Uncertainty Analysis of Geothermal Well Drilling and Completion Costs

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ABSTRACT

The goal of this project is to characterize the uncertainty involved with the cost of drilling and completion of geothermal wells. Previous research and publications have produced correlations predicting the average cost of geothermal wells as a function of depth. This project develops this concept further by using a probabilistic approach to assess the cost of geothermal wells. The uncertainty is characterized by identifying the most important cost components of geothermal well drilling and completion and determining the probability distributions of the key variables controlling each of these costs. These distributions are found based on drilling records of geothermal wells located in the U.S. and information from drilling equipment manufacturers and vendors. The probability distributions are then modeled in WellCost Lite software and simulated using Monte Carlo method with a goal of developing total well cost distributions as a function of depth.

Introduction and Scope

Although many of the high-grade hydrothermal resources in the United States have already been developed for electricity generation, the potential for production from lower-temperature hydrothermal and deep geothermal reservoirs is still quite widespread. One of the primary obstacles in developing these deep resources using Enhanced Geothermal Systems (EGS) technology is the cost of drilling, and specifically the increased risks associated with drilling deeper wells. Therefore, characterization of geothermal well drilling costs is critical to the growth and expansion of geothermal projects to include lower-grade, deeper resources. A thorough characterization of EGS drilling costs was presented in The Future of Geothermal Energy assessment (Tester, et al., 2006). This MIT-led study included a well cost index named the MIT Depth Dependent (MITDD) index, which correlated the nonlinear dependence of geothermal drilling costs with well depth. This report includes a plot of well cost versus depth based on data from hydrothermal wells and WellCost Lite model predictions for EGS wells. WellCost Lite is a detailed well costing model developed by Bill Livesay and co-workers that was used extensively for estimating EGS drilling costs in The Future of Geothermal Energy study.

The WellCost Lite model has been similarly employed in our analysis to provide well cost predictions. The well cost versus depth curves, originally documented in The Future of Geothermal Energy report, were updated by Lukawski et al. (2014) and are

![Figure 1. Actual and Predicted Oil and Gas and Geothermal Well Costs as a Function of Depth (Lukawski, et al., 2014).](image-url)
reproduced in Figure 1. While these curves provide a deterministic prediction of the average well cost at depths ranging from 1,820 to 30,000 ft (555-9,144 m), they do not characterize the range of uncertainty around them. This paper aims to expand upon these previous works by identifying the main variables influencing the cost of a geothermal well and analyzing the probability distribution of each of these variables. These distributions will then be modeled using the WellCost Lite model and simulated using the Monte Carlo method to produce a set of well cost distribution curves as a function of depth.

**Methodology**

The first step taken towards characterizing the uncertainty was to gather well cost data from available sources. These sources include data documented in our group’s earlier publications such as Cost Analysis of Oil, Gas, and Geothermal Well Drilling (Lukawski, et al., 2014), actual data from fourteen hydrothermal wells drilled in the U.S. from 2008 to 2013, and example EGS well costs from a Baker Hughes report titled Enhanced Geothermal Systems Directional Well Costing (Baker Hughes, 2012). The costs were then itemized according to the categories commonly used in authorizations for expenditure (AFE) and were sorted by contribution to the total well cost. An example itemized well cost from real hydrothermal well data is shown as a pie chart in Figure 2. Each of the thirty-two wells in the data set was itemized into twenty-five categories; investigation revealed that eleven of these categories each constituted 5% or more of the cost of each well. These eleven were identified as the most influential well cost factors that require further Monte Carlo analysis. The remaining fourteen factors were assumed have negligible uncertainty and were treated as constants with a value equal to the sample mean in this study.

For each influential cost component, data from all thirty-two wells were gathered, normalized by well depth or total drilling days as appropriate, sorted into bins, and plotted in a histogram to reveal the shape of the probability distribution for that particular well cost factor. Figure 3 shows an example of the histogram for depth-normalized drilling mud cost data. Using these histograms, supplemented by industry experience, each factor may be approximated by a common distribution, such as normal, triangular, or Weibull.

Once the probability distributions of the primary cost components were determined, each of these factors was identified and traced back to its origin in the WellCost Lite model. @RISK (a Monte Carlo simulator) was used in conjunction with WellCost Lite to simulate the total uncertainty of well cost based on the probability distribution of each variable determined with the assistance of the histograms. An example of the Weibull distribution for depth-normalized drilling mud costs input to the @RISK Monte Carlo simulation is reproduced in Figure 4. Each of the influential factors was modeled by its corresponding probability distribution and input to the @RISK simulation in similar fashion, after
which a full simulation with of the total cost of the WellCost Lite model was run. This full simulation with 100,000 iterations yielded a probability distribution for total well cost at a given depth, and was repeated at a range of depths to find the total uncertainty of geothermal well cost drilling as a function of well depth.

**Results**

As of June 2014, we are waiting for additional data from well drilling contractors and equipment manufacturers, so the results are not yet finalized and validated. We will carry out this additional work as data become available and update our presentation at the 2014 GRC Annual Meeting accordingly. Preliminary results are presented below. Figure 5 shows an estimated probability distribution for the total drilling and completion cost of a 10,000 foot EGS well with a diameter of 8.5 inches, produced by WellCost Lite used in conjunction with @RISK. The x-axis depicts total cost, while the y-axis shows the probability of each cost range. Figure 6 and Figure 7 show well cost distributions for wells of 8,000 feet and 12,000 feet total measured depth respectively. The diamond markers above the graphs indicate the 5% and 95% probability percentiles for each depth. After creating these graphs for a range of well depths and recording the 5% and 95% boundary curves, a graph of total well cost versus depth, with 5% and 95% uncertainty curves, was determined and is shown in Figure 8 below. The probability values given in Figure 5 – Figure 8 are estimates, and their accuracy is uncertain until the values are verified with new data from drilling contractors and equipment manufacturers.

**Conclusion**

The methodology described in this paper, applied to the WellCost Lite model with the assistance of @RISK for Monte Carlo
simulation purposes, yields a graph of the median total completed well cost versus depth, bounded by upper and lower probability curves for the 5th and 95th percentiles. The 5% - 95% bounding curves given in Figure 8 slowly diverge with depth, meaning that the uncertainty of the total well cost increases with depth, as is to be expected. However, the range of the uncertainty about the median is still low. Even at a depth of 14,000 feet (4,267.2 meters), the total range of the uncertainty on either side of the median is still less than $1 million. As discussed in the results section of this report, the above graphs are based on estimates, and the accuracy of the values is awaiting verification against data provided by drilling contractors and equipment manufacturers. The final validated predictions will be presented at the 2014 Annual GRC Conference. With the validation of final results, this graph will provide a quantification of the uncertainty involved with the total cost of drilling and completion for EGS wells as a function of depth.

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References

