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Examining the Monetary and Time Costs of Lost Circulation

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ABSTRACT

Geothermal drilling environments tend to be under-pressurized and consist of multiple zones of highly fractured and altered material. As a result, lost circulation is more common in geothermal drilling than in other applications. The implications of lost circulation are numerous, but it can lead to a cascade of unwanted drilling and well completion events from which recovery is difficult (although it is desired within the production zone, as it indicates that permeability has been encountered). In many cases, the well bore needs to be abandoned or redrilled, which can quickly put a geothermal project into economic difficulty. In the order of the least time-consuming and expensive to the most, lost circulation mitigation strategies include 1) drilling ahead "blind", 2) drilling with lower density muds to reduce the static head in the borehole to below the formation pore pressure, 3) adding lost circulation materials (LCM's) to the drilling mud to plug the formation and regain circulation, and 4) sealing the lost circulation zone with materials (usually cement) that can be drilled out later. In this project, we examine drilling and cost data from four geothermal fields to better understand the relative costs in time and money associated with lost circulation events. These fields include McGinness Hills and Don A. Campbell in central Nevada, Steamboat Hills in western Nevada, and Puna, on the Big Island of Hawaii. To varying degrees, these fields have all experienced problems with lost circulation that in some cases have resulted in tens of thousands of barrels of mud loss, stuck pipe, twist offs, expensive fishing operations, or redrills.

1. INTRODUCTION

Lost circulation (LC), is caused when the drilling fluid (mud) flows into the geologic formation instead of returning to the surface (Figure 1) and is estimated to cost the oil and gas industry a $1 billion per year in rig time, materials, and other financial resources (Ferron, et al. 2014) and add an estimated $185,000 per well (Cole et al. 2017) to geothermal costs.

Geothermal well drilling is more susceptible to LC because geothermal environments tend to be under pressurized with multiple zones of highly fractured and altered material (Finger and Blankenship 2010). The time and material costs for lost circulation can represent 10% of the total well costs in a mature geothermal field, and often exceeds 20% of the costs for exploratory wells and reservoir development (Finger and Blankenship 2010; Almagro, et al. 2014).

LC has far-reaching implications beyond just the loss of mud to the formation and can sometimes lead to a cascade of events from which recovery is difficult. In some cases, the well bore needs to be abandoned or redrilled, which can quickly put a geothermal project into economic difficulty (Mansure 2002). If the drilling fluid is unable to clean the hole, cuttings can fall back on the bottom-hole assembly causing stuck pipe and twist off from which expensive and time-consuming mitigation strategies must be employed. If lost circulation suddenly lowers the fluid level in the well, hot water, steam, and/or gas can enter the wellbore causing a loss of well control. Furthermore, if circulation is lost in the production zone, it may be difficult to cure or manage the lost circulation without compromising the well's productivity. LC can also result in bad cement jobs, which can lead to further issues down the road.

In the order of the least time-consuming and expensive to the most, lost circulation mitigation strategies include 1) drilling ahead "blind", 2) drilling with lower density muds to reduce the static head in the borehole to below the formation pore pressure, 3) adding lost circulation materials (LCM's) to the drilling mud to plug the formation and regain circulation, and 4) sealing the lost circulation zone with materials (usually cement) that can be drilled out later (Garcia, et al. 2005; Finger and Blankenship 2010). Drilling ahead blind is usually the first course of action but runs the risk of causing stuck pipe or losing directional control of the well. Lowering the density of the drilling fluid can be done by mixing air with the fluid or adding other lower density fluids or additives to the mud. LCM's are used to "heal" the fracture zone by filling fractures and lowering formation permeability, however one must be careful when using LCM's in the production zone to avoid lowering the well productivity. Historically, LCM's were selected from materials that were readily available and inexpensive, such as cottonseed hulls, shredded leather, sawdust, straw, and ground walnut shells (Almagro et al. 2014). More recent advancements have created LCM's that are now fully engineered materials with specific applications based on formation type, fracture size, cause of lost circulation, etc. (Lowry et al., 2017). The final option of cementing and then drilling out the hole is only used in the most extreme cases as it is expensive in both time and materials.

In this project, we examine drilling and cost data from four geothermal fields developed and operated by Ormat Technologies Inc. (Ormat) to better understand the relative costs in time and materials associated with LC events. The fields are McGinness Hills and Don

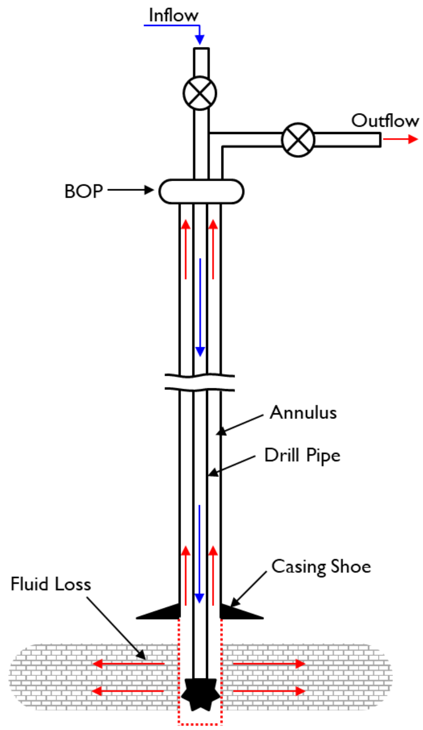

Figure 2: Typically, drilling fluids are pumped down the drill pipe, through ports in the drill bit, and back up the annulus space between the drill pipe and the borehole. Lost circulation occurs when returns to the surface are less than the amount pumped down the drill pipe.

A. Campbell in central Nevada, Steamboat Hills in western Nevada, and Puna, on the Big Island of Hawaii. To varying degrees, these fields have all experienced problems with lost circulation that in some cases have resulted in tens of thousands of barrels of mud loss, twist offs, expensive fishing operations, or redrills.

2. APPROACH

This work is a piece of the larger Lost Circulation Project funded by the Department of Energy's (DOE) Geothermal Technologies Office (GTO) and led by Lawrence Berkeley National Laboratory. Sandia National Laboratories and Ormat are part of the research team. The GTO funded the project to identify solutions to LC (characteristics of LCMs, slurry volume fraction, pumping rates, etc.) that have a higher chance to "plug" unwanted lost circulation zones before drilling is adversely affected. As part of the LC project, Ormat has provided a large database of drilling records, mud logs, and costs from which to study LC characteristics and occurrences. It is those data that form the basis for this study.

The database contains 89 wells across the aforementioned four geothermal fields. The first step was to filter the data to only include wells that drilled "virgin" rock. Records of redrills, cores, workovers, clean-outs, and the like were not included. Wells without cost data were also excluded since the intent of this study is to examine the monetary impact of LC. After culling the original database, 44 well logs remained: 19 at McGinness Hills, 9 at Steamboat Hills, 8 at Puna, and 8 at Don A. Campbell.

The cost data were not detailed or consistent enough to directly query costs associated with LC events. Thus, a "time-based" approach was used whereby the time spent addressing LC was determined for each well and then compared to the total drilling time. To reduce variability between the wells, an "Active Drilling Time" (ADT) was defined to be the time between the spud date (the first day drilling after the conductor is installed) to the first date terminal or total depth is reached, minus time spent on necessary operations such as casing operations and routine maintenance (Figure 2). Necessary operation times were adjusted to exclude time that was spent addressing LC issues.

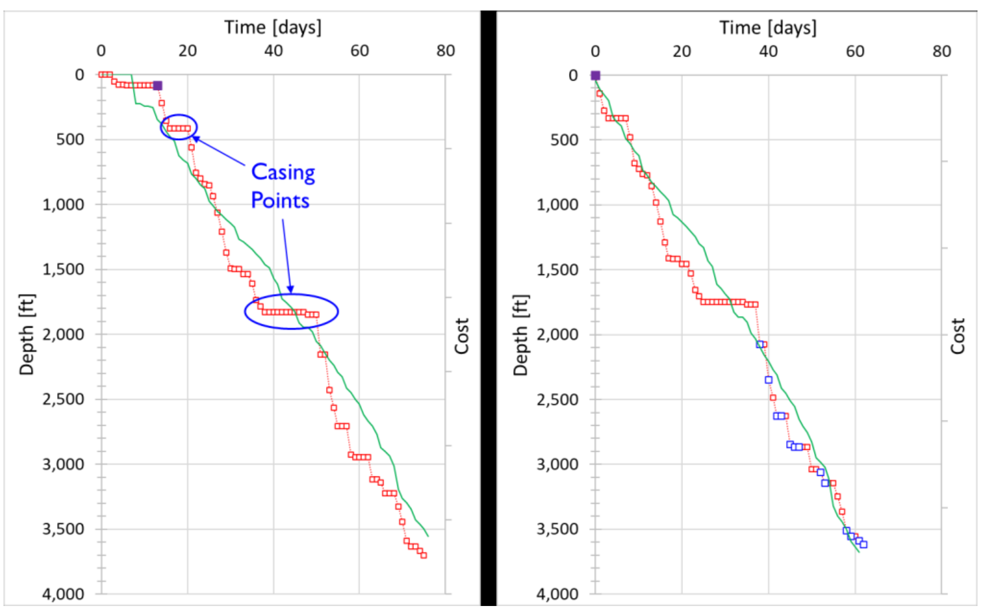

Figure 1: Time versus Depth plot showing the full drilling time (left) and the adjusted drilling time (right). The purple square at the top of both plots corresponds to the spud date, which is set to day zero on the right plot. The blue squares in the right plot show days with LC. The green line shows the spending rate as a function of depth (right axis).

Two categories of LC time were identified: direct LC time and changes in rate of penetration (ROP) due to LC. Direct LC time is time that is specifically listed in the well log "Operations Summary" as being allocated to addressing LC. This includes time for rigging up to drill with air, time to trip in and out of the hole, time for mixing and placing LCM, as well as time for waiting on equipment, such as the arrival of fishing tools for cases where LC caused equipment to be left in the hole. Changes in ROP are also determined from the well logs' Operations Summary based on the times indicated to drill each listed interval (Figure 3). For each interval with LC, the ROP is calculated and then compared to adjacent intervals that had full returns. Outlying values that are well below full return ROP's were used to calculate the portion of that interval's drilling time that is included as LC time. For example, if the LC drilling ROP is half of the average non-LC drilling ROP, then half of the time drilling that segment is considered LC time. The assumption is that *some* of that time was productive in that there was footage drilled, but just at half the rate of what it might have been. ROP's are calculated individually for each bit size.

26-Jan-14	Current Depth (ft): 2,430	Hole Drilled (ft): 273	Avg ROP:
	Current Ops: Drilling ahead at 2476 ft.		
	Operation Summary: • 5 hrs: Continued drilling with 14-¾-inch drill bit from 2237 feet to 2276 feet. • 0.5 hrs: Surveyed well at 2274 feet (1.3° inclination). • 5 hrs: Drilled from 2276 feet to 2365 feet. • 0.5 hrs: Surveyed well at 2360 feet (1.5° inclination). • 6 hrs: Continued drilling to 2430 feet by midnight. Drilled placing 38 K on bit rotating 90 RPM. Decreased weight on bit down to 36K lbs and back to 38k lbs and increased RPM to 95 and back down to 90 RPM trying to establish best MSE and rate of penetration. Best parameters at the time were 38K lbs weight on bit rotating 90 RPM. • 7 hrs: Drilled from 2295 feet encountering mud losses of 85 to 15 bph healing with prime seal to 2405 feet. Lost a total of 420 bbls.		

Figure 3: Sample of an Operations Summary for a single day from a well in McGinness Hills field. The last entry describes an interval with LC.

Log entries had varying degrees of completeness, mainly due to different people emphasizing different aspects of the drilling operations. For cases where the ROP's were low (e.g., 12 hours to drill 10 feet), we assumed that the discrepancy is due to non-drilling activities that are occurring during that time interval but whose detail is un-reported in the log. For times when LC is occurring, it is assumed that these un-reported activities are associated with LC and thus, portioning the LC drilling time based on the ROP is valid. In the end, adjustments based on ROP only accounted for about 12% of the total LC time and thus uncertainty in un-reported activity is not that impactful.

About half of the well logs contain enough detail in their respective reports to calculate the "bit on the bottom" ROP for specific intervals. For wells that do not have that level of detail, a daily ROP was calculated and then compared. It should be noted that changes in the ROP are not necessarily negative in that fractured and altered rock can, in many cases, be faster to drill than solid, intact rock. In these cases, the portion of LC time attributed to changes in ROP time was assumed to be zero (although direct LC time can still occur).

Time for addressing trouble events such as stuck pipe was considered LC time but only if the records showed that LC preceded the trouble event and that the event most likely occurred because of LC. This also includes follow-on events such as losing a downhole assembly as part of the effort to get the drill string unstuck. Failure time of equipment used to mitigate LC was also included under the assumption that that equipment would not have been put into service had the LC event not occurred (e.g., the failure of an air compressor for drilling with aerated fluid).

The final calculation of the total LC time for each well is the sum of the direct LC time and the adjusted ROP time. The LC time is then divided by the ADT to get the percentage time spent on LC. An example for the calculations along with the explanation are shown in Figure 4.

To look at the impacts on cost, the average daily expenditure for "LC days" (i.e., each day where LC is reported) versus "non-LC days" (no LC reported) are compared. Additionally, the drilling cost in terms of dollars per foot and the ROP for each well for LC days and non-LC days are also calculated and compared.

Bit Size [in]	Day	Hour	Start [ft]	End [ft]	ROP [ft/hr]	Adjusted Hours	Note
14.75	37	6	1849	1939	15.00	0.00	Full returns
		5.5	1939	2025	15.64	0.00	Full returns
	39	5.5	2157	2194	6.73	0.00	Full returns
		6.5	2189	2237	7.38	0.00	Full returns
	40	5	2237	2276	7.80	0.00	Full returns
		5	2276	2365	17.80	0.00	Full returns
		7	2365	2430	9.29	1.00	15-85 bph
	41	3	2430	2489	19.67	0.00	Top drive torqued up
		2	2489	2510	10.50	0.00	Full returns
		3	2510	2521	3.67	0.00	Full returns
		11	2521	2566	4.09	0.00	Full returns
	45	7	2705	2884	25.57	0.00	LC at 2884
		8	2884	2928	5.50	3.94	100-500 bph, rigging up for air
	46	1	2928	2945	17.00	0.00	Air, losing 500 bph
	47	3	2946	2961	5.00	1.61	Blind with air
	50	3.5	3059	3100	11.71	0.00	Full return with water
		1	3100	3116	16.00	0.00	Twisted off at 3116
	52	4	3116	3140	6.00	1.78	20% returns
	53	5.5	3140	3180	7.27	1.81	Blind
		4	3180	3222	10.50	0.12	Blind
	56	8	3222	3300	9.75	0.80	Aerated
		7.5	3300	3327	3.60	5.01	High vis sweep circulated clean
	58	7	3442	3480	5.43	3.49	70-80% return
		10.5	3480	3566	8.19	2.56	50% return, Aerated, LC at 3512
		4	3566	3591	6.25	1.69	Aerated fluid
	61	10.5	3632	3667	3.33	7.27	Aerated fluid
	62	10	3667	3700	3.30	6.95	Aerated fluid. TD.
		Average Full Return ROP [ft/hr]			10.83		
				TOTAL [hrs]		38.02	

Day	DT Adjustment [hrs]	Direct Tiime [hrs]	LC time [da]
40	1.00	0.0	0.04
45	3.94	9.0	0.54
46	0.00	23.0	0.96
47	1.61	12.5	0.59
48	0.00	15.5	0.65
49	0.00	24.0	1.00
50	0.00	0.0	0.00
51	0.00	24.0	1.00
52	1.78	15.0	0.70
53	1.93	0.0	0.08
56	5.80	6.5	0.51
61	7.27	4.0	0.47
62	6.95	0.0	0.29
		TOTAL [da]	6.82

Figure 4: Samples of the ROP time adjustment (left) and the determination of the LC time (right) for a well in the McGinness Hills field. In this case, the portion of the drilling time that is added to the LC time is based on the full-return average ROP of 10.8 ft/hr and is listed in the "Adjusted Hours" column. The table on the right sums the ROP time adjustment and the direct time to get the LC time for each day (and total for each well). Only days with LC are listed in the table on the right. Note that some days (e.g., day 48) where no drilling progress is made will be listed in the right-hand table with a zero ROP time adjustment but not listed in the left-hand table.

3. RESULTS

3.1 Time Cost

The mean, standard deviation, and the coefficient of variation for the time analysis are listed in Table 1, broken out by the geothermal field and collectively for all fields. The coefficient of variation (CV) is used because it enables a more direct comparison across the fields due to the variations in the means, which is a function of the number of drilling days and depth of the well (among other things).

Table 1: List of the mean, standard deviation, and coefficient of variation for the parameters calculated as part of the time-based analysis.

	# of Wells	Mean				
Field		ADT	ROP Adjustment [da]	Direct Time [da]	LC Time [da]	% Time
McGinness Hills	19	21.45	0.47	2.41	2.82	14.38%
Steamboat Hills	9	20.89	0.36	3.96	4.32	24.85%
Puna	8	42.75	0.99	8.71	9.69	24.68%
Don A. Campbell	8	13.63	0.43	2.47	2.90	20.41%
TOTAL	**44**	**23.79**	**0.53**	**3.88**	**4.39**	**19.49%**
Field		**Standard Deviation**				
McGinness Hills		13.30	0.59	2.52	2.72	9.85%
Steamboat Hills		11.36	0.31	3.43	3.55	20.48%
Puna		23.72	1.20	5.84	5.86	14.42%
Don A. Campbell		2.45	0.23	1.62	1.67	8.51%
TOTAL		**17.16**	**0.70**	**4.17**	**4.37**	**14.17%**
Field		**Coefficient of Variation**				
McGinness Hills		63%	128%	106%	98%	69%
Steamboat Hills		56%	87%	89%	85%	85%
Puna		57%	125%	69%	62%	60%
Don A. Campbell		19%	56%	67%	59%	43%
TOTAL		**73%**	**132%**	**108%**	**100%**	**73%**

Collectively, 19.5% of the ADT is attributed to dealing with LC, although Steamboat (24.9%), Puna (24.7%), and Don A. Campbell (20.4%) are all higher than the average, which is pulled down by the relatively low value at McGinness Hills (14.4%). If the ADT values are adjusted upward to include the time for necessary operations, the collective value of LC time falls to 11.9%. The CV's are large, ranging from 43% to 128% for the ROP Adjustment, Direct Time and LC Time parameters (meaning that the standard deviation is 43% to 128% the value of the corresponding mean). This is especially true for collective values where the CV ranges from 100% to 132% for the same parameters, but which also reflects the variability across the fields. It is important to note that the variability for the individual fields is likely overstated due to the small sample sizes.

Figure 5 is a box and whisker plot of the LC time ADT percentage showing the 5th, 25th, 50th, 75th, and 95th percentiles of the data. Steamboat Hills and Puna have the largest variation while McGinness Hills and Don A. Campbell have the lowest. Companion papers to this work by Winn et al. (2021a, 2021b, 2022) discuss the geology of the McGinness Hills, Don A. Campbell, and Steamboat Hills fields and how it impacts the frequency and magnitude of LC. Future work will connect these differences in geology to the monetary and time costs of LC.

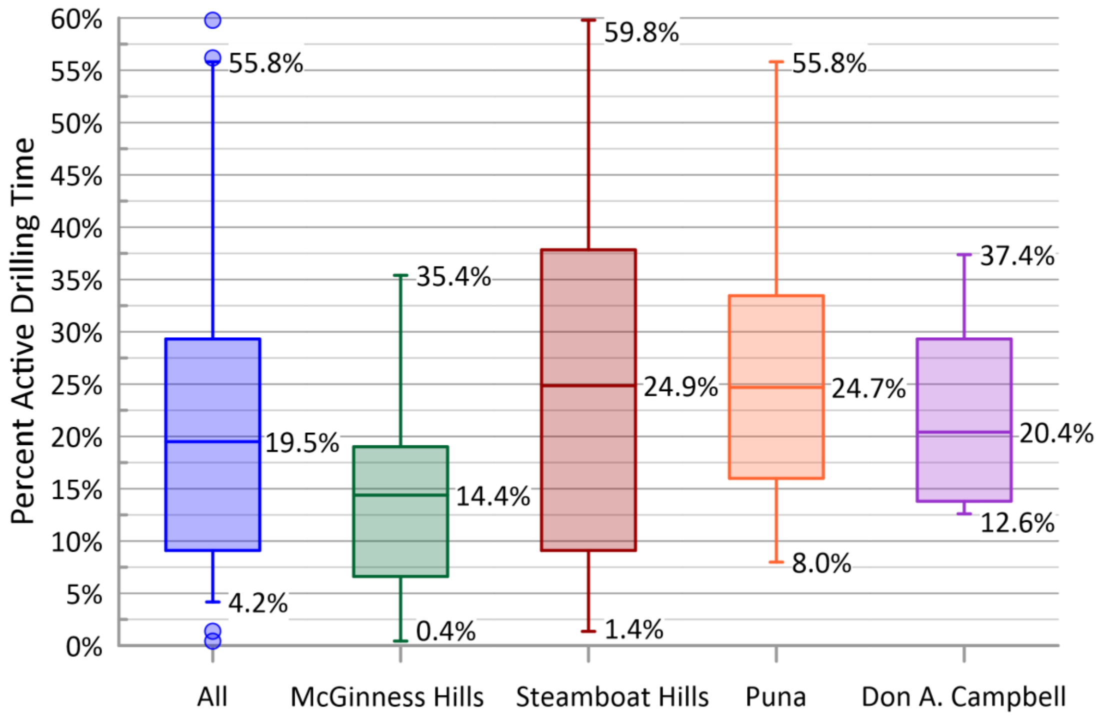

Figure 5: Box and whisker plot of the LC time as a percentage of the ADT. The box and whisker intervals are the 5th, 25th, 50th, 75th, and 95th percentiles.

3.2 Monetary Cost

Table 2 lists the mean, standard deviation, and CV of the daily cost, the cost per foot, and the ROP for days with and without LC. The expectation is that the average daily costs should be higher for days with LC than for those without. However, the split is fairly even; 21 wells have an average non-LC daily cost that is higher than their LC daily cost (23), although the variation amongst the fields is high. For McGinness Hills and Steamboat Hills, 63.1% and 66.7% of wells respectively, had average daily costs that were higher for non-LC days versus LC days. For the Puna and Don A. Campbell fields, the trend is reversed where 12.5% of the wells for both fields had average daily costs that were higher for non-LC days than LC days. It should be noted that some of the variability in these percentages comes from how the expenditures are reported in the logs. Ideally, expenses in the database should be reported on the day they were expensed. However, in many cases, capital expenses for materials (cement, casing, LCM, etc.) and parts and equipment were reported later, apparently when invoiced or when put back into service. Overall, the average daily cost between LC days and non-LC days are virtually identical: $51,882 and $51,934 respectively.

Significant differences between the drilling cost per foot and the ROP do exist between LC days and non-LC days. On average across all fields, the drilling costs are $662/ft for LC days versus $403/ft for non-LC days, a 64.3% increase. This is also reflected in the ROP where the average ROP is 4.2 ft/hr for LC days and 6.1 ft/hr for non-LC days (Table 2). It should be noted that these ROP values refer to daily rates and not "bit on the bottom" rates. For all 44 wells, there were only 5 wells that had higher daily costs, higher drilling costs, and a lower ROP for the non-LC days versus the LC days: 2 wells at McGinness Hills and 3 wells at Steamboat Hills. For all 5 wells, there were significant expenses associated with other trouble time versus LC time, such as losing equipment down-hole and equipment failure. The box and whisker plots for the data in Table 2 are shown in Figure 6.

Table 2: List of the mean, standard deviation, and coefficient of variation for the monetary cost analysis.

	Mean					
	Daily Cost		$/ft		ROP [ft/hr]	
Field	**LC Days**	**Non LC Days**	**LC Days**	**Non LC Days**	**LC Days**	**Non LC Days**
McGinness Hills	$ 46,372	$ 45,614	$ 642	$ 347	4.31	6.45
Steamboat Hills	$ 52,454	$ 54,533	$ 704	$ 537	4.18	5.14
Puna	$ 67,444	$ 72,980	$ 701	$ 439	4.42	7.20
Don A. Campbell	$ 48,761	$ 41,692	$ 622	$ 337	3.86	5.26
GLOBAL	**$ 51,882**	**$ 51,934**	**$ 662**	**$ 403**	**4.22**	**6.12**
Field	**Standard Deviation**					
McGinness Hills	$ 7,141.60	$ 5,553.29	$ 536.31	$ 138.25	2.11	2.58
Steamboat Hills	$ 19,437.99	$ 11,216.52	$ 637.16	$ 290.25	2.11	2.12
Puna	$ 22,483.49	$ 24,868.05	$ 342.48	$ 138.26	2.44	2.52
Don A. Campbell	$ 7,718.61	$ 9,456.66	$ 244.20	$ 94.65	1.73	0.64
GLOBAL	**$ 16,156.61**	**$ 16,973.86**	**$ 490.42**	**$ 192.77**	**2.12**	**2.39**
Field	**Coefficient of Variation**					
McGinness Hills	0.16	0.12	0.85	0.40	0.50	0.40
Steamboat Hills	0.38	0.21	0.93	0.56	0.52	0.42
Puna	0.34	0.35	0.50	0.32	0.57	0.36
Don A. Campbell	0.16	0.23	0.40	0.29	0.46	0.13
GLOBAL	**0.31**	**0.33**	**0.75**	**0.48**	**0.51**	**0.39**

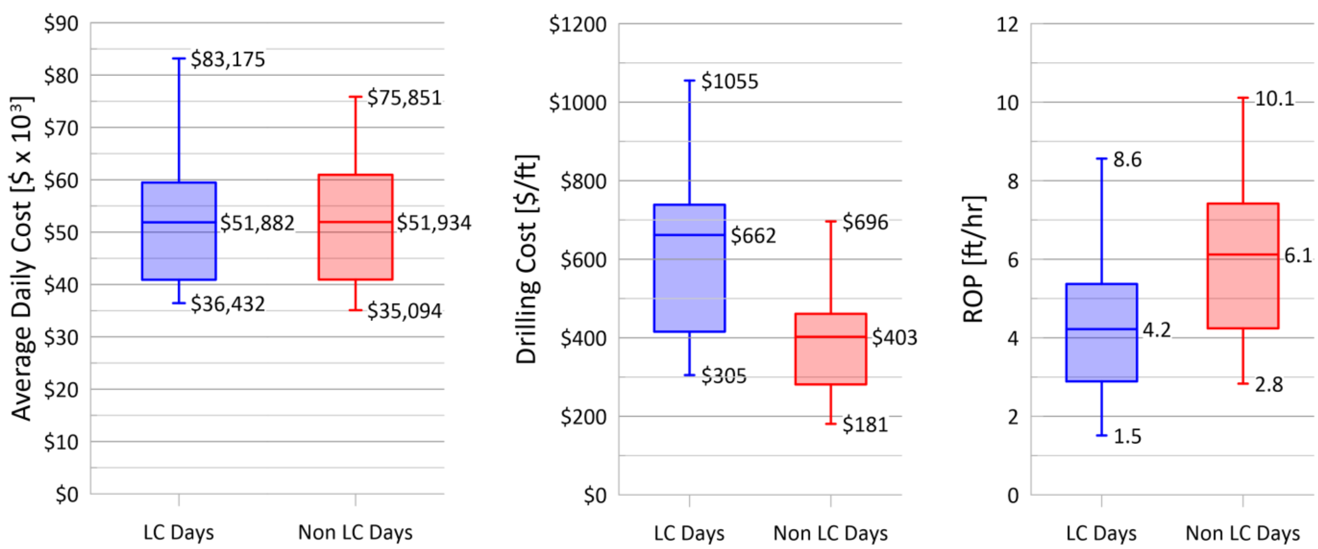

Figure 6: Box and whisker plot of the Average Daily Cost (left), Drilling Cost (center), and ROP (right) when drilling with and without LC. The box and whisker intervals are the 5th, 25th, 50th, 75th, and 95th percentiles.

3.3 Active Drilling Costs

While not part of the original scope of this work, we used the data to compare the drilling costs for each well against the Base Case drilling cost curve (Lowry et al., 2017) of a vertical, large diameter (12.25”) well that was created for the DOE GeoVision report (DOE, 2019, Figure 8). The drilling costs shown in Figure 8 for the fields in this study are the costs from the spud date to the first date of terminal depth plus a constant added to reflect mobilization and de-mobilization, site preparation and conductor placement, pre-spud engineering, and wellhead equipment. The constant amount is the default value used in the GeoVision curves. With the exception of a few outliers, all the costs are above the GeoVision curve. Despite this discrepancy, the values, with the exception of Puna, are close to the GeoVision curve and the change in cost as a function of depth is consistent. It should be noted that the curve used in the GeoVision report is meant to be representative of a generic well system and is not meant to be used to predict drilling costs for individual sites or wells. When uncertainty in both the data and the GeoVision curve are considered, there would be considerable overlap.

It should be noted that the high relative costs for wells in the Puna field come from it being in a remote location, which adds to the costs of materials, labor, and transportation and thus the Puna costs cannot be directly compared to the GeoVision curve.

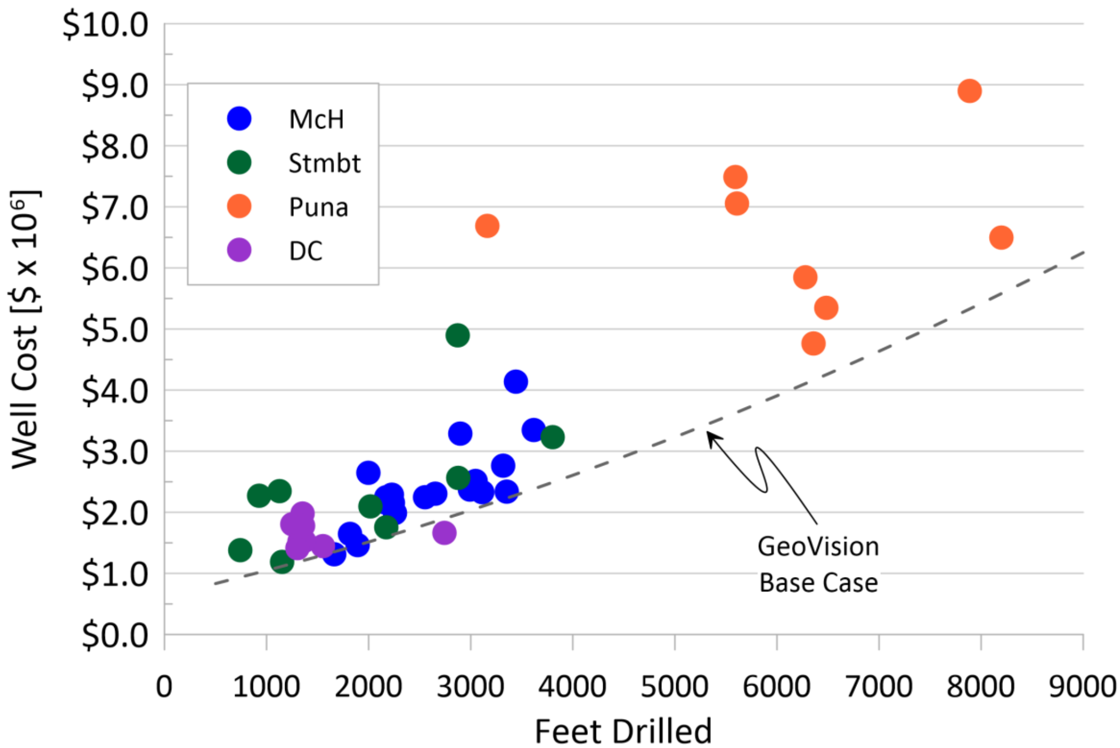

Figure 7: Plot of the adjusted drilling costs versus depth against the Base Case, vertical, large diameter (12.25") curved developed for the DOE GeoVision report. Adjusted cost curves are the actual costs from the spud date to the date of reaching terminal depth plus a default value used in the GeoVision curve to reflect mobilization and de-mobilization, site preparation and conductor placement, pre-spud engineering, and wellhead equipment costs.

4. CONCLUSION

This project examined the well log records from four geothermal fields to determine the time and monetary costs of LC. Those fields are McGinness Hills and Don A. Campbell in central Nevada, Steamboat Hills in western Nevada, and Puna on the Big Island of Hawaii. Two analyses were completed, a time-based assessment that looked at the time costs of lost circulation and a monetary assessment, that compared the monetary differences of drilling with and without lost circulation.

For the time-based assessment, an "Active Drilling Time" (ADT) was established that is defined as the time between the spud date and the first day of reaching terminal depth, minus down time for necessary operations such as placing casing. Time spent for necessary operations that were affected by LC were added back into the ADT. For each well, two types of lost circulation time were estimated; a direct time that is specifically noted in the drill log and that may or may not coincide with deepening the hole, and time arising from changes in the ROP while drilling with LC. Of the two, direct time represents 88% of the total LC time while time arising from changes in the ROP represents 12%.

The time-based assessment shows that collectively across all four fields, LC time was 19.5% of the ADT. If time for necessary operations is added back into the ADT, the LC time is 11.9%. Individually, the values for the McGinness Hills, Steamboat Hills, Puna, and Don A. Campbell fields are 14.4%, 24.9%, 24.7%, and 20.4%, respectively. While there is much variability in these values with standard deviations on the order of the mean values, these values are consistent with those found in the literature.

The monetary analysis shows that the collective average daily spending rate is virtually identical whether or not one is drilling with or without LC. While this result is slightly unexpected, it is supported by the fact that the well cost versus depth plots for each well, such as is shown by the green line in Figure 1, show a fairly consistent spending rate over time. The most common deviation from this consistency is when casing costs are posted, and the line steepens considerably for a day or two. Large differences were found in the drilling cost per foot ($662/ft and $403/ft for LC and non-LC drilling) and the ROP (4.2 ft/hr and 6.1 ft/hr for LC and non-LC drilling).

The fact that LC does not show up in daily rates but is clearly evident in the cost per foot and the ROP indicates that the main source of monetary cost of LC is due to a loss of daily drilling efficiency and the additional time spent on activities that do not deepen the hole. *Thus, to reduce the costs of LC, the focus should be on reducing the LC down time versus reducing the material costs of addressing LC.*

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