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Technical Requirements for Geothermal Resource Confirmation

Koenraad F. Beckers and Katherine R. Young

National Renewable Energy Laboratory
***corresponding author: koenraad.beckers@nrel.gov**

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ABSTRACT

In 2017–2018, the Bureau of Land Management's Renewable Energy Coordination Office, through its Geothermal Program, funded the National Renewable Energy Laboratory (NREL) to analyze technical and environmental considerations related to geothermal resource confirmation drilling. NREL solicited input from a group of technical and environmental experts in the geothermal industry, along with analyzing National Environmental Policy Act of 1969 (NEPA) documentation for previously approved projects. The collected data and analysis will be used by the Bureau of Land Management to examine the possibility of developing a new classification of wells and/or expediting the NEPA compliance process, which could potentially reduce permitting and regulatory compliance timelines when compared to the current process for obtaining a geothermal drilling permit for resource confirmation drilling activities.

This paper provides a summary of the technical requirements for confirming a geothermal resource. The analysis showed that confirming a geothermal resource requires confirming reservoir temperature, chemistry, permeability, and flow rate. Obtaining these data requires drilling at least two—preferably three—successful wells into the resource to conduct the necessary tests, including an interference test. Bottom-hole well diameters of at least 6" to 8" (0.15 to 0.2 m) are needed to limit the wellbore frictional pressure drop to effectively perform well flow and interference tests. Drilling these wells requires a drill rig with a mud pump and derrick capable of holding three drill pipes. This type of rig requires a minimum well-pad size of 2.5 acres (10^4 m^2) including surface area for a 1 million-gallon (3.8 million-liter) pit. Up to 15 acres (5×10^4 m^2) of total surface disturbance are needed for developing access roads and well pads to drill a total of three to five wells.

1. Introduction

The Bureau of Land Management's Renewable Energy Coordination Office, through its Geothermal Program, has funded the National Renewable Energy Laboratory (NREL) to analyze technical and environmental topics related to geothermal resource confirmation. Geothermal drilling has high up-front costs and high potential risk of unsuccessful exploration efforts, making it difficult to secure financing for these projects before the resource has been confirmed. This analysis looks at the possibility of developing a new classification of wells and/or expediting National Environmental Policy Act of 1969 (NEPA) compliance that could potentially be permitted more quickly than the current process for obtaining a geothermal drilling permit (GDP) for resource confirmation drilling activities.

Confirming a geothermal resource is defined as obtaining sufficient subsurface information that proves with high probability that a resource of certain magnitude can be developed. When a resource has been confirmed, banks are willing to provide financing for further project development. The resource confirmation phase follows the resource exploration phase. Geothermal exploration uses various techniques—such as interpreting geologic maps, analyzing surface manifestations, conducting seismic and resistivity surveys, and drilling core holes—to find promising geothermal resources (Stober and Bucher, 2013; Glassley, 2014). Once a promising region has been identified, larger-size wells are drilled, and additional tests are conducted (as discussed in Section 4) to confirm the resource.

This paper summarizes the technical interviews, monthly calls, and in-person workshop dedicated to technical requirements. Section 2 provides the methodology for this project. Section 3 provides an overview of the different types of geothermal wells and discusses which ones are used during the resource confirmation phase. Section 4 lists the resource confirmation tests conducted; well, well pad, and surface disturbance technical requirements; and project time needed for the confirmation phase. A conclusion of the results is included in Section 5. A parallel paper focusing on environmental concerns and mitigation strategies related to geothermal resource confirmation is presented at this conference by Levine et al. (2018).

2. Methodology

NREL conducted a series of technical and environmental interviews with geothermal stakeholders (i.e., Geothermal Expert Team) to understand the minimum technical requirements for confirming a geothermal resource, the associated potential environmental concerns, and measures to mitigate these concerns. As a follow-up to the one-on-one interviews with geothermal stakeholders, NREL organized a series of monthly calls with the Geothermal Expert Team to gain consensus on the feedback documented as part of the one-on-one interviews. In addition, NREL held an in-person workshop open to the public in February 2018, inviting a broader industry audience, during the Stanford Geothermal Workshop in Palo Alto, CA. The "technical experts" on the Geothermal Expert Team had backgrounds in geothermal exploration, geothermal drilling, well design, reservoir engineering, and project development (see Section Acknowledgments).

Table 1. Comparison of different geothermal well types. (T = temperature, P = pressure, and OD = outer diameter)

Well Type	1	2	3	4	5
Well Name	Temperature-Gradient Hole (TGH)	Core Hole *(into reservoir)*	Slim Hole *(into reservoir)*	Standard-Completion Confirmation Well	Standard-Completion Production/ Injection Well
Main Objective	Measure shallow temperature-by-depth profile	Obtain subsurface core samples	Penetrate reservoir to assess T/P, chemistry and geology	Conduct flow and interference test	Regular production/ injection
Data Obtained	T gradient, geology	T/P, chemistry, limited flow test, geology	T/P, chemistry, limited flow test, geology	T/P, chemistry, flow test, interference test, geology	T/P profiles, flow test, interference test, chemistry, geology
Range of Typical Measured Depth	150 to 500 ft (46 to 152 m) (up to 1,500 ft [457 m] in some areas)	1,500 to 5,000 ft (457 to 1,524 m)	1,500 to 5,000 ft (457 to 1,524 m)	up to 12,000 ft (up to 3,658 m)	up to 12,000 ft (up to 3,658 m)
Conductor Size	Typically N/A	Hole Diameter: 15–20″ (0.38–0.51 m) Casing OD: 9–14″ (0.23–0.36 m)	Hole Diameter: 15–20″ (0.38–0.51 m) Casing OD: 9–14″ (0.23–0.36 m)	Hole Diameter: 22–24″ (0.56–0.61 m) Casing OD: 16–20″ (0.41–0.51 m)	Hole Diameter: 30–40″ (0.76–1.0 m) Casing OD: 20–30″ (0.51–0.76 m)
Surface String Size	Typically N/A	Hole Diameter: 10–15″ (0.25–0.38 m) Casing OD: 6–10″ (0.15–0.25 m)	Hole Diameter: 10–15″ (0.25–0.4 m) Casing OD: 6–10″ (0.15–0.25 m)	Hole Diameter: 16–18″ (0.41–0.46 m) Casing OD: 13–16″ (0.33–0.41 m)	Hole Diameter: 20–30″ (0.51–0.76 m) Casing OD: 18–22″ (0.46–0.56 m)
Size of Final Cemented String	None (2″ [0.05 m]) blind tubing)	4–6″ (0.10–0.15 m)	4–6″ (0.10–0.15 m)	6–10″ (0.15–0.25 m)	8–18″ (0.20–0.46 m); most common: 9-5/8″ (0.24 m) and 13-5/8″ (0.35 m)
Final Hole Size	3–6″ (0.08–0.15 m)	<6″ (<0.15 m)	<6″ (<0.15 m)	6–10″ (0.15–0.25 m)	8–12″ (0.20–0.30 m)
Drilling Time	1–5 days	15–45 days	15–45 days	30–60 days	30–70 days
Cost Range ($US)	$20–150K	$0.5–2M	$0.5–2M	$2–6M	$3–10M
MW_e Potential	0	<2 MW_e	<2 MW_e	< 5MW_e	< 20 MW_e
Lead Time (Designing and Permitting)	1–3 months	4–8 months	4–8 months	5–10 months	9–12 months

3. Types of Geothermal Wells

Various types of geothermal wells exist, which are drilled for different purposes in a geothermal project, and they include different designs, dimensions, drilling times, drilling costs, and more. In collaboration with the Geothermal Expert Team, five main categories of geothermal wells were identified, based on the (original) objective of the well (see Table 1). Other classifications and labels exist—for example, an "observation well," which could fall under any of the well types 2 to 5 in our classification—but are not discussed further here. At a specific geothermal site, typically at least one of each of these well types are drilled: temperature-gradient holes and core holes during initial exploration, slim holes for obtaining additional subsurface data, standard-completion confirmation wells for well and interference tests to further characterize and confirm the resource, and eventually, standard-completion production and injection wells used for regular geothermal plant operation. As discussed in Section 4, the geothermal wells needed for geothermal resource confirmation need to have sufficiently large bottom-hole diameter—at least 6” to 8” (0.15 m to 0.20 m)—to allow reliable flow and interference tests. These wells are of type 4 or 5.

4. Results

The Geothermal Expert Team stated that to confirm a geothermal resource, various tests are required (Section 4.1) to confirm temperature, pressure, flow rates, and more. To effectively execute the well flow and interference tests, a minimum number of wells of sufficiently large bottom-hole diameter is required (Section 4.2). Drilling these types of wells requires surface disturbance for access roads and well pads (Section 4.3) as well as a large enough drill rig and surface fluid storage (Section 4.4). The resource confirmation timeframe (Section 4.5) should be long enough to conduct all on-site activities (e.g., drilling, testing) and account for delays (e.g., securing financing, snow fall, species breeding season).

4.1 Tests

Confirming a geothermal resource requires conducting tests to confirm temperature, pressure, chemistry, flow rate, and near-wellbore and overall reservoir permeability. These tests include:

- **Pressure/Temperature (P/T) or Pressure/Temperature/Spinner (P/T/S) survey:** Gives pressure and temperature (the S – or “spinner” – can be used to identify reservoir feed zones).
- **Chemical analysis test:** Conducted on fluid samples to estimate corrosion, theoretical reservoir temperature, and presence of non-condensable gases.
- **Well flow test:** Provides flow rate (after steady-state condition is obtained) and, when combined with pressure, provides productivity index/injectivity index. This test typically takes two to seven days. In case of two-phase flow for flash plants, the individual gas and liquid volume rates are measured to estimate the vapor fraction. Data obtained from a well flow test give developers an initial indication of reservoir transmissivity and allow for assessing the drilling-mud damage to the formation (also called skin factor). Banks generally require developers to demonstrate that a certain percentage (in the United States, typically 50%) of the target production flow rate is obtained during the confirmation phase. Depending on the size of the plant considered, fulfilling this criterion requires drilling a certain number of wells (see Section 4.2.1).
- **Interference tests:** Provides average reservoir permeability and can take four to eight weeks. Fluid is produced from one well and reinjected into another well to measure connectivity between the two wells. Preferably, a third well is instrumented to obtain additional transient pressure data.

4.2 Wells

4.2.1 Number of Wells

One well penetrating the reservoir would be sufficient to obtain data on reservoir temperature, pressure, and chemistry. However, multiple wells are needed to conduct well flow and interference tests:

- **To conduct interference test:** An interference test is conducted to estimate overall reservoir permeability. For this test, a minimum of two—preferably three—flowing wells are needed. One well can only provide information on near-wellbore permeability.
- **To conduct well tests:** A percentage (typically 50% in the United States) of the total target production flow rate should be demonstrated during the resource confirmation phase. For example, considering a 20 MW_e plant, and sizing wells for a 5 MW_e power output per well, two flowing production wells would be required. The percentage required can be 70% to 80% for other countries such as Chile, Peru, and Uganda.

Several project-dependent factors impact the final number of wells that are required for well and interference tests to confirm a geothermal resource:

- **Field history:** An established geothermal region (e.g., Iceland) or a brownfield with prior development may need fewer wells to confirm a resource than new regions (e.g., Cascades) and greenfields.
- **Project size:** For the same geothermal resource, a 50 MW_e plant would need more wells than a 10 MW_e plant.
- **Resource quality:** For the same plant size, a high-enthalpy resource (e.g., high-temperature two-phase liquid/vapor) would need fewer wells than a low-enthalpy resource (e.g., low-temperature single-phase liquid).
- **Company history:** Smaller, less established companies may need more wells to convince a bank that a resource has been confirmed than larger, more established companies.

4.2.2 Diameter of Wells

Sufficiently large wellbore diameters are required to limit the wellbore frictional pressure drops to effectively run well flow and interference tests. These tests depend on several parameters including well depth, resource temperature and pressure, and target plant size; but, in general, a bottom-hole diameter of 6” (0.15 m) or larger is desired.

A slim-hole well with 4.5” (0.11 m) bottom-hole diameter allows for collecting fluid samples for chemical analysis, measurements of resource temperature and pressure, and for conducting initial transient pressure tests. However, this diameter is normally too small to effectively flow fluid during well flow and interference tests. Some developers may use a slim-hole well as a monitoring well in combination with two other wells with larger-diameter holes for interference tests.

If large flow rates are targeted, a 6” (0.15 m) bottom-hole diameter may be too small for the criterion of a 50% target flow rate. However, this well can still be used to obtain data on near-wellbore reservoir permeability with a well flow test and overall reservoir permeability with an interference test. In the latter test, this well is likely used as an injection well with a larger bottom-hole diameter (e.g., 8.5”) serving as a production well.

If developers have enough confidence in the resource, they may choose to drill full-size production and injection wells with bottom-hole diameters of 8” (0.2 m) or larger during the resource confirmation phase. These wells will eventually be used for fluid production and injection during regular plant operation. In some regions, 20 MW_e wells have been drilled with bottom-hole diameters larger than 10” (0.25 m), but this is not likely for most U.S. resources. If the well must be pumped, the well should be sized appropriately to fit the pump in the well. For example, installing a 12” (0.30 m) pump requires at least 13-3/8” (0.34 m) casing.

4.2.3 Fate of Standard-Completion Confirmation Wells

Standard-completion confirmation wells with sufficiently large bottom-hole diameter (generally 8” [0.20 m] or larger) can be used as regular production or injection wells during plant operation. If the bottom-hole diameter is only 6” (0.15 m), in some circumstances—e.g., the well is right next to a power plant and intersects a fracture—the well can be used as an injection or even a production well. However, in most cases, these wells serve as observation wells and the developer may drill a new larger-diameter production or injection well from the same well pad.

4.3 Surface Disturbance

Developers need about 15 acres (5×10^4 m^2) of surface disturbance to confirm a geothermal resource. Developers use this acreage for three to five well pads and access roads.

4.3.1 Size of Well Pad

The minimum well-pad size for drilling standard-completion confirmation or production/injection wells is 2.5 acres (10^4 m^2). This acreage is distributed as follows:

- **Drill rig and equipment:** 1.3 acres (5.3×10^3 m^2).
- **Sump:** 0.6 acres (2.4×10^3 m^2). This assumes a 1 million-gallon (3.8 million-liter) sump at 5 ft (1.5 m) depth. However, depth will depend on location (e.g., in Nevada, typically a shallow sump depth is required because of a shallow water table). Experts stated that sumps up to 10 ft (3.0 m) deep are not uncommon. This includes 1 to 2 ft (0.3 to 0.6 m) of freeboard required to prevent spills.
- **Equipment moving:** 0.5 acres (2.0×10^3 m^2).

4.3.2 Number of Well Pads

Wells need to be spaced a significant distance apart to effectively run an interference test. A minimum distance of 1,000 ft (305 m) has been put forward by the expert team, measured from where the wells touch the reservoir. Depending on how much deviation from drilling vertically, the surface spacing may be slightly different. Directional drilling is not common for early-phase exploration wells. Hence, for drilling three wells, three well pads are needed (for a total acreage of about 7.5 acres). Developers may only know after drilling each well where they want to locate the next well pad.

4.3.3 Access Roads

The ability to construct access roads is desirable to have freedom in selecting the drill sites. Access road dimensional requirements are as follows:

- **Minimum width:** 18 ft (5.5 m)
- **Average length:** 0.25 miles (0.4 km). One access road of 0.25 mile (0.4 km) length and 18 ft (5.5 m) width has an area of about 0.5 acres (2.0×10^3 m^2).

- **Strength:** Sufficient road strength to allow a semi tractor-trailer load that is overweight highway permittable.
- **Turnouts:** Periodic (every 0.25 mile [0.4 km]) turnouts to allow 2-way traffic are desirable. In theory, an 18-ft-wide road would not require turnouts, but they are still preferred by developers to facilitate two large semi-trucks coming from opposite direction to pass each other.

Rubber mats can be used on access roads in muddy/swampy environments as a base for the first layer to keep that layer from sinking. However, the expense can go up quickly when placing mats on access roads, so they are rarely used.

4.4. Well Pad Components

4.4.1 Drill Rig

To drill a standard-completion confirmation or production/injection well—with bottom-hole well diameter of 6” to 8” (0.15 m to 0.2 m) or larger, and typical depth of 5,000 ft (1,524 m) or deeper—a drill rig is required that uses a mud pump and has a derrick capable of holding three drill pipes. This type of drill rig is not mobile and cannot be mounted on a truck. Instead, this drill rig is usually deconstructed into 20 to 40 truckloads (overweight highway permittable) and requires a sufficiently large well pad (see Section 4.3.1) and sufficiently wide and strong access roads (see Section 4.3.3). A helicopter drill rig can be used for drilling core-hole and slim-hole wells, but not for confirmation and production/injection wells.

4.4.2 Fluid Storage

Surface fluid storage is needed during drilling and for well flow and interference tests. A 1 million-gallon (3.8 million-liter) open pit is preferred. Pits are typically clay-lined. Surface fluid storage can also be obtained with temporary tanks (e.g., Baker tanks). However, tanks are more expensive, typically have less total volume, lines can freeze in winter, and they can be difficult to clean out. Tanks are generally only used in an emergency or when no pit excavation is possible or allowed.

During a long-term interference test, the pit acts as a storage buffer. All fluid produced from one well gets reinjected into the other well. Fluid is not being stored from several weeks of production, but rather, only from a few hours or days maximum. A 1 million-gallon (3.8 million-liter) pit can store 12 hours of produced fluid flowing at 1,360 gpm (86 L/s).

4.5 Timeline

The resource confirmation timeframe can take up to 5 years. The clock starts ticking when “a rock gets kicked,” i.e., when the first access road or well pad starts getting built.

This timeframe encompasses:

- On-site activities: Up to 1.5 years
  - 60 to 100 days for preparing roads

- 30 to 75 days per well for well drilling and well tests. The decision to drill each consecutive well is made after evaluating data from previous wells (i.e., wells are not drilled concurrently).
- 1 to 2 months for interference test.

- Account for delays due to securing additional financing, negotiating power purchase agreement, avoiding species breeding season, snowfall, and more: Up to 3.5 years[1]

5. Conclusions

The results presented in Section 4 provide typical technical requirements for confirming a geothermal resource with focus on average-sized hydrothermal systems in the United States developed by established companies. Requirements may vary in other countries, for different companies, for different-type geothermal resources, and for different-size geothermal systems. The technical requirements are heavily governed by the need for performing effective well flow and interference tests. These tests require two to three wells penetrating the reservoir with large enough bottom-hole diameter. Drilling these wells requires large enough drill rigs and fluid storage, which translates into requiring access roads, large enough well pads, and a long enough timeframe.

For this study, geothermal resource confirmation was defined as obtaining sufficient subsurface data to state with high probability—e.g., with 90% confidence level (Sanyal and Morrow, 2010)—that a resource of certain magnitude (in MW_e) can be developed. At this point, banks are willing to provide financing for further project development. An exploration phase (using data obtained, for example, from geologic maps, seismic surveys, and core-hole drilling) precedes the confirmation phase. The data collected during both phases become input in geothermal reservoir and geothermal resource assessment models to quantify the developable resource size (Glassley, 2011; Grant, 2011). Other terminology has been used in the literature to describe the geothermal resource confirmation activities, e.g., production testing (Grant and Bixley, 2011), resource confirmation testing (Glasspey et al., 2008), test drilling (Gehringer and Loksha, 2012), and confirmation drilling (Sanyal and Morrow, 2010).

The conclusions of the analysis on technical requirements for geothermal resource confirmation are as follows (typical requirements with focus on the United States):

- **Tests:** Tests are conducted to confirm temperature, pressure, chemistry, permeability (near wellbore and overall reservoir), and flow rates.
- **Wells:** Up to three successful wells are required that penetrate the reservoir with bottom-hole diameter of at least 6”–8” (0.15–0.20 m). A large enough wellbore diameter is needed to effectively run well flow and interference tests.

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[1] Note: This includes additional time for smaller companies that may be slower in developing wells than more established companies.

- **Well pad components:** A drill rig with mud pump and derrick capable of holding three drill pipes is required. A sump with typical size of 1 million gallons (3.8 million liters) is required to store fluid during drilling and tests.
- **Surface disturbance:** Up to 15 acres (5×10^4 m^2) of surface disturbance are required for developing access roads and well pads. The type of rig needed requires a well-pad size of 2.5 acres (10^4 m^2).
- **Timeframe:** A resource confirmation timeframe of up to five years may be required to conduct all on-site activities (e.g., drilling, testing) and account for delays (e.g., securing financing, snow fall, species breeding season).

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