Millimeter-Wave Directed Energy Deep Boreholes

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April, 2017

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Abstract

The analytic basis of high temperature, full bore directed energy opening in rock is presented including energy requirements, rates of penetration, high temperature physics replacement of drilling mud, and diameter control. Millimeter-waves are ideally suited for long distance, high power guided transmission into typical borehole dimensions, but deep high pressure induced absorption will ultimately determine depth limits. The feasibility of this technology is established in the laboratory with granite and basalt specimens heated to temperatures in the 2500 - 3000 °C range using a low power 10 kW, 28 GHz gyrotron. A possible application to an Enhanced Geothermal System (EGS) is described using an engineered heat exchanger (EHE) with a potential useful lifetime of 100 years.

Introduction

Most, if not all studies of geothermal energy, such as that by Tester et al [1], are done through the veil of existing drilling technology or small improvements thereof. Generally they conclude that there is a great potential for geothermal energy, but in fact one that is far short of the actual heat energy beneath our feet. Just 0.1% of the total heat content of planet Earth would be equivalent to the total world energy needs for about 20 million years [2, 3]. This virtually limitless base power, green energy source cannot be practically accessed on large scales with current mechanical drilling technology or stimulated heat transfer reservoir approaches. New game changing developments are needed. Such development is now possible with commercially available, powerful (1 - 2 MW) and efficient (> 50%) millimeter-wave (28 – 170 GHz) beam sources [4] that have the potential to open self-cased boreholes in deep basement rock at faster penetration rates, greater depth limits, and at lower cost. Unlike infrared lasers, millimeter-wave (MMW) gyrotrons are continuously more powerful, more efficient, and the wavelength of operation makes the beam energy immune to most losses suffered by shorter infrared waves in an industrial environment. The physics/ technology advantage of millimeter-waves is so great that full borehole opening in crystalline rock can be reduced to just an energy-material interaction without any mechanical components in situ. All drilling functions performed with mechanical drilling systems: borehole stabilization, sealing, and extraction can be performed with superior function by the high temperatures and pressures generated locally to melt or vaporize the rock, circumventing the current drilling bottleneck to geothermal energy.

Melting and Vaporizing Rock

Thermodynamics of Rock

The energy required to melt and vaporize rock can be expressed by the formula adapted from Maurer [5]:

$$H = c_p(T) \cdot \Delta T + H_f + H_v$$  \hspace{1cm} [1]

where $c_p(T)$ is the heat capacity at temperature $T$, $\Delta T$ is the increase in temperature, $H_f$ is the latent heat of fusion if $\Delta T$ includes the melting point, and $H_v$ is the latent heat of vaporization if $\Delta T$ includes the vaporization point. Granite and basalt basement rock, of interest to EGS, begin
to melt at about 1200 °C and are vaporized at somewhat over 3000 °C at atmospheric pressure. The heat capacity of granite is plotted in Fig. 1 with data from three references below 2000 °C [6-8] and extrapolated ad hoc to 3000 °C. Waples and Waples [6] show that the heat capacity of all rocks as a function of temperature is the same and only shifted in magnitude for different rock types. In their work the heat capacity of basalt is within 7% of granite.

Integrating Eq. 1 over the plot in Fig. 1 to 3000 °C and adding the latent heat of fusion (0.9 kJ/cm³ for granite) results in about 12.5 kJ/cm³ that is necessary to heat granite up to the vaporization temperature. The latent heat of vaporization for rock is not well known, but from observations of stony meteor burn up in the atmosphere [9] it can be conservatively estimated to be about 14 kJ/cm³ for granite. It can take more energy to vaporize a rock than to just heat it to the vaporization temperature. The electricity required, assuming 50% efficiency, would be about 7,000 kWhr/m³ to melt and heat from 20 °C to 3000 °C or about 15,000 kWhr/m³ to fully vaporize near the surface. For a 10 km deep, 20 cm (8") diameter hole the electricity would cost about 230 k$/US at $0.1 kWhr for heating to the melt temperature just below vaporization. As a point of reference, a mechanically drilled hole to 10 km costs about 100 times more [1].

Rates of Penetration

The directed energy rate of penetration will depend on how quickly the energy can be delivered into the rock for a given method of extraction or displacement. It will be a function of beam power, borehole diameter, and required energy as expressed by:

\[
R_p = \frac{4}{\pi D^2 H}(\varepsilon_{mm} P_i - P_L)
\]

where \(D\) is the hole diameter, \(H\) is the energy given by Eq. 1, \(\varepsilon_{mm}\), is the millimeter-wave emissivity (how well the beam is absorbed by the rock), \(P_i\), is the beam power incident on the rock surface, and \(P_L\), is the total power loss from the heated volume. Experiments have shown that the millimeter-wave emissivity of melted rock is about 0.7 and that the total losses, dominated by radiative heat transfer, are about 0.4 kW/cm² at ~3000 °C [10]. Assuming all electromagnetic radiation is trapped in a deep borehole simplifies Eq. 2 to \(\varepsilon_{mm} = 1.0\) and \(P_L = 0\).

A further assumption is necessary on whether the super-heated material is extracted or displaced to determine the appropriate value to use for \(H\). As will be discussed below, very high local pressures that are generated, along with the compressible low melt viscosity, will make it possible to displace rather than to vaporize. Potential rates of penetration are plotted in Fig. 2 under this assumption. The penetration rate scales linearly with power when \(P_i >> P_L\) and inversely with borehole diameter squared. Beam powers over 1 MW will be needed for rates > 5 m/hr in boreholes of 20 cm (8") diameter or more. A 100 m/hr rate may be possible for small boreholes of 10 cm (4") diameter or less with a 4 MW beam if the pressure is sufficient to suppress plasma breakdown.

Replacing Drilling Mud

High Temperature Physics

All the functions of drilling mud: to stabilize the borehole, seal the wall from inflows (blowouts), and to extract or displace the rock, can be replaced by the physics of boring at high temperatures. The governing equation is the real gas law, which applies to gasses and super critical fluids. Its form in per mole of gas is given as [11]:

\[
P V = Z R T
\]
where \( P \) is pressure, \( V \) is volume, \( Z \) is the compressibility factor, \( R \) is the gas constant, and \( T \) is absolute temperature. In a confined borehole volume if temperature is increased, the pressure will also increase independent of the starting local pressure. At high temperatures and pressures the compressibility factor also increases to a value greater than 1 [11] multiplying the pressure rise. For example, assuming a pressure gradient of 18 kPa/m (0.8 psi/ft.), a depth of 10 km (33,000 ft), and a factor of 10 increase in temperature, a pressure of up to 2 GPa (290,000 psi), about ten times ambient, could be produced. This would be sufficient to stress the local rock formation and displace the high temperature melt. Rock melt viscosity decreases significantly with temperature, particularly for low silica basalts [12] and becomes compressible at high pressures [13] facilitating the displacement.

Collapse Strength

The displaced rock melt can form a strong dense glass casing. The volume of rock material inside a borehole before it is displaced is sufficient to make a diameter to wall thickness ratio of \( D/t = 4.83 \), if all the melt could be moved to that distance without compression. Such a large casing wall thickness is outside the validity of pipe collapse strength formulas. Using 5% of Young’s modulus to estimate collapse strength, which for glass is in the range of 50 – 90 GPa, would in principle allow an open borehole to depths all the way to the mantle at \( > 30 \) km (100,000 ft.) to remain open after the pressure generated by the MMW beam is turned off.

Another unique strengthening capability of full borehole directed energy opening is the possibility to shape and align the hole to remove ellipticity weakening in an asymmetric stress environment using an elliptical shaped beam.

Controlling Borehole Diameter

A metallic waveguide carries the MMW beam to some standoff distance from the target surface, which after launch into free space increases in size due to diffraction to make a borehole larger than the waveguide. The borehole in turn becomes a new waveguide analogous to a hollow fiber optic cable. The borehole diameter will be determined by the boundary of the MMW beam where the energy deposited into the wall equals the energy required to melt the rock (Eq. 1 integrated through the heat of fusion). The borehole diameter will increase until the wall deposited energy is less than the melting energy at which point it can no longer increase in diameter.

The power loading on the wall is determined by the borehole waveguide propagating losses, the backward reflection, and radiation from the hot melt surface. The attenuation constant for hollow dielectric waveguides is given by [14]:

\[
\alpha = \frac{X_{nm}}{2\pi} \left( \frac{x^2}{2\sqrt{n^2-1}} \right) \left( \frac{\lambda^2 (n^2+1)}{a^3} \right) \quad [4]
\]

where \( X_{nm} \) is the guided HE_{nm} mode root, \( \lambda \) is the beam wavelength, \( a \) is the borehole radius, and \( n \) is the index of refraction of the wall. Note that the wall beam losses are inversely proportional to the cube power of the borehole diameter making the wall loading a strong function of beam size.

Assuming the forward and backward propagating beam power in the borehole is much larger than the radiative heat transfer contribution (Eq. 7) to the wall, the borehole diameter can be estimated by:

\[
D \approx \frac{\alpha P (2 - \varepsilon_{mm})}{\pi h R p H_m} \quad [5]
\]
where \( h \) is the thickness of the wall layer into which heat is absorbed and \( H_m \) is the heat threshold for melting (about 4.5 kJ/cm\(^3\) for basalt and granite). The other terms are as previously defined. Values in Equations 2 & 5 need to be consistent so as to agree in diameter. For example, a 20 cm (8") borehole in basalt (\( n \approx 2.6 \)) [15] could be achieved with a 3.2 mm (95 GHz) wavelength beam of about 1.4 MW incident on the rock using a mode with a root (\( X_{nm} \)) of about 6.1 (~2% wall loss per m), a rate of penetration of about 9 m/hr (0.15 m/s), and a melt thickness of about 4 mm (consistent with laboratory observations). This example is very approximate to illustrate the connection between beam parameters and borehole diameter. In practice borehole diameter deviations from uniformity and surface roughness would cause higher propagation losses and variations in the rock composition/structure would cause variations in the index of refraction and absorption depth in the wall. Field experience will be needed to accurately establish the actual relations between borehole diameter and beam power, launched mode(s), and rate of propagation for specific rock types and saturation.

Transmitting Millimeter-Wave Beam Energy

Near the Surface

The most efficiently transmitted mode in a hollow waveguide is the lowest order hybrid mode, \( HE_{11} \), which is supported in hollow smooth dielectric and in metal waveguides having an internally corrugated surface. The required corrugations at MMW frequencies are small and can be fabricated with a tap [16]. When the fill medium of the waveguide is transparent such as low humidity surface air at frequencies of 95 GHz or 140 GHz or a pure nitrogen fill, the transmission losses in perfectly straight guide are primarily due to the wall surface resistivity. For optimized \( \lambda/4 \) wavelength deep corrugations in circular guide the loss factor is given by [16]:

\[
\alpha = \frac{R_s}{2Z_0} \left( \frac{2.405}{2\pi} \right)^2 \frac{\lambda^2}{a^3} \left( \frac{1+\frac{\lambda}{4p} - \frac{1}{1-(t/p)^2} + 1}{(1-t/p)^2} \right) \tag{6}
\]

where \( R_s \) is the surface resistivity, \( Z_0 \) is the impedance of free space, \( p \) is the period of the corrugations, \( t \) is the corrugation wall thickness and the other parameters as defined previously.

The transmission \( (T = \exp(-\alpha L)) \) of a 95 GHz beam as a function of distance \( (L) \) is plotted in Figure 3 for 127 mm (5") diameter copper and carbon steel waveguides. Near the surface there is the potential to transmit 20 km distances with 88% efficiency. This long distance guided efficiency in combination with multi megawatt power handling capability in typical borehole diameters is unique to the MMW range of the electromagnetic spectrum.

The insert in Figure 3 shows \( HE_{11} \) transmission in a 200 mm (8") diameter smooth dielectric granite borehole (from Eq. 4) after launch from the metallic waveguide. The beam could go about 100 m with 65% efficiency guided by the borehole alone.

Deep Transmission

Gases transparent to MMWs at one atmosphere pressure become absorptive at high pressures due to molecular collision-induced absorption [17]. For example, at 95 GHz \( N_2 \) at 0.1 MPa (1 atm.) pressure has an 86.5% transmission efficiency to 750 km, but decreases to about 4 m at 50 MPa (7,500 psi) and 200 °C. The most transparent nonpolar molecular gas, \( H_2 \), at 0.1 MPa has the same transmission efficiency to 19,000 km and drops to about 70 m at 50 MPa. To reach deep subsurface distances it will be necessary to find a more transparent waveguide fill medium or operate the waveguide over most of its length at a pressure lower than that surrounding it.
The only apparent candidate for an alternative fill medium would be a pure noble gas. Argon, the 4th most abundant gas on earth, has been used as the zero absorption calibration medium for the collision induced absorption studies of nonpolar molecular gases [17]. Unfortunately, there is no data for MMW transmission in pure supercritical noble fluids in the 0.1 to 10 GPa (1.45x10^6 psi) pressure range that is of interest here.

A high pressure window deep in the waveguide would not be practical. However, a dynamic pressure drop may be possible. The waveguide could be constricted for a short distance and a high velocity flow induced without significant beam loss to waveguide wall absorption. For example, a waveguide diameter reduction to 5.0 cm (2.0") in corrugated pipe for about 100 m length (0.99 transmission at 95 GHz) and a N2 flow of about 0.17 m^3/s would produce a pressure drop of about 300 MPa (43,000 psi). Detailed analysis would be needed to determine the practicality of this approach.

The depth limit of full bore MMW directed energy penetration will ultimately be determined by the distance to which MMWs can be transmitted efficiently in a high pressure environment.

Laboratory Results

The feasibility of melting and making holes in granite and basalt was demonstrated in the laboratory with a low power 10 kW, 28 GHz CPI HeatWave Model VIA-301 gyrotron. A custom transmission line system was built to convert the gyrotron beam from a circular, hollow azimuthally polarized beam (TE01) produced by the commercial system to an axially peaked linearly polarized beam [18]. Several waveguide launch ends were available. For the results shown here a smooth copper down taper to 20 mm (0.787") internal diameter was used to launch TE11 (transverse electric) mode. Changing the waveguide launch antenna to achieve a different beam size, profile, and divergence is similar to changing a drill bit for a given job.

The transmission line included backward reflected power rejection to protect the gyrotron and a 137 GHz radiometer view superimposed onto the heating beam for real time temperature measurements. An air purge toward the target of up to 235 lpm (500 scfh) was also introduced into the transmission line to control plasma breakdown.

Rock specimens were exposed inside a steel test chamber that trapped all unabsorbed MMWs for safety and power balance measurements. The MMW beam waveguide was introduced vertically through the top of the test chamber with the specimen lying a short distance below the waveguide.

Both granite and basalt would melt within 2-3 minutes of beam exposure at about 2 kW incident power. Increasing incident power to 4.5 kW would typically raise the melt temperature into the 2500 – 3000 °C range in 5 – 10 minutes. Maximum temperature was limited by radiative heat loss as given by the Stefan Boltzmann equation:

\[
P_{\text{rad}} = \varepsilon_{\text{IR}} \sigma (T_{\text{hot}}^4 - T_{\text{cold}}^4) A
\]

where \( \varepsilon_{\text{IR}} \) is the infrared emissivity, \( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \) is the Stefan Boltzmann constant, \( T_{\text{hot}} \) is the temperature of the melt, \( T_{\text{cold}} \) is the surrounding temperature, and \( A \) is the area of the melt. For the maximum temperatures and melt sizes achieved the radiated power equals the absorbed power for an infrared emissivity less than the MMW emissivity. MMW emissivity was measured to be \( \varepsilon_{\text{mm}} = 0.7 \pm 0.1 \) for the rock melts at the highest temperatures.

Since it was not possible with this laboratory system to definitely reach the vaporization point due to too low a power and too low a frequency (diffraction limited focusing), it was necessary to provide a leak path for the melt to make a borehole. Typically a 12 mm (0.5") hole...
was drilled into the specimen for this purpose. Basalt melts flowed much better than granite melts.

Figure 4 shows a 50 mm diameter hole in a dense basalt specimen from Inner Mongolia (Coverall Stone, Inc., SeaTac, WA) with 4.5 kW TE_{11} incident power on the basalt located 38 mm from the waveguide. Due to beam diffraction of about 50° full angle after launch, the borehole diameter is larger than the outside of the waveguide, which was 42 mm (1.66”) in this case. The MMW beam would have continued to diverge in free space after launch, but the borehole that was created confined and guided the beam.

The very high temperature gradient (> 400 °C/cm) between the heated spot and the rest of the rock caused significant thermal fracturing as is evident in Figure 4. All the laboratory samples had to be constrained by steel bands around the periphery to keep them from breaking apart in these experiments. In a deep subsurface environment lithostatic forces would constrain the rock. Thermal stresses would add to pressure stresses to create fractures for melt displacement. Figure 5 shows a broken part of another basalt borehole revealing the melted wall to be about 4 mm thick without any pressure behind the melt, an indication of beam wall absorption depth used earlier here in beam controlled diameter calculation. This specimen was exposure to the MMW beam for 41 minutes, long after an equilibrium was established between the basalt and the MMW beam propagating through it. If the waveguide was advancing and not stationary the borehole would be smaller.

**Application to EGS**

The capability to open deep, self-cased sealed boreholes of moderate diameter in crystalline basement rock at lower cost creates the potential for an engineered heat exchanger (EHE) approach to EGS. An ENE can be more predictably designed over a larger crustal volume and would have longer lifetimes at higher temperatures than a stimulated heat reservoir. The heat power that is mined by an EGS is governed by Fourier’s Law for thermal conduction:

\[ P_{geo} = -k\nabla T A \]  

where \( k \) is the thermal conductivity of the rock, \( \nabla T \) is the temperature gradient at the heat exchanger wall-rock boundary, and \( A \) is the area through which the heat flows. The negative sign indicates that the heat is being extracted.

The thermal conductivity of hot dry rock (HDR) is low and decreases with depth, dominated by the temperature increase rather than the pressure increase. For granite, on average, it deceases from about 2.8 W/m/K near the surface to about 1.8 W/m/K at 20 km depth [19]. Strategies for ENE design need to maximize the temperature gradient and area since the conductivity is fixed by nature. The temperature gradient can be controlled by the volume rate flow of the heat exchanger fluid and the area by the size and number of boreholes.

Two dimensional finite element heat transfer computations were carried out in a horizontal plane with parameters representative of granite at a depth of about 15 km (45,000 ft) for pairs of boreholes with various diameters, separations, and fluid fill temperatures. It was found that temperature gradients are larger for smaller holes. For a pair of 20 cm (8”) diameter boreholes separated 100 m (328 ft.) with a heat exchanger fluid flow maintained 25 °C cooler than the surrounding rock results in a temperature gradient starting from greater than 56 K/m in year 1 and decreasing to 37 K/m over a 100 year lifetime.

An area of 11.3 km² is required to achieve 100 MW heat power extraction with a temperature gradient of 44 K/m, corresponding to that after 15 years of operation. Such a surface area can be achieved with 106, 18.2 km (60,000 ft.) deep boreholes assuming the plane at 15 km depth is an average for the entire hole and discounting the top 1.5 km (5,000 ft.) length as too cold to contribute significantly.
The temperature at the bottom of these boreholes for an average crustal temperature gradient of 25 °C/km would be 470 °C. The heat capacity of water increases significantly near the supercritical point at 374 °C. Assuming an average heat capacity of 7 kJ/kg/K over the entire length of the borehole, a water flow of about 273 lpm (72 gpm) would be required to achieve an average temperature gradient of 44 K/m. In practice the temperature gradient would vary significantly as the heat capacity of the water increases with temperature. The resulting higher temperature gradients near the bottom of the boreholes would mean more of the heat power will be extracted from those depths.

One output well of larger diameter would be used for 30-35 injection wells to minimize heat losses on the way back up. A 30 cm (12") return borehole per 35 input wells and a return fluid temperature of about 400 °C would introduce about 15% losses. This could be made up by additional injection boreholes.

An array of 106 boreholes on a 100 m grid separation would cover about 0.134 km² (33 acres) of surface area. The boreholes would be connected at the bottom by turning the directed energy beam horizontally at a 90° angle by a miter mirror bend at the waveguide launch aperture as is commonly done with MW gyrotron beams now. As discussed previously, the MMW beam could be guided by the basement rock borehole for distances of about 100 m.

The heat output would continually decrease as the rock around the boreholes cools. Figure 6 shows the temperature profiles in the granite with time. After 100 years the rock temperature midway between the boreholes has dropped by 1.1%. The 100 MW heat output at year 15 would have been 126 MW after year 1 and 83 MW after year 100. Additional boreholes could be added as needed over time to maintain a desired power output and to extend the lifetime of the EGS site to beyond a century.

Discussion

Intense energy will dominate matter and create a propagation path through it. Such continuous beam energy intensities are now commercially available in the MMW range of the electromagnetic spectrum at efficiencies to make full bore opening in basement rock practical. There is no need for mechanical components to interfere with the process. The beam launched from a waveguide brought to the proximity of the target rock diverges in size after launch to make a hole larger than the waveguide to allow it to advance. The diameter of the hole is determined, with knowledge of the properties of the rock formation, by controlling beam power, beam profile, and the rate of penetration. The high temperature, high pressure environment that is produced performs all the necessary borehole opening functions of stabilization, sealing, extraction/ displacement, and casing. The only consumable for this process is the electricity required to operate the high power MMW source. That cost could be as much as 100 times less than the current costs for mechanical drilling to depths of 10 km.

The resulting glass walled borehole makes an ideal high temperature conduit for a heat transfer fluid that would be immune to chemical dissolution. Arrays of such holes to great depths of over 10 km and connected using the ability to turn a MMW beam optically at 90° to create an engineered heat exchanger has the potential to produce high temperature, long lasting EGS power plants with potential lifetimes of a century or more. Additional studies will be needed to determine the optimum tradeoff between borehole number, diameter, and depth to achieve heat exchange areas of over 10 km² necessary for useful power plant sizes.

The cost could also be significantly lowered by engineering the heat exchanger in magma where it is accessible. Since magma is plastic it would take less energy to raise the temperature sufficiently to displace it out of the beam path and solidify the wall with a concurrent cooling gas flow. One could even imagine pursuing this approach to the mantle if it could be reached.
The depth limit of MMW directed energy boreholes is not know at this time. It will not be limited by subsurface temperatures or collapse strength during creation or completion. It will depend on how far a high power MMW beam can be efficiently transmitted into the deep high pressure environment. This will require either a MMW transparent supercritical fluid in the waveguide and/or a dynamic pressure drop to lower waveguide pressure over most of its propagation length. A recyclable noble gas, such as argon, seems to be the most likely candidate for the waveguide fill medium at this time. Waveguide diameter constrictions and high velocity gas/ supercritical fluid flow can produce high pressure drops to improve transmission. More studies will be needed to identify the best approach for propagating MMW beams into the pressure range of 0.1 – 10 GPa to determine the ultimate depth achievable.

The science is sound, the technology is largely available, and the outstanding engineering issues could be quickly resolved. The feasibility has been established in the laboratory. If successfully pursued into the field, MMW directed energy full borehole opening could have a greater impact on a shorter time scale than other approaches to expanding the viability of EGS power plants and could open new depths to geoscience research.

References
3. www.eia.gov/cfapps/ipdbproject
Figure 1. Heat capacity of granite extrapolated to 3000 °C from data at lower temperatures.

Figure 2. Potential rates of penetration from equation [2] at different beam powers assuming rock heated to 12.5 kJ/cm³ for displacement.

Figure 3. Transmission of a 95 GHz, HE11 beam in 127 mm (5") diameter corrugated hollow copper and carbon steel waveguide, and in a 200 mm (8") diameter granite borehole (insert) at surface pressure.
Figure 4. 50 mm (2") diameter hole in 100 mm square, 30 mm thick basalt made with a 4.5 kW, 28 GHz beam (TE_{11}) launched from a 20 mm diameter copper waveguide 35 mm away.

Figure 5. Cross section of a basalt borehole in a 38 mm (1.5") thick specimen made with a 28 GHz 4.9 kW beam diverging at a full angle of about 50° launched from a 20 mm (0.787") i. d. waveguide.

Figure 6. Temperature distribution between a pair of 20 cm (8") diameter boreholes for an average crustal temperature gradient (25 °C/km) at 15 km depth (357 °C) in granite (2 W /m/K) with water flowing at a temperature of 332 °C for up to 100 years.