Penetrating Rock with Intense Millimeter-Waves

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Penetrating Rock with Intense Millimeter-Waves

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Abstract—The use of directed energy millimeter-waves to bore into hard rock is being investigated in the laboratory as an advanced drilling technology. Experiments at 28 GHz show that with peak intensities of 1 - 2 kW/cm² granite, basalt, and limestone can be melted and vaporized to over 3000 °C in a few minutes. Heating is limited by radiative heat transfer loss. Key features for practical field implementation of a gyrotron drilling system have been shown on a small scale in the laboratory.

I. INTRODUCTION

There is an important need to reduce the costs of penetrating or drilling into deep hot hard rock to access geothermal heat as well as other hard rock applications such as proposals for borehole nuclear waste storage where mechanical grinding technologies can be very costly. Many thermal methods to penetrate rock have been tried in the past including flame jets, plasma discharges, steam lances, microwave heating, and infrared laser beams without achieving widespread applicability. It is now possible to show that millimeter-wave (MMW) directed energy from a gyrotron offers significant advantages that could make full bore thermal penetration into hard rock a practical reality.

The advantages of MMW directed energy include: good long wavelength beam penetration through optically obscured paths, efficient long distance guided propagation in typical borehole dimensions, possible simultaneous borehole wall vitrification for casing, improved real-time monitoring diagnostics, and the availability of efficient megawatt gyrotron sources. A study of the energy requirements to penetrate rock has shown that melting and vaporizing rock could be economic with gyrotron technology [1]. Initial experiments at 28 GHz have shown that granite can be melted with MMWs [2]. Since those initial experiments improvements in control over reflected power and plasma breakdown has been achieved to extend rock melt observations to longer duration MMW exposures and other rock types.

II. EXPERIMENTS

A 10 kW, 28 GHz CPI HeatWave Model VIA-301 gyrotron was used for the present experiments. The circular TE01 gyrotron output from a 32.5 mm diameter waveguide was converted to a linear polarized TE11 mode and then transformed between the TE11 and HE11 modes and diameter changes between 32.5 and 76 mm several times in transmission to the rock sample test chamber where a down taper to 20 mm diameter was used to concentrate the beam. The transmission line design incorporated a copper grill polarizer and circular polarizing miter bend to isolate spectral reflected power [3], a waveguide gap to isolate scattered reflected power, a 137 GHz radiometer view through a small hole in the miter bend above the test chamber, and the introduction of waveguide airflow through the reflected power water load. Inefficiencies in the transmission system reduced maximum power at the test samples to about 4.5 kW. Real-time signals that are recorded include gyrotron power incident on the sample, 137 GHz thermal emission proportional to the emissivity–temperature product (εT) of the sample surface, incident power that is absorbed by the water load (and not the sample) in the test chamber, and reflected power to the waveguide gap, isolator, and gyrotron.

Maximizing power intensity requires locating sample surfaces in close proximity to the waveguide launch aperture before beam divergence. An exposed sample of granite is shown in Figure 1. Granite begins melting in about 1 minute with peak incidence intensities of ~ 1 kW/cm². Basalt and previously melted granite start to melt within 5-7s due to increased absorption of these materials. A basalt melt crater appears more uniform black without the white particle structures evident in the granite melt of Fig. 1. Limestone, on the other hand, appears to begin vaporizing within about 30 s before a residue melt forms at some later time. Fig. 2 shows a limestone sample with 28 GHz beam exposure similar to that for granite in Fig. 1. The limestone is converted to a white powder by intense MMW exposure before it melts after emitting a black material that coats the inside test chamber.

Within 2–3 minutes for all these samples the radiometer sees temperatures, uncorrected for emissivity, in the 2000 – 4000 °C range. The higher temperatures are due to plasma formation, either in the beam path or on the heated surface.
which can be suppressed by increased waveguide airflow.

III. RESULTS

The present experiments are limited primarily by radiative heat transfer losses which depend on the fourth power of temperature. This is evident in the temperature measurements which have a power dependence of three or more relative to the incident power and by evaluation of the Stefan-Boltzmann equation that predicts the radiate power should exceed the incident power at the measured temperatures if the infrared emissivity is assumed to be near one.

The gyrotron beam exposure record for the limestone is shown in Fig. 3. When the incident gyrotron power is varied by a factor of two as shown in the top plot the observed change in limestone surface temperature must be raised to approximately the third power to follow, unlike the change in the water load temperature shown in the middle plot which changes linearly with input power as expected for a convective load. Similar measurements with granite and basalt show the observed temperature change must be raised to a power of four or more to follow incident power changes. Lower power temperature dependence with limestone is most likely due to the developing convective vaporization loss.

Evaluation of the Stefan-Boltzmann equation \( q = \varepsilon \sigma T^4 \) for the observed melt area \((A)\), temperature \((T)\), and an assumed emissivity \((\varepsilon)\) of 1.0 results in a peak radiated power loss of 3.2 kW in the limestone exposure. Here we have assumed the melt area is limited to the white glassy spot (28 mm dia.) as shown in Fig. 2 and the peak steady state temperature is 2830 °C as shown in Fig. 3. The peak gyrotron power absorbed by the limestone is only 3.1 kW obtained by subtracting the water load power from the incident power (4.2 kW) in Fig. 3. This difference in lost power exceeding the gyrotron absorbed power is actually much higher than this conservative analysis suggests because we have not taken into account other heat transfer loss mechanisms such as vaporization, or corrected the surface temperature for the 137 GHz emissivity. Assuming the emissivity at 137 GHz is the same as observed for 28 GHz in Fig. 2 of 0.75, then the surface temperature would be 3780 °C and the radiated heat loss 9.4 kW. Similar differences between the estimated radiated heat loss and the incident absorbed power are seen with granite and basalt exposures. This difference can best be reconciled by a low infrared emissivity near 1 mm wavelength where the black body emission peaks for the observed rock melt temperatures. Previous observations have also suggested that rock melt infrared emissivity is low [2].

IV. DISCUSSION

The laboratory experiments so far show that hard rock can be melted and vaporized with MMWs, but high intensities are required (≥ 1 kW/cm²) and that radiated heat loss is a major competing mechanism. In these experiments the power intensity incident on the rock samples is limited by the diffraction limit at 28 GHz and the maximum available power after transmission to the rock samples. In a practical rock penetrating system with a higher power gyrotron the intensities will need to be increased until thermal losses are clamped by vaporization or until radiative losses are trapped inside a borehole to propagate a borehole penetration. Radiated heat could help contribute to vitrifying the borehole wall. Plasma breakdown can be controlled with gas flow and at the high pressures found in deep drilling applications it is unlikely to be an issue.

We have demonstrated on a small laboratory scale the major features that will be required in a gyrotron drilling system which include a reflected power isolator, collinear combination of real-time diagnostics on the high power MMW beam, and a waveguide directed gas purge flow.

REFERENCES