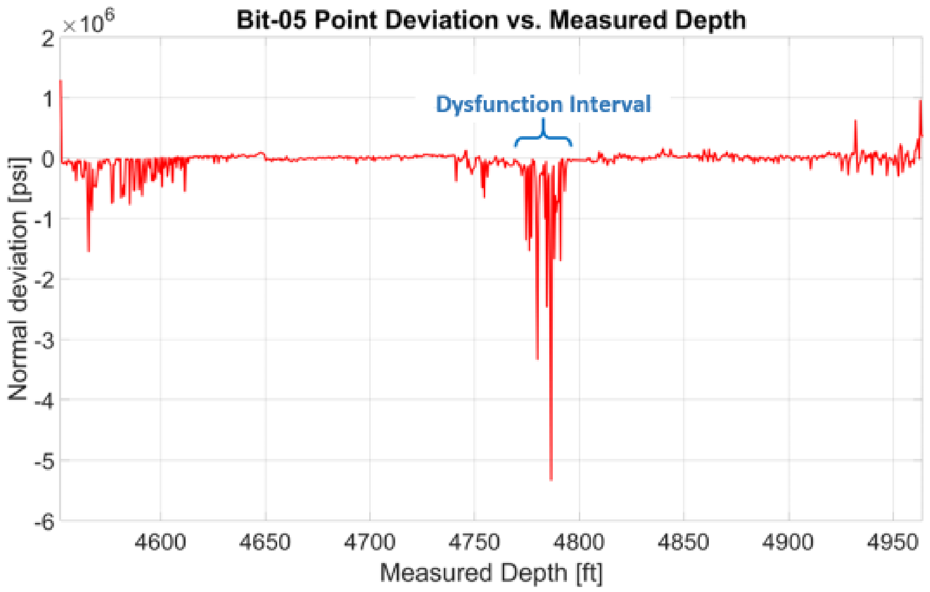
Utah FORGE Bit Evaluations – Cutting Structure Damage

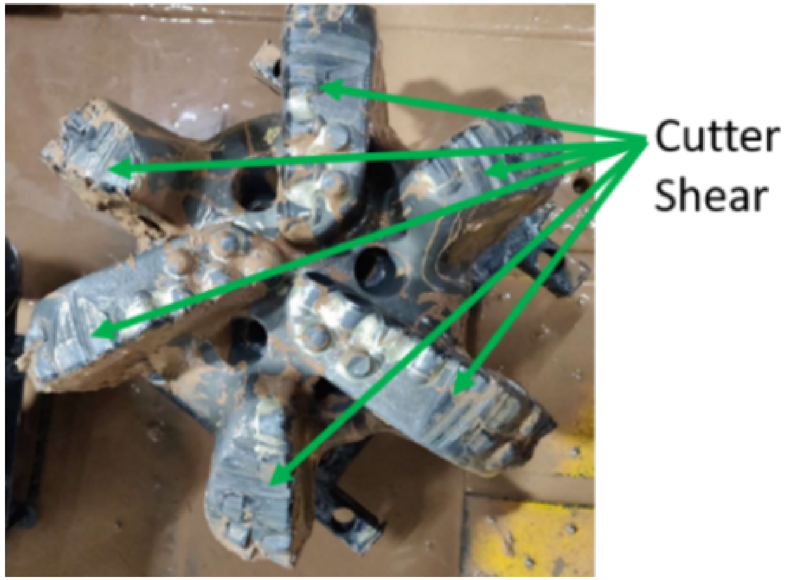


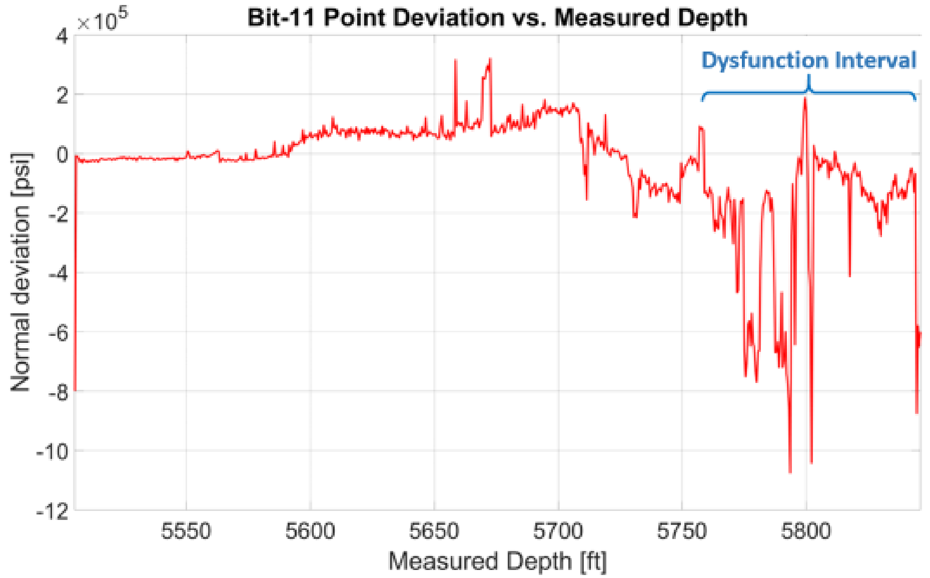


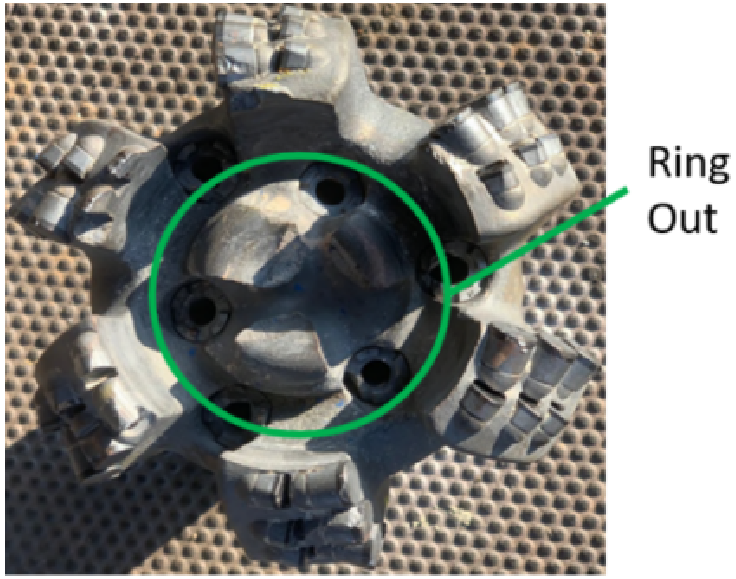


Utah FORGE Bit Evaluations – Cutting Structure Damage (cont.)



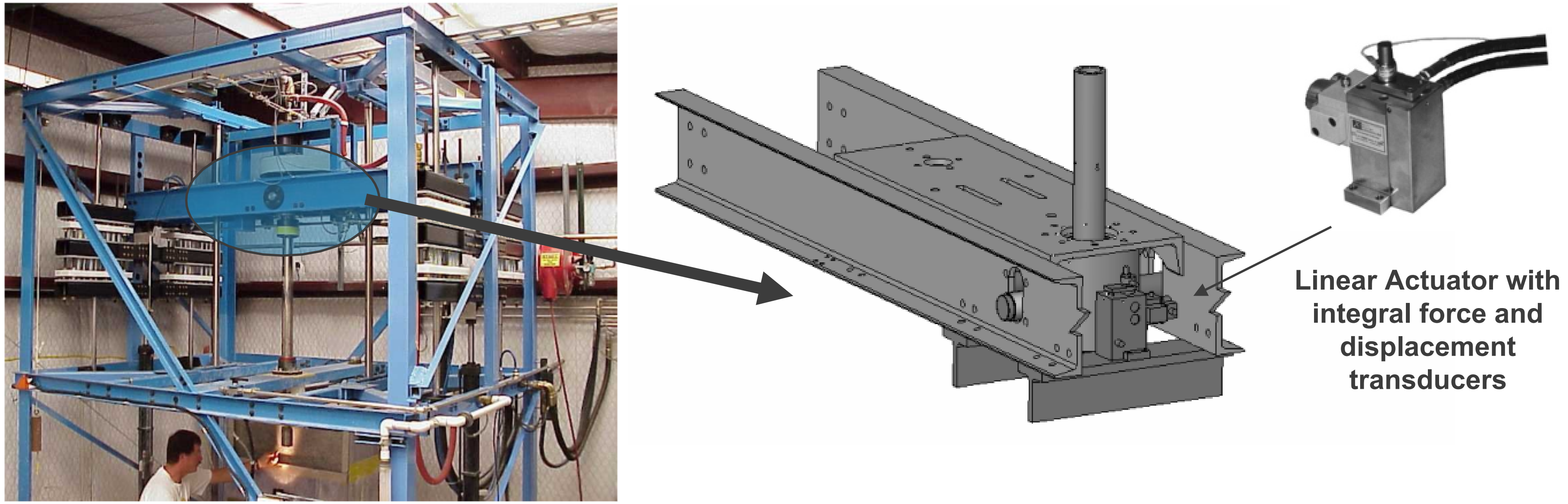


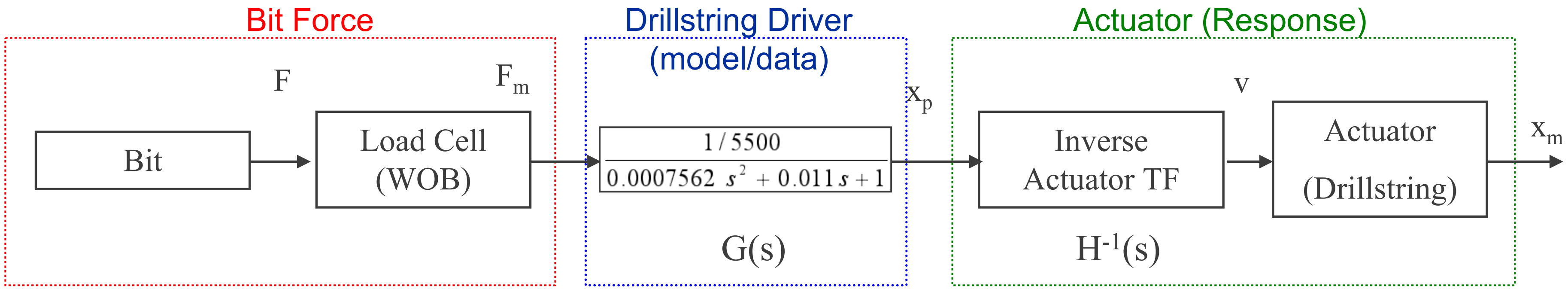




Utah FORGE Bit Evaluations – Drilling Vibration Detection

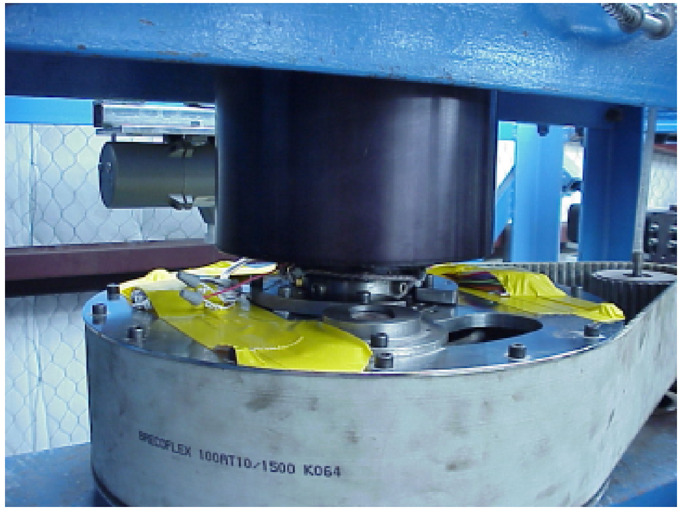
Sandia Hard Rock Drilling Facility Simulations with Axial Drillstring Compliance

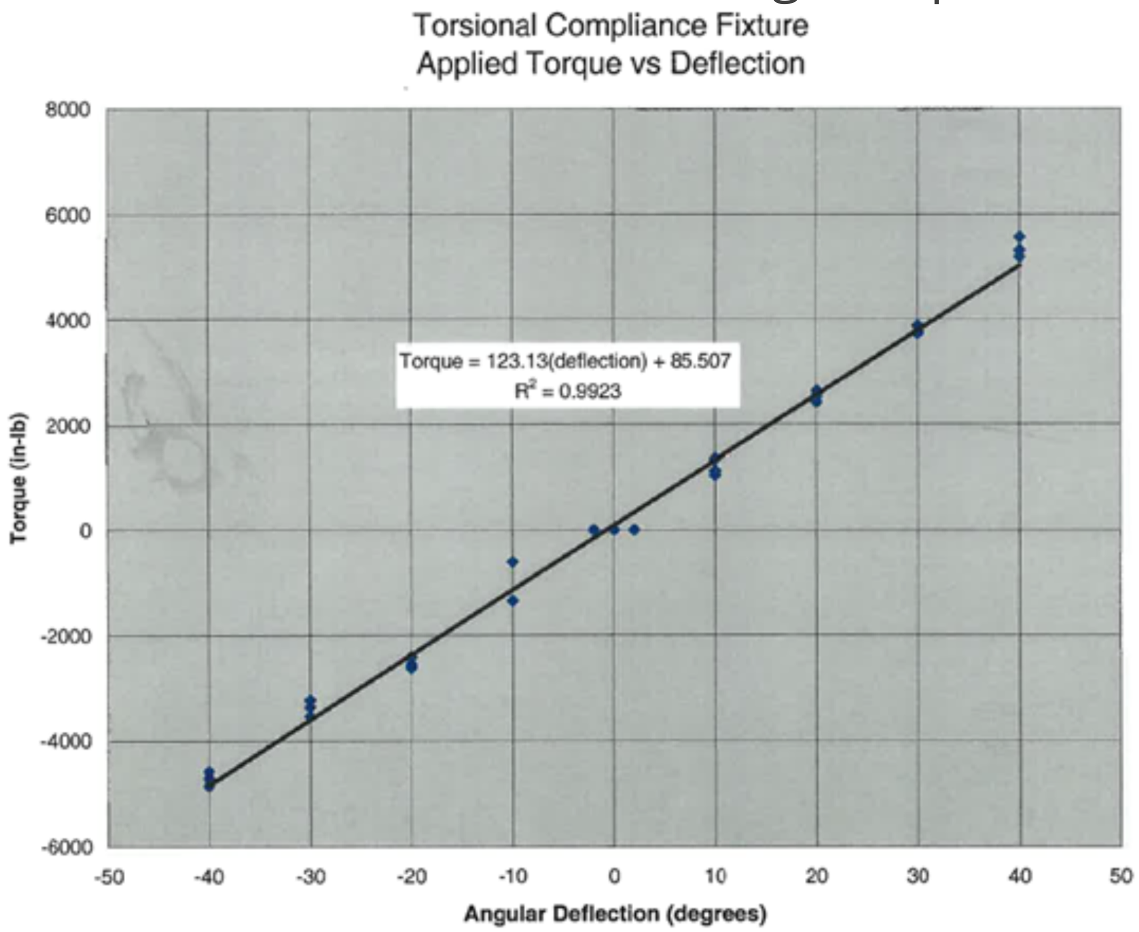




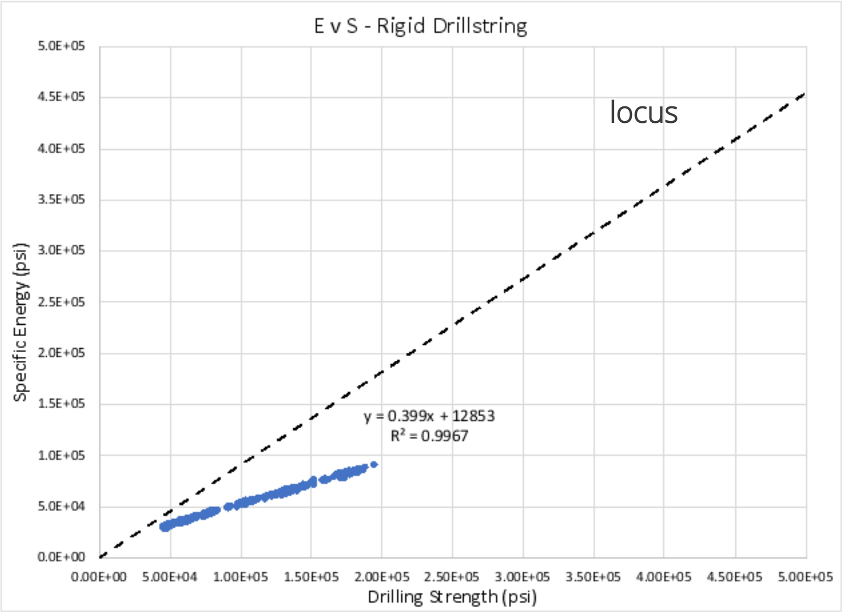
Utah FORGE Bit Evaluations – Drilling Vibration Detection (cont.)

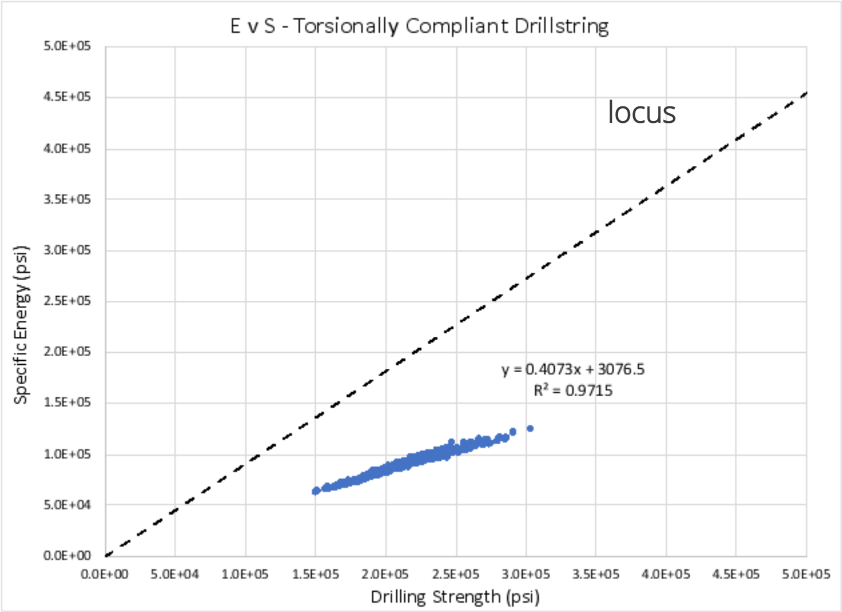
Sandia Hard Rock Drilling Facility Simulations with Rotational Drillstring Compliance

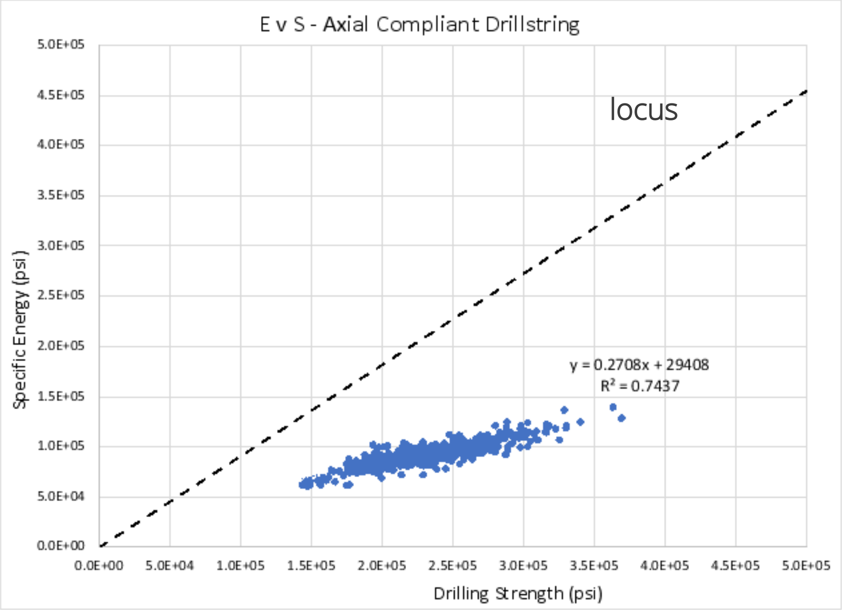


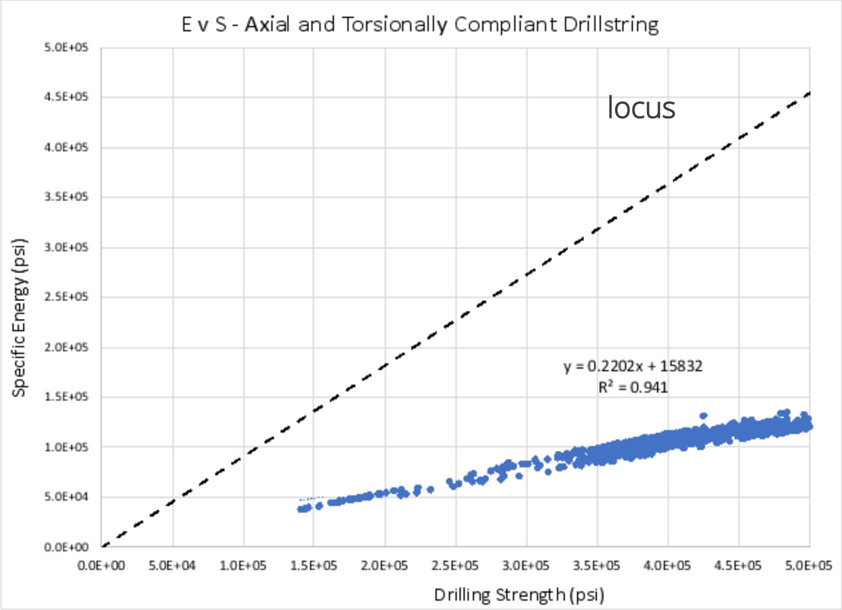


Utah FORGE Bit Evaluations – Drilling Vibration Detection (cont.)









Drilling Cost Constraints

$$CPF = \frac{BC + RR(DT + TT)}{L} \quad (A-1)$$

$$DT = \frac{L}{ROP} \quad (A-2)$$

$$\bar{D} = D_0 + \frac{L}{2} \quad (A-3)$$

$$TT = \frac{\bar{D}}{TR} = \frac{D_0}{TR} + \frac{L}{2TR} \quad (A-4)$$

$$k_1 = \frac{RR}{BC} \quad (A-9)$$

$$k_2 = \frac{\left(\frac{RR}{BC}\right)}{2TR} = \frac{k_1}{2TR} \quad (A-10)$$

$$CPF' = \frac{1}{L} + \frac{k_1}{ROP} + k_2\left(1 + \frac{2D_0}{L}\right) \quad (A-11)$$

$$CPF = CPF' \times BC \quad (A-12)$$

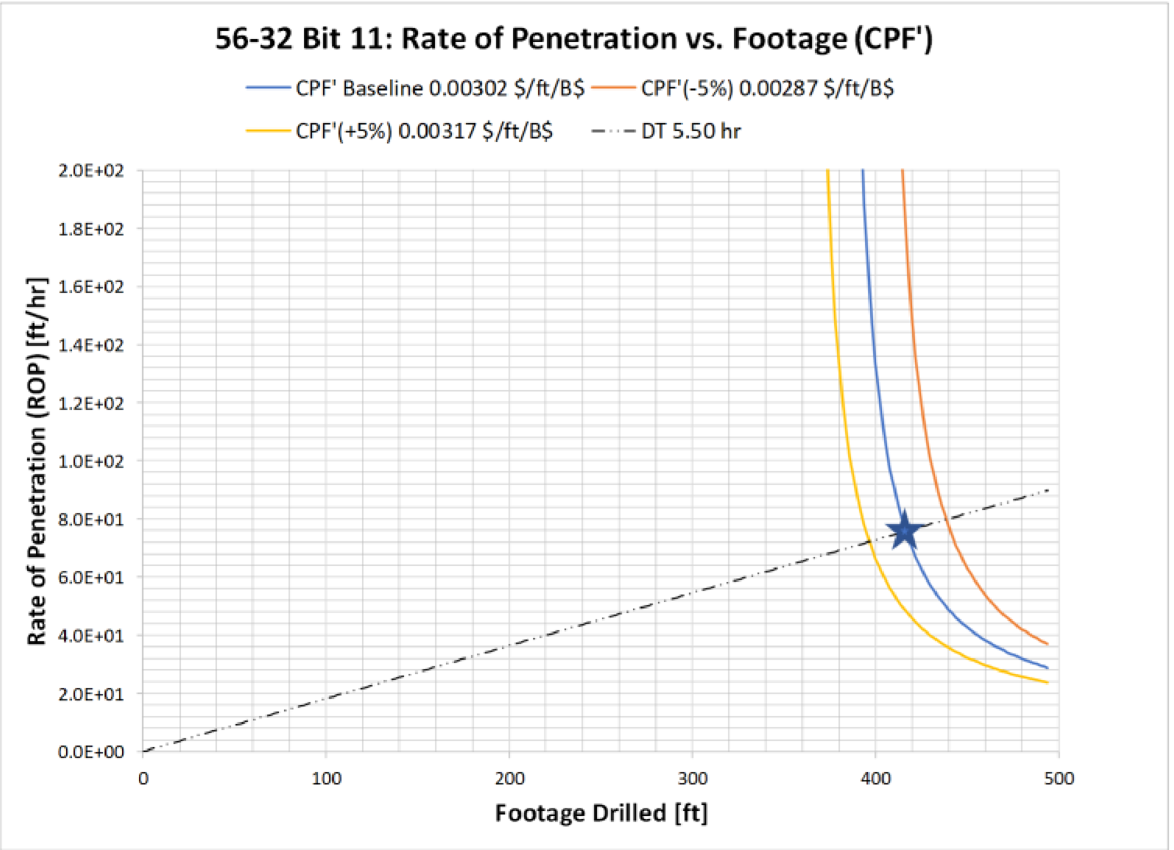
(Bourgoyne, A.J.T., et al, 1986)

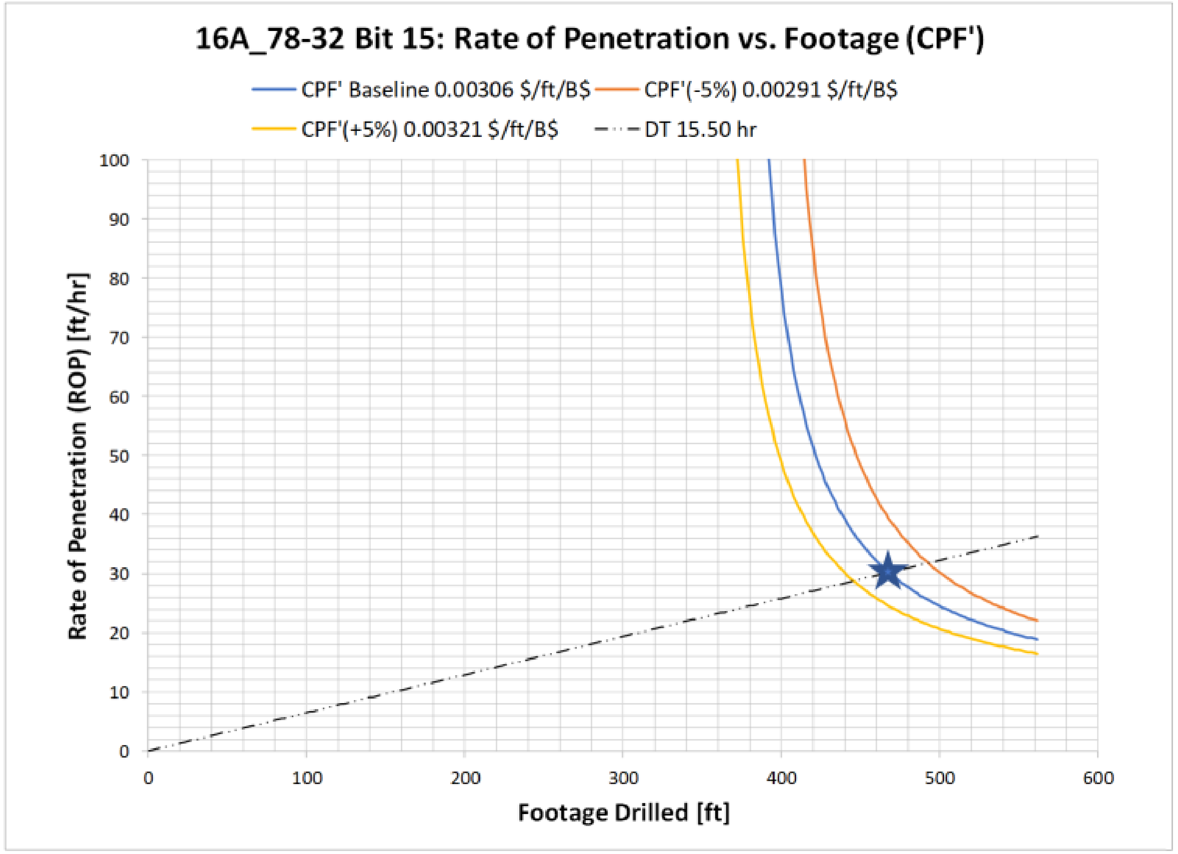
CPF = cost per foot [$/ft]
BC = bit cost [$]
RR = rig rate [$/hr]
DT = drilling time [hr]
TT = tripping time [hr]
L = footage drilled [ft]

D_0 initial interval depth [ft]
$\bar{D}$ average interval depth [ft]

CPF' Contour in ROP-Footage plane

Improve ROP or Footage?





CPF’ Comparisons

Well	Bit No.	Start Depth	Footage Drilled	End Depth	Dbar	ROP	CPF'
16A_78-32	7	4987.0	125.0	5112.0	5049.5	20.8	0.00977
16A_78-32	8	5113.0	232.0	5345.0	5229.0	13.3	0.00626
16A_78-32	15	5892.0	468.0	6360.0	6126.0	30.2	0.00306
16A_78-32	16	6360.0	166.0	6526.0	6443.0	15.1	0.00812
16A_78-32	17	6526.0	419.0	6945.0	6735.5	20.0	0.00371
16A_78-32	18	6945.0	444.0	7389.0	7167.0	24.7	0.00338
16A_78-32	19	7389.0	635.0	8024.0	7706.5	27.0	0.00256
16A_78-32	21	8025.0	216.0	8241.0	8133.0	36.0	0.00594
16A_78-32	22	8241.0	150.0	8391.0	8316.0	25.0	0.00858
16A_78-32	23	8391.0	144.0	8535.0	8463.0	24.0	0.00895
16A_78-32	24	8535.0	529.0	9064.0	8799.5	42.3	0.00270
16A_78-32	25	9064.0	684.0	9748.0	9406.0	33.4	0.00234
16A_78-32	26	9748.0	742.0	10490.0	10119.0	42.4	0.00209
16A_78-32	27	10490.0	465.0	10955.0	10722.5	33.2	0.00321
56-32	6	3506.0	1089.0	4595.0	4050.5	37.7	0.00152
56-32	7	4595.0	548.0	5143.0	4869.0	20.9	0.00296
56-32	8	5143.0	467.0	5610.0	5376.5	30.1	0.00304
56-32	9	5610.0	389.0	5999.0	5804.5	26.3	0.00363
56-32	10	5999.0	1209.0	7208.0	6603.5	23.2	0.00180
56-32	11	7208.0	412.0	7620.0	7414.0	85.8	0.00302
56-32	15	7667.0	1233.0	8900.0	8283.5	33.3	0.00155
56-32	16	8900.0	245.0	9145.0	9022.5	76.6	0.00508

Conclusions

- Bit performance metrics for Utah FORGE Well 16(A)_78-32 and Well 56-32 have been evaluated and reported
- A rock reduction model has been presented with laboratory validation
- This model may be used to provide insight into field drilling performance
- This model has been applied to the drilling response of bits from the FORGE drilling campaigns
- Examples presented allow insight into the methods used to evaluate bit response, formation hardness, wear rate, cutting structure damage, and drilling dynamic dysfunction conditions
- The analyses have been conducted post drilling yet may be applied to real-time evaluations for improved drilling performance
- The relative cost-benefit of improving the penetration rate response and bit durability has been evaluated
- In addition to bit design enhancements that may be evaluated using this method, the impact of ROP and bit life performance improvements on drilling cost savings can also be addressed

Acknowledgements

- The authors are indebted to Utah FORGE, Nabors, Pason, NOV, Scout, and GeoGuidance for permission to use information in preparing this work

- The sponsorship of the US Department of Energy Geothermal Technologies Office (DOE/EERE/GTO) is gratefully acknowledged

- In particular, funding for drilling activities at the FORGE site was provided by the U.S. DOE under grant DE-EE0007080 “Enhanced Geothermal System Concept Testing and Development at the Milford City, Utah FORGE Site”

Thank You