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Millimeter Wave Deep Drilling For Geothermal Energy, Natural Gas and Oil

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Accomplishments
The scientific basis, technical feasibility, and economic potential of directed energy millimeter-wave (MMW) rock drilling at frequencies of 30 to 300 GHz has been investigated as a new approach to access Earth's internal energy resources. Directed energy drilling would overcome the limitations of rotary drilling at great depths or high temperatures. Thermodynamic energy requirements for rock vaporization have been updated from first principles and compared to past experiments with lasers. It is shown that current and future commercial MMW sources could deliver the required energies at affordable costs. Also, the longer wavelengths are superior to shorter wavelengths for directed energy drilling and thereby make it likely that practical directed energy drilling systems can be realized. MIT has filed for a patent (MIT case # 13021), the Plasma Science and Fusion Center (PSFC) has joined forces with the MIT Rock Dynamics Laboratory in a proposal to U. S. DOE to continue and expand the research, and a gyrotron system has been acquired by the PSFC for the proposed rock ablation research.

Directed Energy Drilling
Mechanical drilling technologies are fully mature. New approaches are needed to make future major advances in increasing access to and reducing costs for underground energy resources. A number of novel techniques have been proposed as reviewed, for example, by Maurer [1, 2] and Pierce [3]. Directed energy penetration enabled by millimeter-wave technology is a new approach investigated here for the first time. The main advantages of using directed energy are: 1) no mechanical systems in the wellbore that could wear out or break, 2) no temperature limit, 3) equal ease penetrating any rock hardness, and 4) potential for replacing the need for casing/cementing by a durable vitrified liner. Directed energy drilling research has been pursued for almost five decades since the invention of the laser. A wealth of data has been collected with 1 to 10 μm wavelength lasers establishing the potential of directed energy drilling systems [4-7], but a transition to a practical system has so far proven to be elusive. The deepest rock penetration achieved to date has been only 60 cm, and that was only possible because the test rock could be turned around to come in 30 cm from each side [8].

There are fundamental physics and technological reasons for the lack of progress with laser drilling. First, the rock extraction flow is incompatible with short wavelength energy which is scattered and absorbed before contact with the desired rock surface. Second, laser technology is deficient in energy, efficiency, and is too expensive. By going to the MMW range of the electromagnetic spectrum this state of affairs can be changed. Longer wavelengths can propagate more efficiently through small particulate filled propagation paths and high power MMW sources are more energetic, efficient, and lower cost by a very large margin. A million dollar class MMW source in Japan has produced more directed energy in eight minutes of operation at megawatt power levels and 52% efficiency [9] than possible by any laser system in existence including the largest laser in the world, the billion dollar class National Ignition Facility (NIF).

MMW Gyrotrons

Gyrotron technology has been developed as part of an international research effort to develop fusion energy [10]. These MMW sources are a subclass of free electron lasers sometimes also referred to as electron cyclotron masers [11]. A high voltage electron beam inside a magnet field causes electrons to gyrate around magnetic field lines to efficiently convert the electron beam energy thorough electron cyclotron resonance into powerful radiation. Gyrotron tubes with continuous output power levels of 1 MW have been developed at 110 and 170 GHz with electrical to millimeter-wave power conversion efficiencies of > 50% [9]. Many gyrotrons are currently in use around the world in fusion research laboratories such as at General Atomics, San Diego with a 5 MW, 6-tube 110 GHz gyrotron system [12]. A 24 MW, 24-tube system at 170 GHz is planned for the International Thermonuclear Experiment Reactor (ITER) [13] in Cadarache, France. The U. S. DOD is field testing 100 kW and developing compact 2 MW, 95 GHz continuous wave (CW) gyrotrons for its active denial weapon. These gyrotron systems are completely contained with all power supplies on a Humvee or a plane. They have been driven around country terrain and shown to be reliable, and therefore could be easily adapted to remote drill sites. Rugged fieldable gyrotron systems could be ordered today and adapted with modest development to drilling.

MMW Drilling Concept

A MMW deep drilling system has no mechanical moving parts except for the advance of the waveguide. All the drilling, extraction, and vitrified liner formation is accomplished by the directional energy and concurrent purge gas flow. Figure 1 shows an elevation cross-section view of the bottom of a borehole with a cylindrical metallic waveguide as a conduit for the beam energy and purge gas flow. The metallic MMW waveguide is of smaller diameter than the borehole, which leaves an annular region of free space between the outside diameter of the waveguide and the inside diameter of the borehole for exhaust. The reaming of the borehole to a diameter larger than the central waveguide is facilitated by the natural divergence of a MMW beam launched from a waveguide [14]. The borehole itself acts as a dielectric waveguide (like a long wavelength fiber optic) to continue the propagation of the energy to the ablation surface, making possible a large stand off distance, Z, that could be over 100 m between the central waveguide and vaporization front.

Rock and product glass melt are good MMW absorbers [15, 16]. A fully absorbed 1 MW beam in a small borehole < 15 cm diameter will rapidly raise the rock surface temperature to a boiling temperature of over 3000 °C. Heat loss to surrounding rock would be small because of the quickly advancing ablation front. The resulting saturated pressure rock vapor will form nano particle smoke [17-19] that would be blown out by the purge gas. The purge gas (e.g. air) can be readily introduced into overmoded waveguide (inside diameter large relative to wavelength) by waveguide gaps that would not introduce significant losses to MMW beam transmission [20]. The purge gas would not only help to form and blow out the rock extraction smoke, but would also keep the waveguide clean and cool. If underground water is present it would be instantaneously converted to superheated steam to augment the purge gas. However, complete rock vaporization may not be necessary for extraction since the viscosity of the glass melt would be sufficiently low at 3000 °C (< 2 Poise) [21] to allow the pressure generated by the high temperature gas products to drive part of the melt into the micro fractures in subsurface rock that occur naturally [22] or that are thermally induced by high temperature penetration. This would reduce the energy requirements to extract the rock, since it would be displaced at lower temperature rather than transported to the surface. It would make for a thicker, stronger vitrified liner. Therefore, rates of penetration could be faster with less energy than what would be predicted based on complete rock vaporization below.

The glass melt on cooling could form a durable high temperature borehole wall that later could be perforated where needed. The formation of glass borehole liners by rock melting penetration has already been documented by research at Los Alamos [23]. Glass materials have the potential to be stronger materials than many rocks or high strength concrete. A separate casing or high specific gravity fluid fill to keep the borehole from collapsing due to lithostatic pressures may not be needed up to some maximum depth far greater than now though. A glass lined borehole would also serve as a robust conduit ideal for transferring high temperature corrosive geothermal fluids. The vision present here is that all the current drilling steps of grinding, extraction, and casing could be replaced with one directed energy operation.

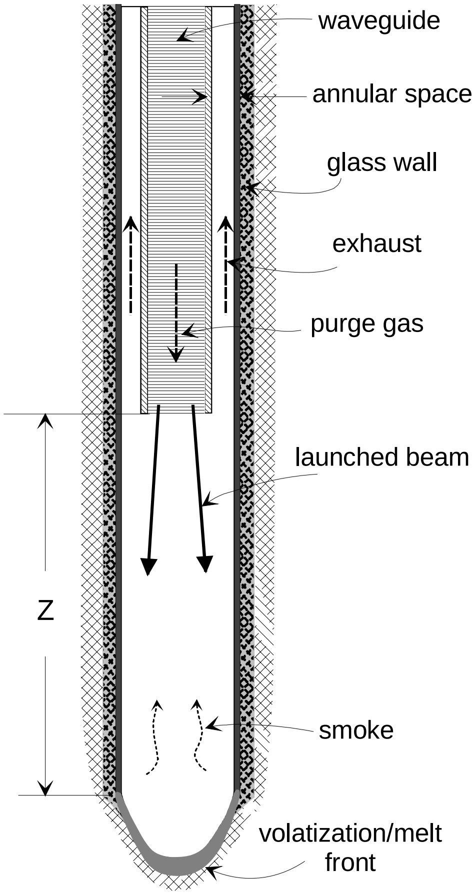

Figure 1. Cross-section of circular borehole with MMW drilling waveguide.

The requirement for a vitrified liner to maintain an open borehole should not be considered as the only option. The high pressures generated by vaporized rock at temperatures > 3000 °C in a confine volume would have an upper limit of 10^3 MPa (10^4 atmospheres), equivalent to lithostatic pressures at 15 km (50,000 ft), based on a simple ideal gas law calculation in constant volume. This is an unexplored parameter space where the ideal gas law may not be valid and a supercritical rock fluid regime may exist. However, this speculation demonstrates that there may be other paths to open well stabilization, unimaginable by current mechanical drilling experience that could make possible record penetration into the Earth's crust with directed energy sources. The technology that has been developed by DOE and the world wide fusion energy research community to heat plasmas to 300 million degrees °C opens up new possibilities for drilling that should be explored. The proposal that has been submitted to DOE in the course of this investigation will pursue some of these issues if funded.

Thermodynamic Basis

The total energy, H, required to vaporize rocks starting from a cold solid state was originally expressed by Maurer [1] as the sum of the energies required to first heat the solid state to the melting point, then the required latent heat of fusion to transform the solid to a molten phase, followed by the energy necessary to heat the molten state to the vaporization point, and then finally the latent heat of vaporization required to transform the melt to vapor phase. This formula is written as:

$$H = c_s\left(T_m - T_i\right) + H_f + c_m\left(T_v - T_m\right) + H_v \qquad (1)$$

where c_s = mean heat capacity of solid rock, J/g/°C
c_m = mean heat capacity of molten rock, J/g/°C
T_i = initial temperature of rock, °C
T_m = melting temperature of rock, °C
T_v = vaporization temperature of rock, °C

H_f = latent heat of fusion, J/g
H_v = latent heat of vaporization, J/g

This is a simplified expression ignoring the intermediate phase transitions in the solid and melt phases and the temperature dependence of the heat capacities, which are averaged here, but should give approximately valid estimates of energy requirements.

Updating the data given in Maurer [1], Tables 1 and 2 give the specific energies necessary to fuse and vaporize rocks from first principles.

Table 1. Estimated Energy to Melt Rocks

Rock	Specific Gravity	Mean Heat Capacity of solid[b]	Melting Temperature	Latent Heat of Fusion[c]	Total Heat of Fusion from 20 °C
	(g/cm^3)	(J/g/K)	(°C)	(J/g)	(kJ/cm^3)
Granite	2.7	1.05	1215 -1260[a]	335	4.3 - 4.4
Basalt	2.8	1.05	984 -1260[a]	419	4.0 - 4.8
Sandstone	2.2	1.04	1650[c]	335	4.5
Limestone*	2.6	1.04	2600[c]	498	11.0

* $CaCO_3$ decomposes to CaO at 895 °C, requiring 1.78 kJ/g.

[a] E. S. Larsen, "Temperatures of Magmas", *American Mineralogist*, Vol. 14, pp. 81-94, 1929, [b]H. K. Hellwege, ed., Landolt-Börnstein Numerical Data …, Vol. 1, subvol. a, section 4.1, 1982, [c]Maurer [1]

Data from the atmospheric sciences community on stony meteorite ablation to nano particle smoke on entry into the atmosphere [18, 24] and Trouton's Rule [25] are used to make estimates of the vaporization parameters. Using the data found in Bornshten [24] and the Clausius-Clapeyron equation it is possible to estimate the pressure dependent rock saturated vapor pressure temperatures from the surface to higher subsurface pressures (~3 atmospheres at 10 km depth open well). Its takes 4 to 5 times more energy to vaporize rocks compared to that needed to melt them, an approach that would not be practical with inefficient laser technology, but would be possible with the more efficient gyrotron technology. The physics of directed energy rock penetration does not degrade with higher pressure and temperature (and may benefit) unlike the principal penetration mechanisms of other drilling approaches.

Table 2. Estimated Energy to Vaporize Rocks

Rock	Molar Weight	Mean Heat Capacity of Melt[a]	Vaporization Temperature 1 - 3 Atm.[b]	Latent Heat of Vaporization[c]	Total Heat of Vaporization[d]
	(g)	(J/g/K)	(°C)	(kJ/g)	(kJ/cm^3)
Granite	69	1.57	2960 – 3230	4.8 – 5.3	25.7 – 28.4
Basalt	70	1.65	2960 – 3230	3.9 – 4.2	24.7 – 27.5
Sandstone	62	1.51	2800 - 3010	4.3 – 4.5	18.7 – 19.9
Limestone	51	1.61	3360 - 3620	6.0 – 6.5	30.9 – 33.4

[a] A. Navrotsky, "Thermodynamic Properties of Minerals", *Mineral Physics and Crystallography*, pp. 18-27, 1995, [b]V.A. Bornshten [24], [c]Trouton's Rule [25], [d]includes results of Table 1.

Remarkably the specific energies derived by this analysis are in approximate agreement with the lower end measurements obtained with laser systems. This supports the interpretation that with laser drilling the infrared energy is typically obstructed by the extraction plume and only under rare circumstances, or at the start of a pulse, is it well coupled to the rock surface. See for example the results of Bacon *et al* [5] and Graves, Ionin *et al* [6]. Using MMW radiation should overcome this limitation because for small particles Rayleigh scattering is proportional to $1/\lambda^4$. Going from a wavelength of 1 μm to 1 mm will decrease scattering losses by a factor of 10^{12}. In addition, the particles will be smaller, nanometer in size by vaporization [17-19] versus micro meter size by spallation, the preferred lower energy laser approach, adding more improvement.

Estimated Rates of Penetration

Having knowledge of the specific energy (S.E.) of vaporization it is a simple matter to determine the rate of penetration (ROP) by complete rock vaporization for a given absorbed power density (P.D.). The relation is given by:

$$ROP\left[cm/s\right] = \frac{P.D.\left[kW/cm^2\right]}{S.E.\left[kJ/cm^3\right]} \qquad (2)$$

This equation is plotted in Figure 2 for three different specific energies 10, 20, and 40 kJ/cm^3. For a specific energy of 26 kJ/cm^3, representative of granite and basalt, and an absorbed power density range of 1 to 50 kW/cm^2, the MMW directed energy penetration rates would vary from about 1.4 to 70 m/hr. Higher power densities are not recommended to avoid plasma breakdown. If a plasma is created then the energy will no longer be directed, but omni-directional reducing the forward penetration rate. Experiments with short pulse gyrotron beam air breakdown show that power densities at one atmosphere pressure need to be over 1 MW/cm^2 for breakdown [26]. Though this breakdown threshold would decease with continuous operation, it would also increase with the higher pressures that would be found in deep wells.

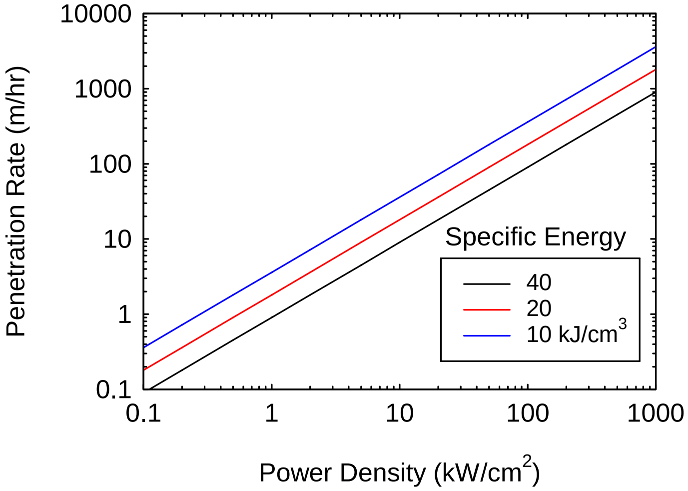

Figure 2. Relation between power density and rate of penetration for rock vaporization.

The size of the borehole that can be achieved with a given level of gyrotron power can now be estimated. The relation between power density and wellbore diameter (D) for a given total gyrotron power (P) is given by:

$$D = 2\sqrt{\frac{P}{\pi(P.D.)}} \qquad (3)$$

This equation is plotted for several power levels in Figure 3. A 5 cm diameter wellbore could be penetrated at 50 m/hr with 1 MW of power. If we consider a 2 MW gyrotron that will be available commercially in the near future it would be possible to penetrate a 15 cm (6”) wellbore at about 10 m/hr. The MMW power ultimately determines the size and penetration rate that can be achieved.

Estimated Costs

The primary cost for MMW drilling will be the electricity necessary to power the directed energy beam not the hardware. A 2 MW gyrotron with magnet sells for \$2.1 M [27] and would amortize to less than \$11 k per well if 200 wellbores are drilled. The rest if the MMW drilling facility cost would be mostly that of the electric power plant which at 4 MW for this example would be similar to present drilling systems. There are a number of other costs associated with drilling, but having such a low capital expense for the heart of a faster drilling system bodes well for a significant reduction in costs over the current mechanical drilling costs that can exceed \$10 M per deep well [28].

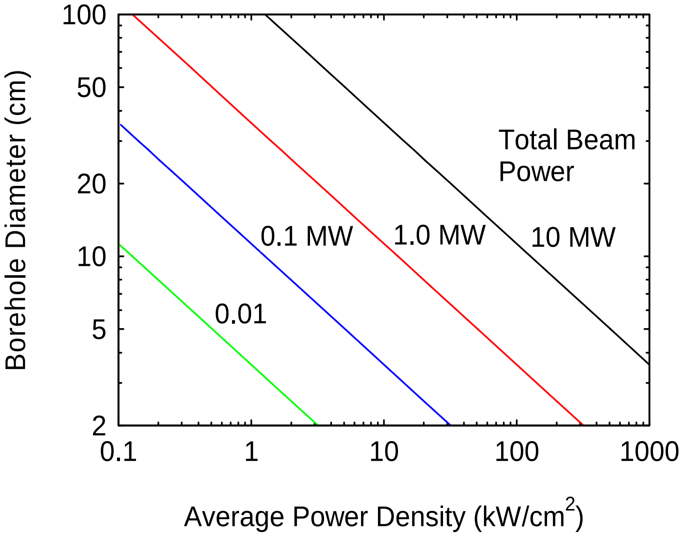

Figure 3. Relation between power density and wellbore diameter

The electricity costs can be readily estimated based the present analysis. For a 7 km deep well penetrated at 10 m/hr with a 2 MW (7” bore dia.), 50% electrical efficient gyrotron, this would correspond to 2.8×10^6 kW hrs or a cost of \$280k (\$40/m) at \$0.10 a kWhr. This is not a large number in comparison to costs of over \$10 M (>\$1400/m) to those depths using mechanical drilling systems which scale exponentially with depth [28] allowing for significant margin for addition of other costs and still be competitive with mechanical drilling. However, it should be cautioned that we are assuming an idealized case with rock removed by vaporization only and that there are no power losses. Also, as mentioned earlier, other costs are involved. The proposed follow on research will help to better define these costs.

Next Step

A continuous 10 kW, 28 GHz turn key gyrotron system has been delivered to the PSFC under a long term loan agreement that includes use for research of enhanced geothermal systems (see Figure 4). It will become operation in the Fall of 2009. The operating range will be in the lower left corner of Figure 3 for directed energy penetration, not ideal, but on the plot. When the switch is thrown on and the first rock is ablated with millimeter-waves it will add a concrete result to support the present study. Such an achievement combined with the knowledge obtained here with the MITEI seed funding could motivate a rapid advance to increase access to underground energy resources.

Figure 4. 10 kW, 28 GHz gyrotron system being installed at MIT PSFC.

References

1. W. C. Maurer, Novel Drilling Techniques, Pergamon Press, London, pp. 87-91, 1968.
2. W. C. Maurer, Advanced Drilling Techniques, Petroleum publishing Co., Chap. 17, 1980.

3. K.G. Pierce, B.J. Livesay, J.T. Finger, "Advanced Drilling Systems Study", Sandia National Laboratories, SAND95-033 1, 1996.
4. R. M. Graves, D. G. O'Brien, StarWars laser technology applied to drilling …, *Proc.-SPE Ann. Tech. Conf. & Exhibition*, v *Delta*, *Drilling & Completion*, pp. 761-770, 1998.
5. J. S. Bacon, S. Russell and J. P. Carstens, "Determination of Rock Thermal Properties", UARL Report No. L-911397-4, NTIS AD755218, Jan. 1973.
6. R.M. Graves, A.A. Ionin et al, "Interaction of pulsed CO and CO2 laser … with rocks", High-Power Laser Ablation II, C, R. Phipps, Ed., SPIE Vol. 4065, pp. 602-613, 2000.
7. M. R. Hallada, R. F. Walter, S. L. Seiffert, "High power laser rock cutting and drilling in mining operations: initial feasibility tests", High-Power Laser Ablation II, C, R. Phipps, Ed., Proc. SPIE Vol. 4065, pp. 614-620, 2000.
8. B. G. Gahan, ""Processing Rock", Indust. Laser Solutions, pp. 16-18, Sept., 2005.
9. A. Kasugi, K. Sakamoto, K. Takahashi, K. Kajiwara and N. Kobayashi, "Steady-sate operation of a 170 GHz - 1 MW gyrotron ..", *Nucl. Fusion*, vol. 48, 054009, 2008.
10. K.L. Felch, B. G. Danly, H. R. Jory, "Characteristics and Applications of fast-wave gyrodevices" *Proc. IEEE* vol. 87, 752-781, 1999.
11. G.S. Nusinovich, Introduction to the Physics of Gyrotrons, John Hopkins Studies in Applied Physics, 2004.
12. J. Lory *et al*, "Practical experiences with the 6 gyrotron system on the DIII-D tokamak", *20th IEEE/NPSS Symp. on Fusion Eng.* (IEEE Cat. No.03CH37469C), pp. 228-31, 2003.
13. J. Jacquinot, "Plasma heating and current drive systems for ITER ….", *17th IEEE/NPSS Symposium Fusion Engineering* (Cat. No.97CH36131), vol.1, pp. 399-404, 1998.
14. L. Rebuffi and J. P. Crenn, "Radiation Patterens of the HE11 mode …", *Intern. J. of Infrared and Millimeter-Waves*, vol. 9, pp.291-310, 1988.
15. L. L. Frach, S. J. Mclean, and R. G. Olsen, "Electromagnetic Properties … Basalt Rock", 1–110 GHz", IEEE Trans. *Geosci. & Remote Sensing*, vol. 36, pp. 754-766, 1998.
16. P. P. Woskov, S. K. Sundaram, W. E. Daniel, Jr., D. Miller, "Molten Salt dynamics in glass melts …", *J. of Non Crystalline Solids*, vol. 341/1-3, 21-25, 2004.
17. R. D. Whitlock and G. M. Frick, "Particle size distributions of aerosols formed by laser ablation of solids at 760 Torr", *J. Mater. Res.*, vol. 9, 2868-2872, 1994.
18. D. M. Hunten, R. P. Turco, O. B. Toon, "Smoke and Dust Particles of Meteoric Origin in the Mesosphere and Stratosphere", *J. of Atmospheric Sci.*, vol. 38, 1342-1357, 1980.
19. A. T. Zimmer, "The influence of metallurgy on the formation of aerosols", *J. of Environ. Monit.*, vol. 4, 628-632, 2002.
20. J.L. Doane and C.P. Moeller, "HE11 mitre bends and gaps in a circular corrugated waveguide," *Int. J. Electronics*, vol. 77, pp. 489-509, 1994.
21. P. Richet, , *Geochimica et Cosmochimica Acta*, vol. 48, 471-483, 1984.
22. V. Nikolaevskiy and I. Garagash, "Earth crust structure as a result of rock fracturing…", in Coupled Thermo-Hydro-Mechanical Chemical Processes in Geo-Systems, O. Stephansson, J. A. Hudson, and L. Jing, eds., pp. 727-732, Elsevier, Amsterdam, 2003.
23. R.J. Hanold, "Rapid Excavation by Rock Melting", Los Alamos Nat. Lab., LA-5979-SR, 1977.
24. V.A. Bornshten, Physics of Meteoric Phenomena, D. Reidel Publishing, Dordrecht, 1983.
25. J.J. Rooney, Trouton's Rule, *Nature*, vol. 348, 398, 1990.
26. Y. Hidaka et al, "Observation of Large Arrays of Plasma Filaments in Air Breakdown by 1.5-MW 110-GHz Gyrotron Pulses", *Phys. Rev. Lett.*, vol. 100, 035003, 2008.
27. Communications and Power Industries, Inc., private communication, 2009.
28. J.W. Tester et al, The Future of Geothermal Energy, MIT, Fig. 1.8, 2006, http://geothermal.inel.gov/.