Delivering commercially attractive geothermal coiled tubing operations

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Keywords: *Geothermal, Coiled Tubing, Well Workover, Risk Analysis Risk Mitigation*

ABSTRACT

Although geothermal coiled tubing (CT) operations are performed globally, making them commercially attractive everywhere is a challenge.

New technology update with the geothermal industry suffers from low project count, technically challenging environments, historically low success ratios and the ever-present need to keep costs down. These hurdles keep many well technologies on the fringes of widespread geothermal adoption.

Adoption of coiled tubing technology for geothermal well maintenance is no different. Some geographies where CT units (CTU) are readily available, such as New Zealand or the USA perform weekly CTU operations which regularly boast the generation savings they deliver. Other geographies do not seem to have the same continuous success. How can more locations reach that flash point where CTU workovers become a routine cost-effective maintenance activity?

This paper will share & discuss the results of a geothermal CT operational data review. It includes data from 10 years of geothermal CT operations in New Zealand. It will share statistics and discussion surrounding root causes for geothermal CT incidents and CT job costs. It will provide recommendations to well operators on how to reduce their CTU workover costs and job cost variability.

The conclusions of this study include reducing CTU equipment failures, noting that every well operator has a unique job cost model & implementing a continuous improvement culture.

For geothermal energy to remain competitive in the global energy market, innovation must be ongoing and deliver generation cost reductions. Uptake of the recommendations presented here presents a great opportunity to achieve this aim.

1.0 INTRODUCTION

Coiled Tubing (CT) has been used in the maintenance of wells since 1962 (IcotA, 2025). Its advantages compared to a drilling rig workover includes dynamic well control (i.e. live well workover), faster trip times, smaller equipment footprint & continuous circulation (IcotA, 2025). These advantages also apply to geothermal well workovers. These advantages drive down the cost of geothermal energy in the growing and competitive global renewable energy market. New Zealand and the USA are two countries which have developed geothermal CT technology significantly in recent years. This is evident from the volume of industry literature they publish on this niche topic (McClatchie, 2000), (Rocha, 2023), (Wilson, 2020), (Ryan, 2021). This literature often boasts of the cost savings that geothermal CT workovers can deliver. Unsurprisingly, other geothermal regions have taken interest in this technology and have also begun trialing CT workovers on their wells. Philippines is one country which has seen a resurgence in geothermal CT activity in the last 3 years. As with any new technology implementation, there is a learning curve in delivering cost savings. Delivering these cost savings sooner rather than later, forms the focus of this paper.

So why are geothermal CT workovers more affordable and more successful in some geographies rather than others? Published literature of this topic would indicate that "perseverance" summarizes the answer in just one word. Papers from as early as 2000 (McClatchie, 2000) in California describe the use of CT jetting for removal of geothermal well scale. However, the study concluded that "numerous equipment and tool issues were addressed before arriving at the system currently in use". Commercially, the result was a "cost effective, efficient, alternative to rig-based cleanouts". This theme of perseverance is mirrored in Rocha's 2023 paper, also from the USA. It describes one US based geothermal operator's journey to arrive at their chosen workover recipe for CT success.

In New Zealand, the industry's experience has been similar. Wilson (2020) describes geothermal operator, Contact Energy & well services company, Western Energy's partnership journey in adopting CT for geothermal conditions. Their continuous improvement efforts from the early use of vane motors to positive displacement motors, and finally to percussive hammers to deliver geothermal CT workovers has resulted in operations achieving a high probability of success. He describes "a clear appetite for innovation" as the means to success.

The early adopters of CT have so far has focused on technical story telling. Each of the mentioned papers describes very openly the design decisions, the technology trialled and the successes and failures. This paper intends to take a more statistical approach. Through the review of geothermal CT operational data, this paper aims to provide "tricks for new players" to shift the perception of geothermal CT workovers from bespoke one-off projects to a regular, low risk, cost-effective activity.

The paper's roadmap to address this problem is as follows. It begins by describing the operational data to be considered and the methods to review & analyze it. Secondly, it presents the results of the analyses in tabular and graphical form. Following this, the paper discusses the significance of the results. Finally, the paper addresses the question, so what? How can the results of the study help deliver more cost-effective geothermal CT operations everywhere.

2.0 METHODS USED

This section will outline the data analysis methods used to address the aims of this paper. The section is divided into three components. Each component focuses on a different data set. Those data sets are (i) Incident root cause data (ii)

Proceedings 47th New Zealand Geothermal Workshop
11 -13 November 2025
Rotorua, New Zealand
ISSN 2703-4275

Job cost data and (iii) Client specific CT project characteristics. Data collection, preparation and analysis method will be covered for each data set. Tables and lists are used to provide detail into the methods used. Results follow in the next section of the report

2.1 Incident Root Cause Data

2.1.1 Data Set for consideration

To analyze incident root cause data, it was vital to firstly define what was considered an incident. All incident data was taken from a single geothermal CT service provider in New Zealand. As such, the incident reporting definitions used by that service provider were used. Those definitions are:

- Accident – an unexpected event which results in serious injury or illness of an employee and/or property/equipment damage.

- Incident – an unexpected event or occurrence that does not result in serious injury or illness but may result in property/equipment damage.

- Near Miss – an event that could have caused an incident or accident.

- Observation/Improvement/Innovation – A safety, quality, environmental or health situation or event that provides an opportunity for improvement.

The data analyzed for this paper considered all four of these categories. From simplicity, this paper will collectively refer to all these as "incidents".

2.1.2 Procedure

All the root cause data from 2014 onwards originally existed in incident reports on the well service company's file server. All the incident reports were reviewed, and key data was collated into a Microsoft Excel worksheet. The following data points for each incident were recorded: (i) Year; (ii) Well; (iii) Client; (iv) Incident Description; (v) Root-cause 1; (vi) Sub-root-cause 1; (vii) Root Cause 2; (viii) Sub-Root cause 2. Following data entry into the excel worksheet, the root causes were analysed using Microsoft excel pivot tables to look for trends and outliers.

2.1.3 Analysis Method

The analysis counted the nature of the root causes, i.e., when an incident was deemed to have multiple root causes, both were counted. For example, if an incident was deemed to be the result of an equipment failure and a knowledge/competency failure, both root causes were counted in the analysis. Some incidents only had a single root cause, and as such, only one root cause was counted for those incidents. A rule was made to permit a maximum of two root causes for each incident. The root cause options for the incidents were restricted to aid the data set in providing meaningful insights. It is acknowledged that there is a level of subjectivity in the assignment of root cause count & root cause type for a given incident. Despite this, the incident reports improved in objectivity over time. This reflected a culture of continuous improvement at the service company. This reflects positively on the data set. The benefit of a continuous improvement culture will be explained further in the paper's discussion section. The root cause and sub-root cause options used for the analysis are included in Table 1. An example of a data entry is shown in Table 2.

2.2 Job Cost Analysis

2.2.1 Data Set for consideration

This analysis aimed to gain insights into geothermal CT job costs trends. The data included service company job invoice totals for geothermal CT well workovers. Note that these invoices do not reflect the total project cost for the operator which would also include non-CT contractor costs such as earthworks and water supply. Chemical bullhead jobs, quenches and other stand-alone pumping jobs were not considered in the data set. Geothermal production tests were only considered if well initiation included a CT air or nitrogen lift operation. Downhole quenches involving CT were counted. Job cost data from 2018 until today (i.e. July,2025) was reviewed. Prior to 2018 job cost data was not easily obtainable due to a change in accounting software at the service company. Note that no normalization for the time value of money has been made.

2.2.2 Procedure

The job cost data from 2018 onwards originally existed within the well services company's accounting system. This data was exported to a .csv file and the following data channels for each CT project were recorded in an excel sheet for comparison: (i) Year (ii) Well (iii) Client (iv) Operation Type (e.g. live well cleanout) (v) Contractor invoice cost. An example of a data entry is shown in Table 3.

The operation types that the data set included are listed below.

- Live Well cleanout
- Killed Well Cleanout (i.e. well under quench during cleanout)
- Well abandonment (2in coiled tubing)
- Well abandonment (3/4in coiled tubing)
- Air lift / Nitrogen Lift
- Downhole Quench

2.2.3 Analysis Method

Following data entry, the data set was analyzed using Microsoft Excel pivot tables to look for trends and outliers. Upon initial review, it quickly became obvious that job cost data needed to be compared in terms of job type & geography to provide meaningful insights. Standard deviation (for a given operation type) was used to provide an indication of cost variability. To compare data between clients, a coefficient of variation was used as a comparative measure (Equation 1). A coefficient of variation in this case is the ratio of the standard deviation of the job cost divided by the average job cost.

$$Coefficient\ of\ variation = \frac{Standard\ Deviation\ of\ Job\ Cost}{Average\ Job\ cost}$$

Equation 1: Coefficient of variation as applied to CT job cost data

Segregation of the data by operation type and geography was also used to search for trends and outliers. However, this meant that some data sets were quite small and statistically weak. Notwithstanding, the global volume of geothermal CT workovers is in the tens of jobs, so it was deemed useful to consider the data available noting its very targeted nature.

2.3 Client Specific CT Project data / casual reasoning Exercise

In addition to the statistical analysis previously described, a casual reasoning exercise was performed on client specific geothermal CT project data. The objective of this exercise was to consider non-numerical cause & effects relationships in addition to the previously mentioned statistical analyses. This casual reasoning exercise involved detailed review of CT project metrics and comparing those metrics to the job costs for various clients. The data was prepared in a Microsoft Excel workbook. No special tools or calculations were used to analyze the data, that is why it is called a casual reasoning exercise. The data was simply reviewed and hypothesis deduction performed. For reader clarity, the complete parameters reviewed in the paper are listed below.

- Client
- Well Depths
- CTU Type
- 12 or 24hr operations
- International personnel & equipment required
- Liquid Nitrogen Volumes required
- CTU Job Frequency
- CT Runs / Workover
- Travel time to location
- CTU Workover Duration

3. RESULTS

This section presents the data reviewed as part of this study. It includes some brief facts regarding the quality & quantity of data reviewed. It also includes graphical representation of the data in different forms. Interpretation and insights from the data are discussed through this section.

3.1 Incident Root Cause Analysis

-129 Incident reports reviews.

-179 root causes counted.

-10 well operators (i.e. clients)

-Data from 2014 to 2025 (inclusive)

-Data from geothermal CT operations in New Zealand, Philippines, USA & Guatemala

-Collected results are shown in Tables 4 and Figure 2.

The root cause analysis indicated that "Equipment & Maintenance (E&M)" is the primary cause of geothermal CTU incidents. This result is shown by total incident count and rank count of leading incident cause per year (Table 4). In consideration of total incident count, E&M is a clear leader however on rank count "Procedures (SOPs)" is a close second. It is important to remember that the four incident categories represent various sub-categories. For example, incidents related to "lack of well data" were categorized as poor planning and hence fall under "Procedures".

The data set has several flaws which reduce its usefulness. Firstly, the lack of reporting from years 2014 – 2016. Secondly, the incident count was dependent on the reporting culture and policy of the contractor who provided the data. It is therefore inherently subjective. Thirdly, without context, the outlier results are not easily interpreted. Nevertheless, these results guide contractors and operators where to focus effort to reduce incidents and hence non-productive time on their geothermal CT operations.

3.2 Job Cost Analysis

As a stand-alone data set, job cost statistical analysis did not provide any obvious solutions to reducing geothermal CT project cost. Differences in project workscope, geography, CTU ownership and market conditions make each operator's data quite unique and difficult to compare without wider context. As mentioned in the literature review, perseverance was key to enabling consistent CT workover success and consistently lower CT job costs. Furthermore, this paper's authors hypothesized "perseverance" to mean that job cost variability for CT workovers would reduce with as the frequency of CT jobs increased. To assess this hypothesis, the data in Table 5 was compiled for the most recent five CT cleanout projects (if available) for various clients.

Only Live Well Cleanout (LWC) projects were selected to limit the effect of workscope on job cost. A LWC is a well cleanout performed with the well flowing (Wilson, 2020). As mentioned in the method section, the cost variability was compared by the ratio of job cost standard deviation to average job cost (i.e. coefficient of variability). The results of this analysis are unhelpful without context.

Client A was the only client with job cost data for five recent LWCs. The cost variability was 10%. This supports the proposed hypothesis that perseverance creates job efficiencies and results in lower project costs. In contrast, Clients C & E have the same job count but vastly different cost variability. Client E's cost variability is high because two of the three projects assessed were technically complex, resulting in longer project duration than a more routine cleanout. This is compared to the third project which was technically straightforward and therefore had a lower overall project cost.

For Client E, all their projects had very similar objectives and well characteristics. In fact, two of the three projects for Client E were performed as a campaign on similar & nearby wells. In conclusion, the benefit of the cost analysis performed is that it provides a snapshot for the current state of LWC cost variability. This data is useful for project budget creation and is not reflected in other literature. More fruitful results may be found by detailed case study analysis of individual projects. This recommendation is discussed further in Section 4.

3.3 Casual reasoning Exercise

A casual reasoning exercise was the most useful of the three analyses performed. The results are shown in Table 6 (see next page). It provided tangible data for comparison & led to plausible reasons for cost differences between clients' projects. Job costs are ranked (rather than quantified) so that no confidential price information is disclosed.

Client E for example has deep wells (i.e. >2000m), requiring larger liquid nitrogen (N2) volumes for LWC operations; 24hr crews that are a non-domestic workforce incurring additional mobilisation/de-mobilisation costs to this client. These factors result in their projects typically lasting weeks rather than days. Considering these factors it's not surprising their jobs have a higher cost ranking. On the contrary, Client A with shallow wells(i.e., <2000m), low travel time to location and low liquid N2 requirements, and only 12-hour crews has a low-cost ranking. Unsurprisingly this client also performs more workovers.

However, the results collated in Table 6 still leaves the reviewer craving more context. For example, Client's B & C have almost identical project factors, but they are quite different in cost ranking. The data set provides no reason for this, only detailed case study analysis of each clients' projects would yield the answer and this was outside the scope of this study.

In summary, the casual reasoning exercise was useful. It has provided high-level justification for why some operators pay more for CT workovers.

4. DISCUSSION

This section includes discussion of the results presented in this paper. It also provides suggestions for how to reduce geothermal CT workover costs going forward.

Overall, the data review and analysis performed indicates that statistical analysis of geothermal CT workovers is nice to have but without context, fails to provide strong conclusions. To begin, the root cause data likely represents the largest data set of its type (i.e. geothermal CT incidents) globally. Despite this, the findings are not groundbreaking. They support findings from other geothermal and oil & gas (O&G) CT literature (McClatchie, 2000) (Rocha, 2023) (Wilson, 2020). Secondly, the job cost data set was found difficult to analyse and interpret. Despite being a large data set for the topic of interest, many of the clients have not completed enough comparable CTU projects to provide statistically significant results. Nevertheless, the data does provide insight into the current cost variability of geothermal CT projects for operators looking to utilize this technology more.

The casual reasoning exercise was a useful activity. It allowed quick comparison of how geothermal CTU projects are being conducted worldwide. The cost ranking allows the reader to infer conclusions from the included project characteristics. However, like the root cause and job cost analyses, the reviewer is left wanting more context to interpret the results.

Overall, the three investigatory activities have provided modest insight into how to reduce the cost of geothermal CT workovers. So apart from the conclusions of this study, how else can operators reduce their CT workover costs? This will be addressed in the next section.

4.1 So where to from here?

This section will discuss three methods for reducing the cost of geothermal CT workovers.

4.1.1 After Action Reviews

A known method for improving project success is a after-action-review or AAR. An AAR is a review held with the project team following completion of the project (i.e. workover). The AAR aims to highlight aspects of the project that went well and improvements to be made. For CT projects, these AARs primarily focus on operational aspects like BHA selection. However, there is a lot of value to be gained by extending them to project commercials & logistics also. Findings from the meeting should be documented, shared, and actioned. This ensures the highlights of the project are carried forward to future projects and the lowlights are actioned by the appropriate party. Once several similar projects have been performed it is also valuable to compare several AARs to one another. This involves comparing those projects and looking for trends & outliers and their effect on job costs. In a sense it is a AAR on a body of work, rather than a single project

4.1.2 Continuous Improvement Culture

workover costs over time is implementing a continuous improvement culture in the workplace. This is more difficult to implement than an after-action-review, but can provide benefits such as long-term efficiency & productivity. This can fuel innovation, enhancing project engagement, improving project delivery, and as a result of these benefits, reduce the cost of CT workovers.

Review of the root cause data for this study (i.e. 2014-2025) revealed a change in reporting culture at the contractor organization. Some of the initial reports were targeted. The reporting focused on individual human errors. However, over time it was obvious from the reports that staff were focused more on open feedback, improving processes (rather than blaming individuals) and continuous learning. This cultural change resulted in additional reporting and provided more data for project teams to make informed decisions going forward, essentially creating a positive feedback loop.

A continuous improvement culture takes commitment from project and management leadership but has proven successful in the geothermal CT world and other industries (Rocha, 2023) (Wilson, 2020) (Basbar, April 2016).

4.1.3 Factory Drilling Concept

The concept of "factory drilling" (Duffy, 2016) could be used to reduce the cost of geothermal CT operations. This concept is based on the principles of LEAN and Six Sigma (Duffy, 2016) which focuses on maximizing value and reducing waste. In a drilling context this means, "standardizing the delivery of quality wells in the shortest amount of time possible in a streamlined fashion with zero process variability" (Duffy, 2016). This definition could also be applied geothermal CT operations. Duffy (2016) has written comprehensively on the topic. A graphic from this work showing types of manufacturing waste is shown below in Figure 2.

Figure 1: 7 Types of waste (Duffy, 2016)

Some examples of how these categories could apply to geothermal CT operations include:

• Overprocessing – developing programs and contingency plans before well diagnostics have been performed. Only to repeat them when more recent well data is sourced.

- Defects – CTU equipment failures resulting in Non-Productive-Time (NPT) &/or extended operations.

- Overproduction – extra cleanout runs which don't deliver additional megawatts to the customer.

- Inventory – additional contingency equipment on location generating standby costs which could have been eliminated by additional well diagnostics before a workover.

- Transport – optimization of loads or CTU configuration (e.g. trailer mounted versus containerized) to reduce transport costs.

- Movement – campaigning well workovers to reduce mobilization & demobilization costs.

- Waiting – Poor scheduling of ancillary equipment such as nitrogen deliveries (or other products) resulting in standby costs and extended operations.

4.1.4 Rig Efficiency Metrics

Another approach to reducing workover costs is rig efficiency metrics (Mansour, 2015). A rig efficiency metric is a quantifiable measure used to assess how effectively a drilling rig performs its tasks; non-productive time is a typical metric for example. As Mansour describes, a rig efficiency framework is more advanced than a efficiency metric as it uses a combination of metrics together as a basis to analyse and enhance rig performance and reduce operational costs. For example, Mansour (2015) successfully developed a framework for rig efficiency metrics in Libya. Mansour's framework composed metrics for availability, performance & quality. CTUs are essentially a type of workover rig, so the concept could also be applied to CTU operations.

To derive value for CT operations however, appropriate metrics need to be used. For example, Client A (Table 6) typically performs 1 x 12hr day of downhole operations. As such, the contractor typically charges on a day-rate basis. Focusing on reducing the rig-up time by a few hours is not going to affect the job cost. However, a CT stuck incident from lack of well data which results in an extra day of operations will have a more substantial effect on job cost. As such, a suitable metric might be "CT stuck incidents from lack of well data".

In contrast, Client E (Table 6) who typically conducts workover for 14-21 days due to the complexity of downhole conditions, a single extra BHA run may not be significant to the overall cost. However, mobilization time, number of truck loads, & liquid N2 consumption may be project characteristics that unlock step changes in job cost.

In closing, rig efficiency metrics are great tools to help identify ways to reduce job costs if selected appropriately for the workscope, and project characteristics are tracked consistently over time.

5. CONCLUSION

This paper endeavoured to review geothermal CT operational and job cost data to gain insight into delivering lower cost CTU projects. The data set reviewed is possibly the largest of its type collected globally. The data showed that the leading incident cause in geothermal CT projects was "Equipment and maintenance" followed closely by "Procedures". These are two important focus areas for operators looking to reduce their CT workover costs.

The job cost data gave insight into global price variability for geothermal CT projects. Apart from this result, client workscope differences made it hard to draw further conclusions from the data.

A casual reasoning exercise was performed and was useful in comparing different geothermal CT operational models across the globe. It showed that factors like well depth & required liquid N2 volumes have a large impact on the workover price. However, the data set leaves reviewers asking for more context.

Finally, the paper closed with suggestions for how to reduce the cost of geothermal CT workovers in the future. These included after-action reviews on single jobs and on work campaigns, implementing a continuous improvement culture, the concept of factory drilling and utilizing appropriate rig efficiency metrics.

6. ACKNOWLEDGEMENTS

The authors thank Western Energy management for access to their incident and job data. Furthermore, all Western Energy staff deserve congratulations for their commitment to open reporting and continuous improvement which has provided the results of this paper.

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Table 1: Table showing root cause options for the data set

Root Cause	Sub-Root Cause
Equipment & Maintenance	Coiled Tubing Pipe
	Coiled Tubing Unit
	Bottomhole Assembly
	Crane
	Other
Procedures	Planning
	Program
	Standard Operating Procedures
	Maintenance
	Other
Knowledge	Training
	Competency
	Technical
Job Factor	Behavior
	Stress
	Communication

Table 2: Example of a data entry for the incident root cause analysis

Year	Well	Client	Incident Description	Root Cause 1	Sub-Root Cause 1	Root Cause 2	Sub-Root Cause 2
2017	Well A	Client A	Stuck BHA	Procedures	Planning	Job Factor	Communication

Table 1: Table used for job cost analysis

Year	Well	Client	Operation Type	Cost (NZD)
2021	Well A	Client A	Well Abandonment	$-

Table 2: Tabulated data from incident root cause analysis

Year	E&M*	SOPs*	T&C*	JF*	Total	Rank Count
2014		1	0	0	1	SOPs
2015	1	1	0	0	2	E&M/ SOPs
2016	1	1	0	1	3	E&M/ SOPs / JFs
2017	10	7	7	6	30	E&M
2018	6	1	4	0	20	SOPs
2019	3	4	2	0	9	SOPs
2020	6	6	8	2	22	T&C
2021	3	3	2	1	9	E&M/ SOPs
2022	3	2	4	3	12	T&C
2023	13	4	7	4	28	E&M
2024	12	7	6	1	26	E&M
2025	10	0	7	0	17	E&M
Total	68	46	47	18	179	-

E&M (equipment & Maintenance), SOPs (Procedures), T&C (Training & Competency), JF (Job Factors)

Figure 1 Graphical representation to data from Table 4.

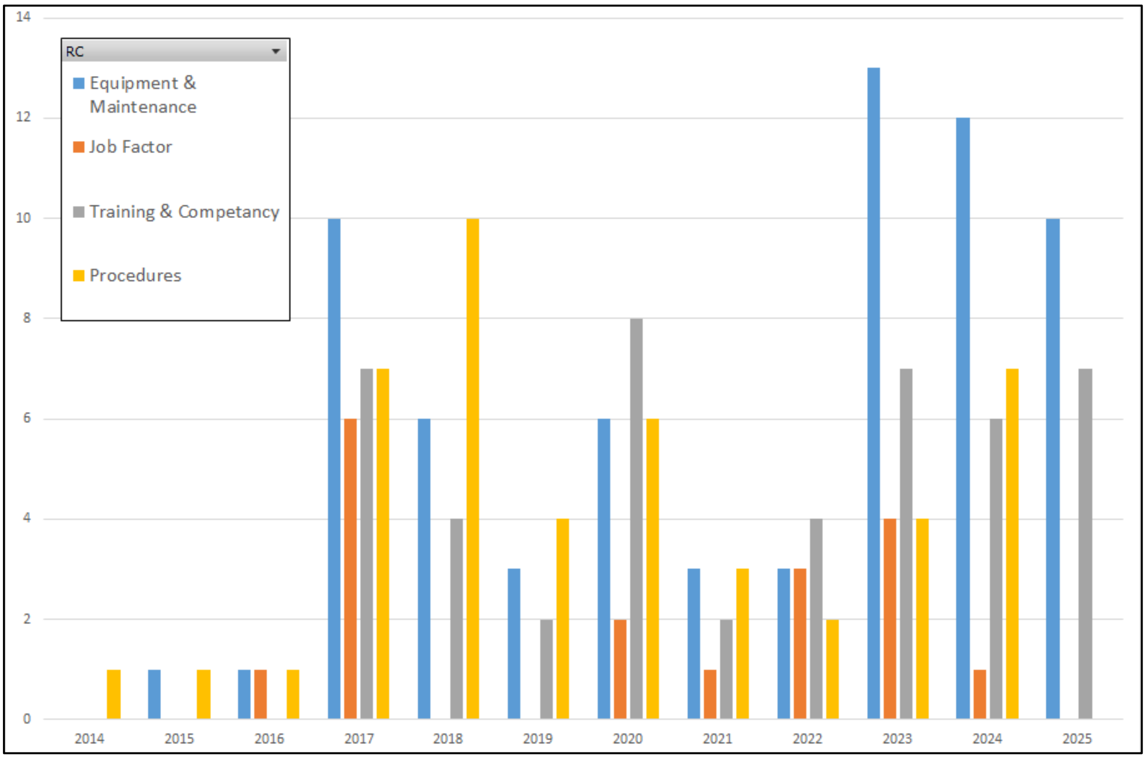

Table 5: Table showing cost variability for Geothermal Well CT Cleanouts for 6 clients. Cost variability is considered the standard deviation of the data set divided by the average cost of a Live Well Cleanout for a particular client

	Client A	Client B	Client C	Client D	Client E	Client F
#Cleanout jobs	5	2	3	2	3	2
Cost Variability	10%	71%	40%	49%	12%	3%

Table 6: A summary of the CTU project data reviewed from various clients to conduct the casual reasoning analysis.

Client	Well Depths (m)	CTU Type (ownership)	CTU Job Frequency	CT Runs / workover	Travel Time to location	Operation Mode 12 or 24hr	CTU Workover Duration (days)	Internationally sourced personnel for operations	Liquid N2 Volume per cleanout (USgal)	Average Job Cost Rank 1 = higher
A	400-2000m Majority ~1000m	Trailer mounted (Contractor)	11 / year	1	15-30mins	Mostly 12hr operations	3	No	<4000gal	7
B	2200	Trailer mounted (Contractor)	0-1 / year	2	15-30mins	12hr	3 – 14	No	NA	3
C	>2000m	Trailer mounted (Contractor)	1 / year	1	30mins	12hr	3 – 7	No	NA	5
D	300-2100	Trailer mounted (Contractor)	0-1 / year	6	30mins	12hr	3 – 7	No	<4000gal	4
E	>2000m	Container Unit (Client)	3-4 / year	4	30min-2hrs	24hr	14 - 21	Yes	~20,000 gal	2
F	1000-2000	Trailer mounted (Contractor)	6-8 / year	1-3	15-30mins	24hr	3-4	Mostly not. Depends on project scope	Unknown	6
G	805-2058	Trailer mounted (Client)	0-1 / year	4	1 hour	12hr	~20	Yes	<4000gal	1