IMPROVING GAS WELL DRILLING AND COMPLETION WITH HIGH ENERGY LASERS

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ABSTRACT

Modern mechanical methods for drilling oil and gas wells have been used by the industry since the mid 1800’s, borrowing from techniques used in early China. The last radical change was implemented around 1900, as rotary drilling displaced cable tools. Since then, great strides have been made in refining the rotary technique, however, no fundamental revolutionary changes in making hole have been introduced.

Alternative methods to mechanical well construction have been considered and reviewed at cursory levels since rotary techniques were first introduced, however none have been seriously considered as a displacing technology. Industry experts in the 1960’s and 1970’s considered the use of photonic energy in well construction, however the technical application of lasers was dismissed as energy intensive and inefficient. Their conclusions from 40 years ago continue to influence industry misperceptions of laser applications, despite massive developments in laser systems and applications, particularly those associated with the “Star Wars” laser development programs.

In 1994, a congressional mandate to transfer cold war military technologies to American industry opened the door to an investigation of laser drilling. GRI funded a two-year research project, "Adapting Star Wars High-Powered Lasers to Drilling Natural Gas Wells," to examine the feasibility of adapting extremely high-powered military lasers for use in drilling oil and gas wells. Several conclusions resulted from this investigation, including: 1) Lasers can cut rock of all lithologies, 2) Sheer power shares importance in cutting rock with such parameters as wavelength, purge gas pressure and hole size, and 3) Historical and widely accepted theoretical calculations of the laser power needed to spall (break), melt and vaporize rock are significantly higher than experimental values.

A follow-up study began in 2000 to investigate laser/rock interactions using pulsed lasers and under in-situ conditions. With the assistance of a 1.6kW Nd:YAG laser at Argonne National Laboratory, a GTI-lead team composed of laser applications and rock property experts, have been observing rock removal energy requirements, effects of pulsed versus continuous wave lasers, and the effect of fluids on laser/rock removal efficiencies.

INTRODUCTION

Rock destruction and removal is a significant issue in the process of oil and gas well construction and completion. Over the years, billions of cubic feet of rock have been removed, with tremendous capital investment. In 1999, approximately 20,000 wells (oil, gas and dry) were drilled onshore in the U.S., with an average depth of 6,000 feet [1]. This is equivalent to approximately 23,000 miles, or approximately three times the diameter of the earth (7,899 miles).

According to a GRI study conducted in 1995 on costs associated with well construction, nearly half of the time was spent on drilling, a quarter of the time on moving tools in and out of the hole, and the remaining quarter on casing and cementing activities. In general, major potential cost reductions related to well drilling were likely to come from increasing the rate of penetration of the drill bit into the earth, and reducing the time involved with moving tools, such as bits and pipe, in and out of the hole.

A significant amount of time can be spent on drilling through rock strata other than the reservoir rock. Drilling in hard rocks, such as granite, is extremely difficult and can expend a great amount of resources with little penetration resulting. Other costly problems associated with the drilling process include stuck pipe, fishing operations for lost tools downhole, and side tracking procedures, all of which are time and money consuming operations [2].

Reduction of costs associated with these drilling issues would have significant economic impacts for exploration and production operations. In order to make improvements in these areas, new technologies and tools would have to be applied that can take advantage of basic rock destruction mechanisms involving thermal spalling, fusion and vaporization, mechanical stresses and chemical reactions [3]. All of these destruction mechanisms can be achieved using lasers. It has been shown that at lower laser power levels, rock spalling (chipping) can be achieved. By increasing the power density of a laser beam, results in phase changes and reactions will occur in the rock, including dehydration of clays, and the release of gases and thermal stresses. Continually increasing the beam power density will then melt (fuse) the minerals within the rock and ultimately vaporize them [2].

DISCUSSION

A laser drilling and completion system was visualized by GTI that addressed many of these issues. Ultimately, this system could be designed to provide higher penetration rates and the ability to drill nonstop surface to total depth will reduce the actual drilling time. The ability to create a tough, ceramic sheath in the borehole while drilling will reduce or eliminate the time required for setting steel casing in the well. Since the system has a permanent, hard-wired connection from the surface to the bottomhole assembly, additional wires and/or optical fibers can be added to the bundle. This will allow the addition of many formation sensors, including televiewers and other imaging capabilities, delivering information to the surface in real-time and at incredibly high data transmission rates. The combination of the casing and sensing capabilities will all but eliminate the time required to run tools in and out of the hole, and will significantly reduce the time required for other activities.

Background

In 1997, a research project was begun, funded by the Gas Research Institute (now Gas Technology Institute) titled “Determining the Benefits of Star Wars Laser Technology for Drilling and Completing Oil and Gas Wells.” The goal of this research project was to examine the feasibility, costs, benefits and environmental impact of applying laser technologies to drill and complete oil and gas wells. Different high-power lasers were incorporated into the research plan, including the Mid-Infrared Advanced Chemical Laser (MIRCAL) at the U.S. Army’s HELSTF facility in White Sands, NM, the Chemical Oxygen-Iodine Laser (COIL) at U.S. Air Force’s Directed Energy Research facility in Albuquerque, NM, and a CO_2 and CO laser at the P.N. Lebedev Institute in Moscow, Russia.

Several conclusions resulted from this investigation, including:

1) Lasers can cut rock of all lithologies,
2) Sheer power shares importance in cutting rock with such parameters as wavelength, purge gas pressure and hole size, and
3) Historical and widely accepted theoretical calculations of the laser power needed to spall (break), melt and vaporize rock are significantly higher than experimental values.

Following on the success of GRI’s initial feasibility study, a second phase of investigation was conducted by Gas Technology Institute together with the US Department of Energy and research partners Argonne National Laboratory, Colorado School of Mines, PDVSA-Intevep, S.A., and Halliburton Energy Services. An investigation was initiated to determine the laser parameters needed to adapt available high power lasers to oil and gas operations. The team conducted a series of tests on different rock types using a 1.6 kW pulsed Nd:YAG laser to quantify the amount of energy required to remove a given unit volume of rock, or specific energy (SE). Comparisons could then be made with similar values generated from traditional rotary drilling techniques.

Samples of sandstone, limestone, and shale were prepared for laser beam interaction with Nd:YAG laser beam to determine how the beam’s size, power, repetition rate, pulse width, exposure time and energy can affect the amount of energy transferred to the rock for the purposes of spallation, melting and vaporization. The purpose of the laser rock interaction experiment was to determine the threshold parameters required to remove a maximum rock volume from the samples while minimizing energy input.

Absorption of radiant energy from the laser beam gives rise to the thermal energy transfer required for the destruction and removal of the rock matrix. Results from the tests indicate that each rock type has a set of optimal laser parameters to minimize specific energy (SE) values as observed in a set of linear track and spot tests. In addition, it was observed that the rates of heat diffusion in rocks are easily and quickly overrun by absorbed energy transfer rates from the laser beam to the rock. As absorbed energy outpaces heat diffusion by the rock matrix, local temperatures can rise to the melting points of the minerals and quickly increase observed SE values. The lowest SE values are obtained in the spalling zone just prior to the onset of mineral melt.

The current study determined that using pulsed lasers could accomplish removing material from rock more efficiently than continuous wave lasers. The study also determined that reducing the effect of secondary energy absorbing mechanisms resulted in lower energy requirements in shale and, to some extent, in sandstones. These secondary mechanisms are defined as physical processes that divert beam energy from directly removing rock, and may include thermally induced phase behavior changes of rock minerals (i.e., melting, vaporization, and dissociation) and fractures created by thermal expansion. Limestone is spalled by a different mechanism and does not seem to be as affected by secondary mechanisms. It was also shown that the efficiency of the cutting mechanism improved by saturating porous rock samples with water, and that a laser beam injected directly through a water layer at a sandstone sample was able to spall and melt the sample.

Specific Energy

In order to break rock by mechanically or by thermally induced stresses, a sufficient force of energy must be applied to the rock such that the induced stresses will exceed the rock's strength. Similarly, when fusing rock sufficient heat must be applied to produce local temperatures that exceed the melting temperature of the rock. Once these threshold values of force or energy are exceeded, the amount of energy required to break or remove a unit volume of rock remains nearly constant. This energy parameter, which is a measure of the efficiency of the rock destruction technique, is defined as specific energy (SE) [3]. In another words, the specific energy is defined as the amount of energy required to remove a unit volume of rock and is mathematically defined as follows:

$$SE = \frac{Energy\ Input}{Volume\ \mathrm{Re}moved} = \frac{P}{dV/dt}$$

$$= \frac{\left[\frac{kW}{cm^2}\right]\!.\mathrm{seconds}}{cm} = \frac{kW}{cm^3/\sec} = \frac{kJ}{cm^3}$$

Where

P = Power Input (Watts)

DV/dt = Volume Time Derivative (cm3/sec)

SE Calculation Factors

There are factors that divert the transfer of energy to the rock known as secondary effects, which include melting and vaporizing rock minerals, decomposed gas in the lased hole and induced fractures. When applying high power lasers on rocks, the laser can melt, chip or vaporize the rock, depending on the application desired. When the laser is exposed over longer time increments, quartz and other minerals melt and form a glass lining in the lased borehole, or sheath. The mechanism and amount of the melt depends on the quartz percentage and the grain contact. The closer the grains are to one another, the easier heat will transfer between the grains, leading to mineral melt. Another mechanisms observed is dissociation in carbonates, producing a physical change in the rock and exsolved gases. The gases and sheath caused by laser radiation reduces the energy transfer to the rock sample. The sheath and gases absorb part of the laser energy so less energy is transmitted to rock [2].

Fractures also have an impact on SE, as they represent energy used for purposes other than rock removal, and translate directly to higher SE values. Fractures are classified as macro- and micro-fracture; macro-fractures are easily observed in hand specimen, while the micro-fractures can be seen under the microscope. The behavior of fractures is different from one rock type to another (figure 1).

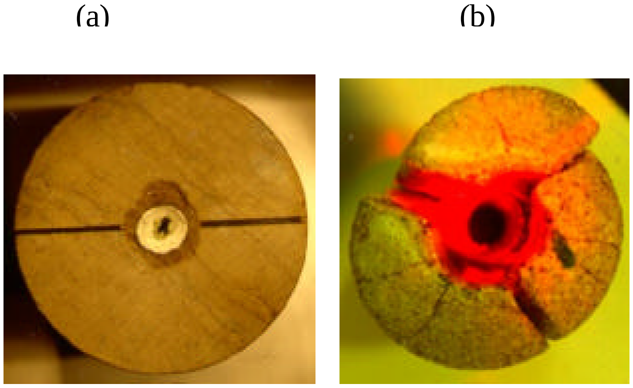


Figure 1. Fracture Comparison of (a) Limestone with no Induced Fractures and (b) Sandstone with many Induced Fractures

Fracture behavior in rocks relies on factors such as mineralogy, thermal properties of the rocks, volume of void space, dimension of the sample and the amount of stress applied. Mineralogy effects fracture formation. Clays contain water that, when subjected to high temperatures, will try to escape in the form of vapor. This increases the volume and pressure in the pore and can cause fractures. Sandstones and shales have high thermal conductivity and contain clays. Limestones, on the other hand, have low thermal conductivity and have low amounts of clay and quartz; therefore fractures can be expected more in sandstone and shale, and less in limestone [2]. As thermal conductivity increases, the rock heats up more efficiently and the temperature distributes better within the rocks. Also, for high thermal conductivity rocks, cooling will be gradual along the core sample. Fractures in sandstones developed regularly not randomly.

Temperature causes quartz grains to expand. At 600 ^{o}C quartz grains expand by 1.75% of their original size [4]. In the case of full grain contact (low void space), grains have no place to expand, a therefore fractures are more likely to develop. The dimension of the sample can effect the behavior of the fractures, it has been observed from the previous tests that the 2.54-cm diameter cores are highly fractured especially around the hole, while the 3.09-cm diameter cores are less fractured. Finally, it has been observed that an application of stress on the core minimizes macro fractures, while micro fractures will be induced [2].

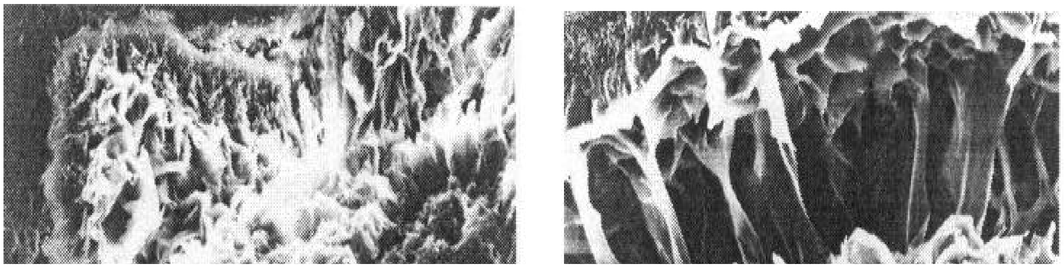
Effect Of Laser On Rock Properties

It was found that high temperatures induced by lasers on rock samples could enhance porosity and permeability. High temperatures have been shown to evaporate or otherwise alter cementation minerals creating additional, connected pore space within the affected region. This results in improved conditions for the fluid to flow from the formation into the wellbore, as compared to the damage created to the rock through conventional applications of rotary drilling and explosive perforations (Table 1).

Table 1. Permeability and porosities before and after lasing for selected rock types.

Sample	Permeability (md) Before Lasing	Permeability (md) After Lasing	Porosity (%) Before Lasing	Porosity (%) After Lasing
Berea Yellow Sandstone	7754	7914	0.25	0.40
Berea Gray Sandstone	554	674	0.18	0.35
Sandstone Reservoir	11.1	30.1	0.18	0.40
Limestone	0.02	0.02	0.02	0.02
Shale	0.43	0.55	0.01	0.03

The increases in porosity and permeability are related to the thermal properties of the rock, such as thermal conductivity. Sandstones, which have a high thermal conductivity, exhibit a wider range of temperature distribution and therefore higher permeability distribution. The results also indicate that the presence of clays could help in enhancing permeability by creating microfractures in the formation. Water contained within the clays is subjected to flash vaporization at intense temperature differentials, and with the expansion creates fractures. Also, some clays collapse at specific temperature. For example, smectite collapses at 550 ^{0}C (figure. 2) [2].



Before dehydration After dehydration

Figure2. Dehydration of smectite clay increasing porosity and permeability [2].

The strength of the rock was reduced as a function of temperature. High temperature results in more evaporation, breaking in the cementation and creating microfractures, consequently increasing permeability and reducing strength.

Rock Phase Behavior

Any phase change observed in rock sample is dependant on the laser power applied and the melting temperature of the minerals in the sample. In general, it was observed that the melting temperature of the rock samples in our experiments increased as the percentage of quartz increased. Further, as the melting temperature of the rock increases, observed rock destruction decreased. Applying this concept to SE, the greater the percentage of quartz in the rock sample, the higher the energy consumed in secondary mechanisms, including melting and vaporization. This concept applies more when making deep holes, however, it could be minimized with shallower holes and a good purging system. Other parameters may also play an important yet undetermined role in laser/rock interaction, including physical characteristics surface roughness, color, and grain cementation; unconformities in the matrix such as vugs and fractures; and thermal properties like conductivity, heat capacity and diffusivity.

Figure 3 provides an example of phase change observed in a shale sample as a function of measured average power applied and SE. The laser power ranged from 0.2 to 1.2 kW while all other parameters remained constant. Two regions were identified as to whether melted material was observed after exposure to the laser. The data points plotted on the left side of the transition zone represent samples that exhibited no traces of melting occurring on the sample, however melted material was present on samples represented by the data points plotted to the right of the transition zone. The no-melt zone represents samples exposed to lower laser power, and shows high SE. With a low lasing power, energy is consumed by mainly by thermal expansion. As power is increased, fractures begin to form and mineral melting temperatures approached. Additional increases in power result in faster heat diffusion and heating up the sample. At higher power, the minerals began to melt resulting in higher SE values[5].

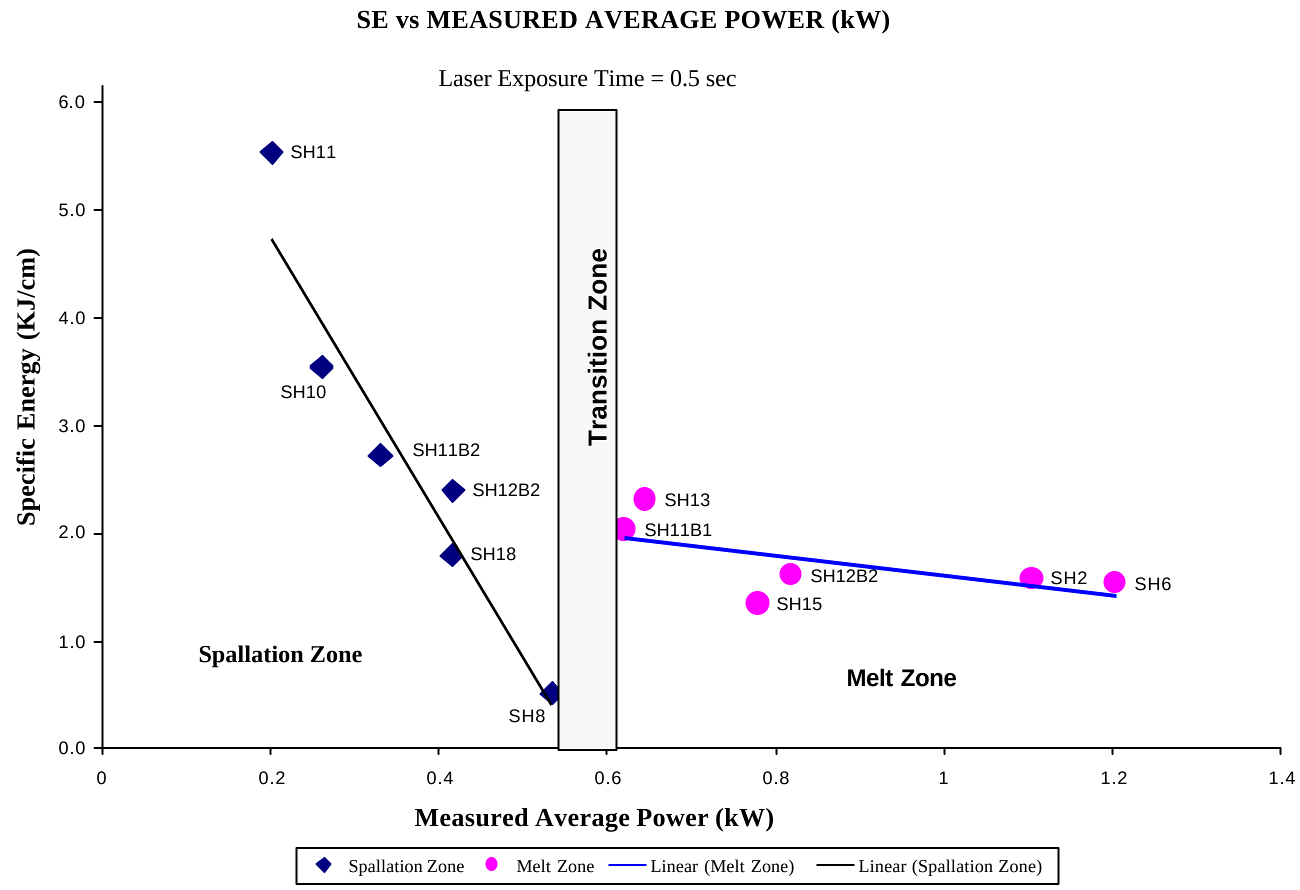


Figure 3. Phase Diagram Showing No Melt - Melt Zone of Shale Sample Lased By Nd:YAG [5].

CONCLUSIONS

Laser research to date has shown potential value to drilling operations, including the ability to cut through rock more quickly than conventional and other non-conventional methods, and could possibly create its own ceramic wellbore casing. In addition, it was also observed that lasers can destroy rock without damaging formation permeability and, depending on laser and rock parameters, can even enhance permeability. This is particularly important when applied as an alternative non-explosive perforation technique or other well completion applications.

Most recent work to date has identified the following:

- Specific energy is the common parameter used for comparison of different methods of rock removal. There are secondary effects that can impact specific energy calculations, and are dependant on mineralogy, thermal properties and rock properties. A greater percentage of quartz present in the rock translates to a higher melting point of the rock, therefore greater SE.
- High power laser-rock interaction tests have proven that lasers can penetrate all rock types including granite, much faster than conventional methods. Laser can also induce fractures in the rocks by thermal expansion.
- The application of high power lasers can also enhances rock properties such as permeability and porosity; as tests showed that permeability and porosity increased in all rock types.
- Laser parameters can be controlled very precisely to achieve spallation, melting or vaporization the rock, depending on the application required.
- The phase change in the rock depends mainly on the rock type, thermal properties and measured average power when all other parameters are held constant. A higher percentage of quartz in the sample will result in higher melting point for the rock, therefore requiring more energy to melt and more energy to vaporize.

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