Unlocking Deep SuperHot Rock Resources Through
Millimeter Wave Drilling Technology

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ABSTRACT

Super Hot Rock (SHR) represents a renewable energy resource with a power density comparable to fossil fuels, an order of magnitude improvement relative to typical geothermal systems. The overwhelming majority of SHR resources are stored in deep continental crust, accessible to 80% of the world’s major population centers at depths ranging from 10 – 20 km. Accessing this Deep SHR resource requires a novel drilling approach that can leapfrog the current limitations to deep mechanical drilling: Millimeter-Wave (MMW) Drilling. Pioneered at MIT and leveraging technology developed for nuclear fusion research, MMW Drilling represents a non-contact, direct energy drilling approach that replaces mechanical drilling with a full bore vaporization approach. High-powered Radio Frequency energy is efficiently transmitted downhole to result in a dielectric heating interaction, rapidly sublimating the rock before the quenched vapors are conveyed up-hole by a circulating purge gas in a manor analogous to air drilling. MMW Drilling can avoid the high temperature, high pressure limitations on current drilling technology while improving drilling rates of penetration for deep formations by an order of magnitude, enabling Deep SHR at a global scale. In this paper, we explain the MMW drilling concept and why it’s an optimal approach to access Deep SHR, provide justification through simple economic models, and demonstrate the technical feasibility by presenting recent results from a lab experimental campaign at Oak Ridge National Laboratory (ORNL).
1. Introduction

Deep-Hot-Dry Rock (HDR) thermal resources can be found in ultra-deep (>10 km) conduction-dominated hot rocks within the crystalline basement underlying the continental U.S. At these depths water and other fluids exceed their critical point to become supercritical in the subsurface HDR reservoir, an energy resource referred to hereon as SuperHot Rock (SHR), describing subsurface thermal energy potential with temperatures greater than 400 °C in deep impermeable basement. To put into comparison how much thermal energy is stored in SuperHot Rock across the continental U.S., the thermal energy stored in supercritical volcanic areas accessible for EGS alone is 1% of the same thermal energy resource in conduction-based crystalline basement rock spanning the entire continental U.S. above 10 km depth [Tester 2006]. Clearly, this same Superhot resource extrapolated to that same continental extant but 10 – 20 km depth interval would be orders of magnitude greater than the conventional EGS resource below 10 km depth. This resource can be accessed in most locations globally when depths greater than 10 km are regularly exceed. PNNL has found that 50% of the global population could be served with SEGS within a depth of 10 km and 95% within a depth of 20 km, which makes SEGS incomparable as a resource that can provide those power densities with local resources and at scale [Cladouhos 2018]. SHR energy is optimal for its high power densities shown in the figure below (100 W/m²) against fossil fuels and other renewable energy resources Geothermal water produced at temperatures above the supercritical point (~400 °C) increases the fluid energy density by a factor of 4x (compared to 200 °C), and high temperature steam turbines imply a 2x-4x increase in energy conversion efficiency, resulting in a 8x-16x increase in extracted energy per well over conventional geothermal wells and 4-5x more energy than typically produced from a shale well.

![Energy per Well](image)

Figure 1: Power density for various subsurface energy systems: MW per well(pad) [Cladouhos et al. 2018]

The key constraint on accessing SHR is resource depth. Accessing hot, hard rock at depths greater than 10 km requires breakthroughs across a spectrum of conventional drilling and extraction technologies. Geothermal requires a revolution in innovation similar to shale gas development to reach this SHR resource when it comes to the economies of scale, to leverage potential innovations via supercritical EGS (s-EGS) high enthalpy steam power generation, which could expand the geothermal industry a hundred-fold and incentivize the O&G industry to extract heat instead of hydrocarbons, as the energy transition can leverage much of their existing infrastructure (including personnel, tech) to extract an energy resource comparable to those fossil
fuels powering the global economy today. SHR is already targeted by the countries with decades experience harnessing geothermal, including Iceland, Italy, Japan, New Zealand, and China. U.S. involvement and international collaboration could benefit the entire industry to bring this resource online and to scale in the record time required to address global climate goals.

Widespread s-EGS requires development of deep drilling technologies to reach beyond 10 km effectively to drill through the brittle-ductile transition zone (BDTZ) to reach a thermal resource in the rock that can still be accessed by novel s-EGS methods. Given the average composition of deep continental basement accessing SHR temperatures at depth require both drilling and s-EGS technologies that can access and extract thermal energy at or past the BTDZ, which is highly challenging for conventional approaches but there is evidence that moderate permeabilities can be enhanced and maintained between deep supercritical wells at these depths to support highly economic and sustainable reservoir flow [Violay 2017] [Watanabe 2017] [Scott 2017].

conventional drilling technologies can get to 10 km in oil and gas wells, but there’s no capability to consistently hit past 10 km in crystalline rock. Steel drilling tools are just not strong enough to reach 10 km into hard (crystalline) rock; hard rock is any material with a Mohs hardness greater than 6. The materials themselves are fundamentally too weak to sustain the loads required for geothermal-sized wells.

2. Millimeter Wave Drilling

A novel solution to overcome limitations to conventional drilling methods is direct energy drilling with MMW technology: MMW Drilling [Woskov 2009]. The mechanical rock destruction methods are replaced with an energy matter interaction: intense energy transmitted to the rock will be absorbed as a dielectric material and that EM energy will be converted into thermal energy via dielectric heating to do work raising the rock temperature to the specific energy needed to vaporize rock past its vapor point [Maurer 1968]. This rock temperature will rapidly increase to melt and vaporize and rock components, and those vapor products can then be removed from the borehole via conventional air drilling methods via a circulating purge gas [Oglesby 2014] [Houde 2021]. Drilling limits from rock hardness, temperature, and pressure would be negated due to the lack of mechanical drilling equipment downhole: the only downhole component is a waveguide, or metallic pipe, to transmit the MMW energy and circulating gas downhole. This dielectric heating process also has the potential to create vitrified layer of glass downhole along the periphery of the ablation front, forming a glass liner that can stabilize the borehole during drilling and potentially replace conventional completion methods with a monobore glass hole for the open-hole production sections downhole [Woskov 2017].

MMW Technology is chosen for its optimal physics an existing suite of technology solutions for generating and transmitting a tremendous amount of power downhole. Non-ionizing Electromagnetic (EM) radiation in the 1 – 10 mm wavelength range (30 – 300 GHz) can transmit high power levels of EM energy long distances in the downhole dimensions required for geothermal drilling, while negating the attenuation losses associated with transmission through a dusty drilling environment. The process is further summed up in figure 2 below.

2.1 MMW Technology and Physics

High-power MMW sources, called gyrotrons, and waveguide transmission lines to transmit the generated MMW “beam”, represent technology developed as part of the nuclear fusion research
program with the purpose of heating a plasma source to generate the internal temperature
conditions required to initiate a fusion reaction. Gyrotrons are able to generate MW-scale power
levels of MMW energy, with high efficiencies (50%) and Continuous Wave (VW) operation,
while corrugated metallic pipe known as Waveguide can conduct the MMW beam across the 10 –
20 km distances needed for SHR drilling with minimal (<10%) attenuation losses. The
gyrotron and waveguide transmission line systems provide the MMW technology approach with
the capability to transmit incredible amounts of energy (1 MW and greater) downhole, enabling
us to rapidly vaporize rock in rate competitive with traditional Rates of Penetration (ROP) in
geothermal drilling.

As described in figure 1, the MMW drilling approach replaces the core functions of the drilling
process required in conventional operation with mechanical drilling equipment. Rock reduction
is completed via the dielectric heating process initiated via MMW absorption by the dielectric
rock surface, heating the rock past its vapor point and reducing the rock to a vapor before it is
rapidly quenched to a nanoparticulate to be conveyed away from the drilling front by the injected
purge gas circulated downhole, completing material removal of the drilling cuttings. This
nanoparticulate is small enough to dilute and convey up the annulus by an air drilling system
rated for deep drilling conditions (100 – 5,000 psi) and with a suitable gas for MMW
transmission (nitrogen, argon, air for shallow demonstrations), so the circulating purge gas is
able to replace drilling muds and gases for material removal and borehole stabilization (albeit in
an underbalanced condition). The circulating purge gas also acts as a downhole cooling
mechanism for the downhole waveguide exposed to high temperatures, balancing the heat
generated within the borehole vs. the temperature ratings of the waveguide material. The ablation
front can be optimized to stabilize the underbalanced borehole during the drilling process, and
potentially replace casing for the downhole sections required to reach the temperature target for
SHR production. Finally, remote diagnostic signals can be transmitted down the waveguide to
record real-time borehole conditions (temperature, depth) during drilling, with the option to
install additional instrumentation downhole to monitor borehole conditions. The glass liner
produced via vitrification along the melt edge of the ablation front can also serve several crucial
purposes. During active drilling operation the completed, thick (1”) glass liner could serve as an
impermeable barrier to water inflows from penetrating the underbalanced MMW drilling
operation. Glass can also retain optimal compressive strengths and thermal properties that can
exceed in-situ rock and conventional well completion. The result is a glass liner that can stabilize
the borehole during active drilling, with another potential function in providing wellbore support
to complete the well. This combination of the underbalanced drill operation (material removal,
borehole stabilization, cooling) and glass liner is particularly well suited for hard, impermeable,
crystalline HDR observed in deep basement, which provides multiple secondary functions
beyond the art of maximizing the ROP while rotating to fully replace conventional drilling
methods with a novel drilling method optimized for accessing energy resources within deep
basement rock.

This value proposition manifests itself in the form of improved Productive-Time (Drilling
time/total time for drill rig/ops onsite) for deep drilling that is, most importantly, linear
(constant) with depth. Other drilling advancements can not account for the improved Productive-
Time that MMW drilling can offer for deep drilling through basement rock for SHR
temperatures, which suddenly become economic as the capital costs to drill past 10 km depth and
extract thermal energy from SHR temperatures to generate electric power at the surface, and the
linear drilling costs offered by MMW drilling make the Levelized Cost of Electricity for Deep SHR resources comparable to the shallow SHR resource accessed with conventional means in supercritical Volcanic areas via mechanical drilling and EGS.

Figure 2: MMW Drilling process illustrated at length. Accessing deep SHR energy within deep crystalline basement rock will require a Hybrid Drilling Operation, where conventional drilling methods provide access from surface to the basement rock for MMW drilling to access to drill towards the SHR temperature range at target depths of 10 – 20 km. Source: Quaise.

### 2.2 Drilling Benchmarks

We believe drilling at the MW-scale can enable us to drill deep geothermal boreholes at ROP = 1- 10 m/hr, competitive with drilling rates for shallow conventional geothermal wells. Most importantly: we improve Productive Time by maintaining this constant ROP and eliminating the Non-Drilling Time (NDT) associated with tripping and replacing equipment for a conventional drilling operation, which becomes exponentially worse at deeper and higher temperatures [Tester 2006]. MMW Drilling could yield an order(s) of magnitude improvement for Productive Time in deep drilling operations past 10 km, which enables an economic case for SHR geothermal energy Accessed via Deep MMW Drilling.
2.2.1 Techno-Economic Analysis for Deep Drilling for SHR Geothermal Energy

AltaRock has demonstrated in prior techno-economic exercises to calculate the LCOE of SHR resources exploited through EGS methods, finding an LCOE below $50/MWh is readily achievable for many shallow SHR resources exploitable via EGS today [Cladouhos 2018]. To maintain or even beat this MMW Drilling’s competitive advantages enable it to drill at rates around $1,000/m. Most importantly, drilling costs will increase linear with depth due to the constant ROP and limited NDT, making it a highly competitive approach to deep drilling compared to conventional (see plot below).

![Drilling Risk Profile](image)

**Figure 3:** Deep drilling Risk as drilling costs with depth for conventional vs. Quaise. Conventional drilling risk increases exponentially with depth whereas MMW is linear (constant).

At a systems scale for converting the entire U.S. energy system to zero-carbon emission, SHR geothermal can play a unique role in cases beyond the LCOE, along with the drilling cost argument presented here. The high power densities of SHR resource enable a renewable resource comparable to a steam power plant, whereby a well field acts as the heat exchanger in place of the typical boiler, to provide hot fluid to the turbine-generator for electric power generation. Well fields that can provide 100 MW at total capital costs below $100M imply $1000/kW capital costs, which is a highly competitive unit for fossil fuel and renewable power plants when the only large capital expense is the power plant itself. Capital costs (drilling) reduced and the power densities at these high temperatures all point towards SHR enabled by MMW drilling as the candidate to scale geothermal up towards a TW-scale energy resource.

2.3 Experimental Results

MIT has performed various MMW drilling experiments over the past decade, including a recent test campaign in 2020-2021 with a 28 GHz, 10 kW gyrotron, transmission line, and test fixture installed at the Plasma Science Fusion Center (PSFC). Various boreholes were drilled through a small Basalt sample with a pre-drilled leak hole to simulate drilling via melting. Pictures of the setup, testing, samples, and data can be observed in the figures below. Note that these experiments were ultimately limited by the low (1-2 kW) of power that could be absorbed by the rock downhole, thus the need for experiments to scale up for higher power levels.
Figure 4: Unconfined and Confined (increased downhole pressure) melt drilling experiments were performed by the 10 kW gyrotron. (Left) Interior of test chamber at test start. (Center) unconfined basalt sample post-exposure to melt drilling. (Right) Planar and cross section views of the 1:1 (1.5-2” diameter x 1.5-2” depth) borehole, except now higher pressures have been achieved at the rock surface with similar drilling results in this lower power setup.

While limited to only achieving a molten state via dielectric heating, given the low power (10 kW) and frequency (28 GHz) to achieve a high power density on the melt surface, key observations from the prior experiments were duplicated, suggesting continuity in the results. Adding a pressure sleeve to confine the waveguide-rock interface can increase pressures at the rock and ablation surface that far exceed the injected purge pressure (5x increase for low-power). The absorbed, reflected, and scattered heat in the test chamber (radiative) heat loss all showed similar behavior to prior melt drilling experiments at these operational powers and temperatures. A radiometer receiver was again deployed succesfully to measure temperature by thermal emission of the melt surface, and those temperature changes illustrate key changes in the MMW melt drilling process, even at this lower power, which will be further explained below. Key insights are the nonlinear rise in temperature where the heated rock surface melts and forms the highly-absorptive melt layer. Sharp temperature spikes indicate plasma breakdown, which can then be suppressed before displacement by melt flow down the leak hole below provides both a radiometric and reflected power signal (V) that indicates the displacement of the surface, inferring depth and standoff distance between the WG and drilling surface. New data generated adds to the knowledge gained from the past decade of research and experimentation to place MMW drilling at the next step for technology development: a 10 x higher-power, larger-scale test fixture to simulate the full MMW drilling process in a lab bench test, and gain the full breadth of data to characterize that will enable us to fully model the MMW drilling process.

3. ARPA-E 10:1 Test Campaign

Our next stage of testing is to scale up the previous MIT experiments up to 10x increased power (100 kW) and drill a borehole with a 10:1 aspect ratio (depth/diameter) with the facility and equipment available at the ORNL Multi-Bay Program High Bay facility, and with supporting equipment provided by Impact technologies. Diagnostics will be provided by MIT, and all three team members will participate in the testing campaign overseen by AltaRock and Quaise, including the final performance goal of a 10:1 borehole in less than 1 hour (>1 m/hr).
3.1 Approach

The layout for the testing campaign is shown in the drawing on the next page. A lift mechanism will be employed to raise the rock target and borehole up towards the fixed waveguide during testing, simulating drilling movement to generate the desired borehole at a ROP greater than 1 m/hr. Diagnostics will be provided by MIT, and all three team members will participate in the testing campaign overseen by AltaRock and Quaise. This methodology is summarized in figure 1? Below: The remote diagnostics operated by MIT provides the key monitoring capabilities that dictate the control processes (output power, gas flow rate, pressure, standoff and ROP) that control the operating parameters of our drilling test.

The drilling program for which this process control will be executed can largely be characterized by 3 stages: Calibration (key equipment, diagnostics, internal processes); Characterization, or define the operating and performance envelopes for MMW drilling at the power levels and dimensions available at the ORNL facility; and Performance: demonstrate the 10:1 borehole with a maximal drilling ROP and optimal completed Borehole Quality (i.e., the Vitrified Glass Liner). This drilling program is expanded further upon in the table below.

![Figure 5: Methodology for 10:1 test campaign. Includes Process control, key team members/personnel and their responsibilities.](image)

3.2 Testing Schedule

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<table>
<thead>
<tr>
<th>Drill Method</th>
<th>Rock Type</th>
<th>Rock Geometry</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Calibration – purge/lift/cooling</td>
</tr>
<tr>
<td>Direct</td>
<td>NA</td>
<td>None</td>
<td>Calibration – MMW beam pattern</td>
</tr>
<tr>
<td>Direct</td>
<td>NA</td>
<td>None (black body)</td>
<td>Calibration – MMW efficiency</td>
</tr>
<tr>
<td>Direct- Heat and Melt</td>
<td>Basalt</td>
<td>Basalt Bricks</td>
<td>Basalt rock melts for Einstein Rock Melt Strength Tests</td>
</tr>
<tr>
<td>Direct - Melt &amp; Vapor</td>
<td>Ceramic</td>
<td>Ceramic</td>
<td>Calibration (Temperature)</td>
</tr>
<tr>
<td>Direct Heat &amp; Vapor</td>
<td>Basalt</td>
<td>Solid Core</td>
<td>Operating Envelope (Suppress Plasma)</td>
</tr>
<tr>
<td>Direct-Vapor</td>
<td>Basalt</td>
<td>Solid Core</td>
<td>Characterization</td>
</tr>
<tr>
<td>Direct-Vapor</td>
<td>Basalt</td>
<td>Solid Core</td>
<td>Characterization</td>
</tr>
<tr>
<td>Direct-Vapor</td>
<td>Basalt</td>
<td>Solid Core</td>
<td>Characterization</td>
</tr>
<tr>
<td>Direct-Vapor</td>
<td>Basalt</td>
<td>Solid Core</td>
<td>Characterization</td>
</tr>
<tr>
<td>Direct-Vapor</td>
<td>Basalt</td>
<td>Solid Core</td>
<td>Performance: 10:1 Base-Case (ROP &gt; 1 m/hr)</td>
</tr>
</tbody>
</table>

### 3.3 Equipment Setup

#### 3.1.1 10:1 Layout (Test Fixture)

The layout for the combined gyrotron, waveguide transmission line, lift mechanism and rock target test chamber, along with supporting exhaust and cooling subsystems that make up the **10:1 test fixture** shown in figure x on the next page. The gyrotron and waveguide transmission line, all the way up to the yellow launch WG, are provided by ORNL in addition the facility space. Note MIT’s primary contribution comes in the form of remote diagnostics (temperature, depth) at the last miter bend to propagate towards the drilling surface. Impact provides the rock target test chamber, in addition to lift mechanism, exhaust removal and storage, and cooling subsystems consists of the test fixture aspects that simulate the more conventional drilling functions of the MMW drilling process at this lab bench scale.

Drilling tests for the 10:1 test campaign will advance upon the prior low-power experiments at MIT by (1) increasing forward power directed to the rock target (drilling surface) by a factor of 10, (2) simulating the temporal and non-stationary drilling process by the lift mechanism and confined rock target/exhaust line interface, which enable full bore vaporization to occur and particulate to be conveyed up the short 10:1 annulus for material removal; and (3) the increased rock target aspect ratio to enable the drilling process to be enable over much greater data points.
than the 10x smaller scale of the 1:1 melt drilling experiments. It should be noted that a wealth of
greater data can be obtained beyond prior experiments, most notably the first demonstration of
directed energy drilling via full bore vaporization induced by dielectric heating, a noted first in
the domain of high-power directed energy drilling approaches.

Figure 6: Test Fixture to Host 10:1 MMW Drilling Test Campaign.
3.1.2 High-Power MMW Equipment

The ORNL Multi-Program High Bay Facility in Building 7625 on the ORNL campus hosts the high-power (200 kW) 28 GHz gyrotron tube that can operate CW for the MMW 10:1 test campaign objectives outlined above. This is an older gyrotron unit that involves a water-cooled copper magnet to produce the 28 GHz frequency, a more inefficient mode converter than modern gyrotrons, and the supporting HV/high-power auxiliary subsystems (e.g. High-Voltage Power Supply). This gyrotron has demonstrated CW operation on the order of an hour in the past and can provide the needed power outputs and durations of operation to achieve the 10:1 drilling goals.

![Figure 7 ORNL Gyrotron and Waveguide Transmission Line. Left two photos show the 28 GHz, 200 kW gyrotron tube and in its magnet/oil socke. Right two photos show an elevated (installed) and close up view of the waveguide transmission line; the far right highlights the front-end waveguide system, which includes the waveguide window (arrow).](image)

ORNL has installed a high-power waveguide transmission line to transmit the gyrotron MMW output to test chambers for rock drilling tests. Transmission line components beyond the metallic waveguide include various miter bends and tapers for redirecting and changing the size of the MMW beam. Also included are a high-pressure waveguide window, manifold for gas injection, and reflected power isolation equipment (based on the setup installed at the PSFC lab at MIT).

3.1.3 Test Chambers and Drilling Support Subsystems

Impact Technologies will be providing the various test chambers with confined rock targets attached, as well as the supporting lift, exhaust, and cooling subsystems. Test chamber consists of an 8” diameter, 42” tall solid rock target confined within a thin steel casing and grouted with a high-temperature grout to achieve a stable, confined rock target for high-power testing. Pictured below are the encased rock samples, as well as the various supporting equipment for the exhaust.
Impact will provide the Raymond Walkie Stacker to simulate the required stroke to achieve a 10:1 borehole in the 42” tall rock target without risking penetrating the top or bottom panels of the steel test chamber. That palette stacker includes a modification to provide the requisite lift rate that can hit our expected ranges of ROP (0.5 – 5 m/hr). The exhaust line starts with a stainless-steel riser tee (‘Riser’) that interfaces with the main WG above (with a WG seal), the outlet exhaust line that conveys hot gas and particulate away from the test chamber and towards a separator for cooling and removal, and a pre-drilled hole with extra refractory elements to tolerate the extreme temperatures closest to the ablation front. Impact will provide sensors, controls, and the requisite instrumentation and software to control and record data from a complex sensor network monitoring all drilling support systems above, as this data serves as a proxy for much of the drilling knowledge targeted to acquire via this lab bench testing. The result is an approach that best de-risks the concerns with temperature, pressure, and mechanical stresses that could limit and potentially damage the MMW drilling operation during 10:1 testing. Impact will provide sensors, controls, and the requisite instrumentation and software to control and record data from a complex sensor network monitoring their drilling support systems, as this data serves as a proxy for much of the drilling knowledge targeted to acquire via this lab bench testing.

3.1.4 Front End Waveguide System

MIT will provide remote diagnostics that can monitor the key parameters at the drilling surface: the ablation front temperature, via radiometry, and the depth/standoff distance, via radar/reflectometry, to enable real-time monitoring and characterization of the ablation front and relate to the core drilling inputs ensure drilling tests reach their stated goals: dielectric heating power (MMW), purge flow rate and pressure, standoff distance, among others that can optimize the 10:1 borehole and ROP in this test campaign.

ORNL will provide the remaining components to the front-end waveguide system that will complement the MIT diagnostics, gyrotron, and main transmission line to cumulatively serve as our MMW applicator. Diagnostics include real-time data on gyrotron output power, forward/reflected power at the rock, along with key cooling measurements along the gyrotron and waveguide monitoring instrumentation for safe operation.
ORNL will also duplicate the reflected power isolator design implemented at the MIT 10 kW setup but retrofitted for higher power operation. Now the polarization grid will include water cooling lines so that the maximum reflected power traveling back up the waveguide can be diverted to a dummy load for absorption: operating under the principle that (1) a circular-polarizing miter mirror can convert between a linear and circular-polarizing beam, and the reflected rock surface in itself will flip the circular polarization downhole so that the linear-polarized reflected beam is orthogonal to the identical beam transmitted through the grid. The result is gyrotron forward power passes through the imperceptible polarization grid while this grid can redirect that reflected power beam via the grates towards an absorptive high-power dummy load. This design is successfully scaled up for mitigating reflected power throughout the 10:1.

3.1.2 Post-testing Evaluation

A scope of work involving post-testing evaluation of the 10:1 results will be undertaken by all team members. That objective is to fully characterize the following fundamental physical parameters that are factors and Key Performance Indicators (KPIs). Some of these include properties investigated before and during the drilling process.

- **MMW:** Input (gyrotron) power, forward/reflected power at rock,
- **Dielectric:** Rock absorption, transmission, reflection coefficients as a dielectric material all with temperature.
- **Thermal:** Temperatures for melt/ablation front, core waveguide and test chamber equipment near extreme temperatures.
- **Fluids:** minimum injection flow rates/pressures to convey and remove particulate, suppress plasma, cool borehole.
- **Liner:** strength, permeability, and thermal testing on glass liner, rock.
- **Particle:** Size and composition of quenched particulate collected from testing.
- **Drilling:**
  - Characterize drilling milestones via drilling program and process control in section 2, **10:1 Borehole quality and ROP**
    - depth, diameter, thickness, composition, roughness, strength (glass)
    - Achieved (10:1), Projected (100:1, future systems study)
  - validate with the multiphysics drilling model to further improve both simulation and experimentation for the next 100:1 (10-m depth) test campaign for MMW drilling.

5. Next Steps

The 10:1 testing campaigned outlined above is scheduled for 2021, which corresponds to the 10:1 column of the Technological development roadmap listed below. Success at mitigating technical risks to move the Technological Readiness Level (TRL) annually. This means completing the 100:1 demonstration through the ARPA-E funded collaboration by 2022, with a 10x larger (10-m) rock target and translating waveguide. The next steps of testing will roughly follow the roadmap listed below, where a common measure of maturity, technological readiness level (TRL) and aspect ratios are used to illustrate our key benchmarks in the technology development roadmap. Note that TRL 3 is the current state of the art (MIT low-power
experiments); the ARPA-E Test campaign enables a TRL 5 by 2022, and subsequent field demonstration developed in parallel can achieve a TRL 7 by 2024.

Figure 9 Development Roadmap for MMW Drilling Technology. Key benchmark is the aspect ratio, the borehole itself.

<table>
<thead>
<tr>
<th>Deep Drilling TRL</th>
<th>TRL 3</th>
<th>TRL 4</th>
<th>TRL 5</th>
<th>TRL 6</th>
<th>TRL 7</th>
<th>TRL 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio (Length : Diameter)</td>
<td>1:1</td>
<td>10:1</td>
<td>100:1</td>
<td>1000:1</td>
<td>10,000:1</td>
<td>50,000:1</td>
</tr>
<tr>
<td>Dimensions (depth, diameter)</td>
<td>5 cm x 2&quot;</td>
<td>50 cm x 2&quot;</td>
<td>5 m x 2&quot;</td>
<td>100 m x 2&quot;</td>
<td>1 km x 2&quot;</td>
<td>10 km x 2&quot;</td>
</tr>
<tr>
<td>Power input</td>
<td>10 kW</td>
<td>100 kW</td>
<td>100 kW</td>
<td>300 kW</td>
<td>500 kW</td>
<td>1 MW</td>
</tr>
<tr>
<td>Frequency (GHz)</td>
<td>28</td>
<td>95</td>
<td>95</td>
<td>50-300</td>
<td>50-300</td>
<td>50-100</td>
</tr>
<tr>
<td>Operational time</td>
<td>1-10 minute</td>
<td>10-100 minutes</td>
<td>10-100 minutes</td>
<td>1-10 days</td>
<td>1-10 days</td>
<td>100 days</td>
</tr>
<tr>
<td>Purge: Flow Rates (m³/s)</td>
<td>NA</td>
<td>0.001-0.01 (air)</td>
<td>0.01-0.1 (air)</td>
<td>0.01-0.1 (air)</td>
<td>0.1-1 (gas)</td>
<td>0.1-1 (gas)</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>NA</td>
<td>0.1-1</td>
<td>1-10</td>
<td>1-10</td>
<td>10-300</td>
<td>10-300</td>
</tr>
<tr>
<td>Material Removed (m³)</td>
<td>NA</td>
<td>0.001</td>
<td>0.01-1</td>
<td>0.01-1</td>
<td>10-300</td>
<td>10-300</td>
</tr>
<tr>
<td>Waveguide dimensions</td>
<td>1 m long, 1.5&quot; diameter</td>
<td>1-5 m long, 1.5&quot; diameter</td>
<td>5-20 m long, 1.5&quot; diameter</td>
<td>10-1000 m long, 3&quot; diameter</td>
<td>10-1000 m long, 6&quot; diameter</td>
<td>10,000-100,000 m long, 6&quot; diameter</td>
</tr>
<tr>
<td>Waveguide Weight Rating</td>
<td>200 kg</td>
<td>200 kg</td>
<td>200 kg</td>
<td>20,000 kg</td>
<td>20,000 kg</td>
<td>1,000,000 kg</td>
</tr>
<tr>
<td>Wellhead Pressure Isolation</td>
<td>NA</td>
<td>1 MPa</td>
<td>1 MPa</td>
<td>100 MPa</td>
<td>100 MPa</td>
<td>300 MPa</td>
</tr>
</tbody>
</table>

6. Conclusion

The case put forward in this paper argues that MMW drilling is a unique early-stage technology for not only resolving key geothermal drilling challenges, but unlocking a whole new form of geothermal resource in Deep SHR that, once the many technical risks can be mitigated and de-risked, provides access to a renewable energy resource that delivers a compelling case for becoming a TW-scale form of energy for intuitive technical and economic considerations. The ARPA-E partners will soon commence high-power bench testing at ORNL, and AltaRock and Quaise will work on the Reservoir creation aspect so that both development roadmaps in mind for MMW drilling (access) and s-EGS (extraction) are in progress to capture the massive reservoir of thermal energy that lies at 10-20 km depth basement rock. Solving the most pressing
needs of reducing carbon emissions in a cost, space efficient, but most important of all, a rapidly deployable TW-scale source of renewable energy that can not be discounted, despite the technical challenges.

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**REFERENCES**


