

Putting the Pressure on Fiber Laser Perforations

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As part of their ongoing investigation into high-power laser applications for well completions, researchers at the Gas Technology Institute were able to perforate steel, cement and rock under high pressure and stress conditions encountered downhole. For the first time, questions about how lasers will operate under real conditions in the field have been answered.

For decades, the use of lasers has continually resurfaced as a quick and easy means of boring through the earth to reach plentiful mineral deposits. Cultural references to lasers or other disintegrating rays emanating from alien spaceships, mountaintop laboratories or handheld weapons have subliminally misled many to believe lasers and photonic energy are infinitely powerful and without limitations. Lasers, of course, are subject to the known laws of physics. Although they have unique capabilities, useful applications for lasers have grown only as technology has advanced. As a result, lasers have been developed to perform multiple tasks across several industries.

Serious investigation of using lasers for cutting and boring through naturally occurring rock is a relatively recent endeavor. Advances in computer technology, control systems and lasers themselves have allowed researchers at the Gas Technology Institute (GTI) to investigate their use as an alternative method for well construction and completion. Several military and industrial lasers with a variety of beam characteristics have been used on an assortment of rock types and other materials to determine the technical feasibility of their use downhole.

High-power fiber lasers represent the next generation for industrial applications offering a number of technical and economic advantages, including higher energy conversion efficiencies;

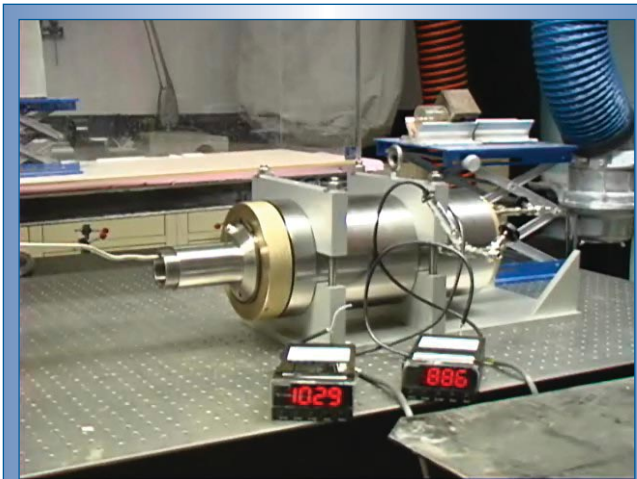


Figure 1. Triaxial pressure cell designed for simulated in-situ laser/rock interaction testing.

low or no maintenance; and a compact, rugged, solid-state design. They represent an enabling technology that opens the door for laser use in remote field sites, and as such, are considered a leading candidate for near-term subsurface laser applications. (For more information, see *New High-Power Fiber Laser Enables Cutting-Edge Research*, GasTIPS, Spring 2004).

A non-damaging alternative

The oil and gas industry has attempted for years to find acceptable non-explosive alternatives to creating downhole reservoir connectivity with the wellbore. Although some methods have proven capable in providing an economic and technical solution, the use of shaped charges remains the preferred technology for most applications.

Shaped charge explosives have drawbacks upon which alternative perforation methods

seek to improve. A prime example is the crushing of the rock matrix near the tunnel zone from the jet's high velocity mass transfer, resulting in a significant reduction of flow from the reservoir into the wellbore. Remedial work with some form of stimulation often is required to overcome this flow restriction. Other concerns voiced by the industry include the inherent safety challenges regarding the transportation, storage and use of the perforating assembly. Regulatory concerns also focus on limitations that may be raised on the use of explosive charges,

challenging the industry's ability to economically complete wells around the world.

The application of high-power lasers to create the path between the wellbore and reservoir could significantly reduce the primary drawbacks of using explosives. In addition to perforating, laser applications could perform other on-site tasks, including cutting windows for side exiting casing or laterals, extended perforations that connect additional reservoir rock to the wellbore and removal of objects lost downhole that would normally require drill out or fishing operations.

Laser perforation experiments in the past have been performed using combinations of laser input parameters on several rock lithologies to determine specific cause and effect relationships. Optimized variables were identified and demonstrations conducted to show the capability of lasers to cut tunnels of at least

12-in. deep into sandstone and limestone. One notable advantage resulting from laser perforation on sandstone is the improvement of near-tunnel fluid flow characteristics. Measured permeability increased between 15% and 30% along the tunnel face of a perforation demonstration on a 12-in. block of Berea sandstone.

Perforating under pressure

Although the application of lasers for perforation provided promising results, downhole pressure conditions had not been investigated. All high-power laser application experiments performed to date had been conducted under ambient pressure conditions in the laboratory. To perform high-pressure tests on rock, a triaxial pressure cell was designed to allow multiple pressure conditions, a simulated pressurized wellbore, a window for the laser beam to interface with the sample and ejection ports for laser material.

As part of a recent laser perforation study, tests were conducted with the triaxial pressure cell to give an initial understanding about how high-pressure conditions similar to that found downhole influence the laser/rock interaction process. The laser used in this experiment was a 5.34-kW ytterbium-doped multiclad fiber laser with an emission wavelength of 1.07 microns. The triaxial pressure cell rated at 3,000psi was designed for this experiment to allow laser beam exposure to a 4-in. diameter by 6-in. in length pressure-charged rock core by means of a sapphire window.

Between the window and the core is a chamber that simulates a wellbore and can be independently charged with pressure to simulate over-balanced conditions. At-balance conditions are simulated with ambient pressure in the wellbore chamber and no pore pressure in the rock sample. Underbalanced conditions are simulated with ambient conditions in the wellbore chamber and pore pressure in the rock sample.

Ports in the wellbore chamber allow ejection of cuttings and other materials. The design of the wellbore chamber minimizes the exposure of the optics to all material ejected from the sample during the lasing process. The design has proven successful in this application and will be incorporated in future field prototype tool designs. A photograph of the completed high-pressure cell is shown in Figure 1.

Pressure test on rock core

Initial tests were performed on cores of Berea sandstone and Indiana limestone under various conditions of axial, pore and confining pressures. The laser settings remained constant for all cases. Full output power of 5.34 kW was applied continuously to each sample through the sapphire window of the pressure cell with a beam diameter of 0.35-in. for 8 seconds. The amount of laser exposure time was calculated from previous laser rock interactions to allow penetration into the core without risk of penetrating the core's full length and avoiding possible dam-

age to the pressure cell.

Five trials were performed on unsaturated samples of each rock type. A base case was established for each rock type by lasing samples in the cell at ambient pressure conditions. A second condition was tested on each rock type with confining and axial stress limited to about 1,000psi. Since the cores were not charged with pore pressure, a high-pressure gas purge of 90psi through a quarter-in. nozzle assisted in particle removal.

A third condition was then tested for each rock type that combined confining and axial stress limited to about 1,000psi, while charging the core to a pore pressure. No gas purge was provided as underbalanced conditions (greater pore pressure than wellbore pressure) served to eject particles from the charged core through pressure cell exit ports. Two additional trials were performed at balanced and underbalanced conditions with double the pressure settings.

To better understand the *in-situ* performance of lasers in the presence of reservoir fluids, sandstone and limestone cores were saturated in brine and liquid hydrocarbon prior to high-pressure lasing. Pressure conditions for each rock type included confining and axial stress limited to about 1,000psi with no pore pressure. Results of all high-pressure core tests are presented in tables 1 and 2.

Pressure tests on composite core

After observing the laser/rock interactions of

Table 1. High-pressure cell tests on Berea sandstone.

Trial Number	Conf. Pressure (psi)	Axial Pressure (psi)	Pore Pressure (psi)	Volume Removed (cc)	Specific Energy (kJ/cc)
B1	0	-	-	2.03	19.75
B2	1,120	1,180	-	2.53	15.80
B3	1,101	1,106	864	1.97	20.31
B4	2,031	2,000	-	2.44	16.38
B5	2,100	2,215	1,565	3.10	12.91
Brine	1,893	1,991	-	5.45	7.84
Oil	1,844	1,956	-	1.60	26.76

Table 2. High-pressure cell tests on Indiana limestone.

Trial Number	Conf. Pressure (psi)	Axial Pressure (psi)	Pore Pressure (psi)	Volume Removed (cc)	Specific Energy (kJ/cc)
L1	0	-	-	0.40	99.97
L2	1,029	1,139	-	0.93	43.00
L3	982	1,056	864	1.02	39.04
L4	2,069	2,169	-	0.98	40.67
L5	2,100	2,225	1,625	3.26	12.27
Brine	1,922	1,981	-	1.87	22.78
Oil	1,800	1,930	-	0.85	50.36

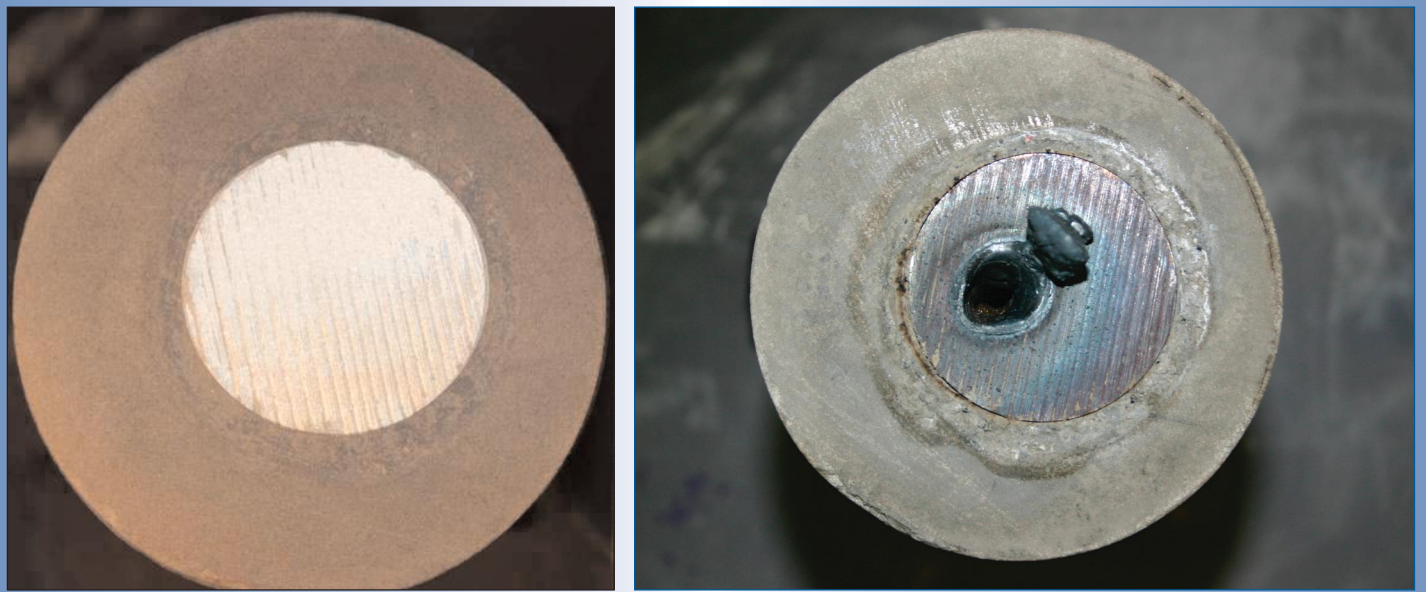


Figure 2. Pre- (left) and post-laser images of 4-in. by 6-in. limestone core inset with 2-in. by half-in.-thick steel plate.

sandstone and limestone under high-pressure conditions and the resulting specific energy values, *in-situ* demonstrations were then executed to best simulate downhole conditions and material encountered during laser perforation. Composite samples of steel, cement and rock were prepared by cementing in place a 2-in. diameter by half-in.-thick steel plate. By using a smaller steel diameter inset, the rubber pressure sleeve jacketing the sample core would not be at risk of melting through direct contact with a full diameter steel plate.

The sandstone and limestone clad samples were exposed to the same laser beam conditions as performed under previous high-pressure trials. For the sandstone sample, axial and confining pressures were measured at 2,100psi and 2,030psi, respectively. Axial and confining pressures for the limestone sample were measured at 2,074psi and 1,966psi, respectively.

Total time of beam exposure was 90 seconds per composite sample. The time was calculated based on earlier laser exposure times to remove a unit volume of steel, cement and rock materials. The laser fired for 30-second intervals buffered with 20 seconds between shots as a precaution to avoid over-

heating the cell assembly. Before and after laser images of the limestone clad sample are shown in Figure 2.

As a result of the high-pressure clad sample trials, the laser penetrated about 2½-in. into the sandstone clad sample, or a half-in. beyond the steel and cement. The laser penetrated 4½-in. into the limestone clad sample, or 2½-in. beyond the steel and cement. An X-ray CT scan image of the limestone clad sample is shown in Figure 3.

Pressure test results

The resulting data generated from the series of sample trials on sandstone and limestone have demonstrated that a laser perforation system will significantly benefit from the high-pressure conditions encountered downhole. For both rock types, specific energy values decreased as confining and axial stresses increased. The effect was more apparent in the limestone than in the sandstone samples.

Sandstone—The removal mechanism for Berea sandstone is spallation, where rapid differential thermal expansion causes grains and cementitious material to fracture. The base case for sandstone with no pressure had an SE value of 19.75 kJ/cc. The conditions

are similar in many respects to much of the previous work performed in the lab. The sample is at ambient conditions during laser and a gas purge nozzle assists in removing broken material.

The lowest SE value observed in sandstone was 12.91 kJ/cc, a 35% reduction from the base case, resulting from the highest-pressure values tested. Material removal was assisted with the differential between the pore pressure and wellbore chamber pressure. As this differential increases, material is more rapidly ejected from the tunnel, thus minimizing travel through the cutting beam and absorbing less beam energy after detaching from the rock matrix. With less beam energy absorbed by exiting particles, more is available for cutting, as evidenced by the drop in the SE value.

At the pressures tested, confining and axial stress had a limited impact on SE values for sandstone. The stresses imparted on the sandstone matrix create tighter grain-to-grain contact and improved the thermal diffusivity of the rock. In both cases, material is purged with an assist gas with the same conditions for each trial.

Limestone—The removal mechanism for limestone is calcination where the energy of

the laser beam causes a thermal dissociation of carbonates into carbon dioxide and calcium oxide (lime). Just as axial and confining stress compressed the sandstone, the effect was more evident in the limestone samples. This quarry limestone was originally unstressed, contributing to an SE drop of at least 60% because of closer grain-to-grain contact and a more efficient calcination process.

The lowest SE value was observed in limestone at the highest pressure and stress conditions. Again, the differential pressure assisting in material removal was evident with a significantly lowered SE of 12.27 kJ/cc, 88% lower than the base case.

Conclusions

High-power laser applications for cutting and boring rocks have been successfully demonstrated under ambient pressure conditions; however, this is the first time samples have been lased at *in-situ* pressure conditions. Research results demonstrated the beneficial effect of stress and pressure on the laser's ability to perforate reservoir rock. Additionally, we were able to demonstrate the capability of a single wavelength laser to penetrate a combination of steel, cement and rock at *in-situ* pressures that would be encountered while perforating downhole.

Operating the laser in underbalanced conditions showed the laser's ability to perform at downhole conditions without requiring a supplemental assist purge system. The differential pressure between the reservoir pore pressure and the wellbore pressure provided the means for ejecting the cuttings.

Operating the laser on rock under axial and confining stress improves the conditions for laser perforation because of a closer grain-to-grain contact and resulting improvement to thermal diffusivity. This extends the influence of the beam energy further into the rock.

Looking ahead

Additional research has been proposed to follow on our initial *in-situ* pressure investigation.

Questions remain about how best to transmit energy down-hole, effects of higher pressures on the lasing process, energy application on the target and whether any fluid flow improvements result from a lased perforation tunnel.

A better understanding is required of high-power laser energy transmission from the surface to the reservoir. Energy losses, or attenuation, of low-energy transmission over long distances through solid-core silica fiber are bet-

ter understood than with high energy transmission. As a result, we need to determine whether a correlation exists between the calculated attenuation losses at low power with those observed at high power. Associated with these energy losses is the need to better understand how lost energy is dissipated and whether there are any negative effects on the physical and light transmission characteristics of the silica fiber.

Although we got our first look at high-pressure lasing of rock, additional experiments should be carried out at higher pressures. A series of experiments can be performed on rock and clad samples, such as steel, cement and rock, at pressures and stresses beyond that previously achieved. We believe the system will continue to behave favorably at greater depths and would like to determine this by lasing samples under pressure and stress conditions simulating at least 15,000ft.

Energy losses at the working surface also require investigation. Experiments on fluid behavior at downhole pressures and temperatures could determine distance limitations because of energy absorption by fluids. In addition, it should be determined how well different gas and liquid purging fluids can extend the effective lasing distance through reservoir fluids.

It has been shown that high-power laser applications avoid damage and can improve

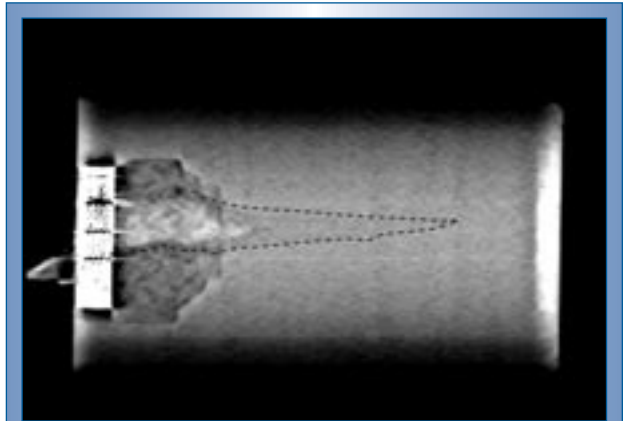


Figure 3. CT scan image of 4-in. by 6-in. limestone clad sample and outline of penetration path after perforation of three 30-second shots by a 5.34-kW ytterbium fiber laser with a 0.35-in. diameter beam.

the porosity and permeability of rock in the perforated tunnel and adjacent zones. Although these enhancements suggest production from a laser perforation should outperform production from an explosive perforation, no comparative tests have been performed. Core flow measurements could be performed and results correlated with lasing conditions and input parameters, including beam shapes and intensity, *in-situ* pressures and stresses, and the effect of lasing across pressure differentials.

The issues addressed in upcoming research should allow the initial design of a downhole prototype tool. Researchers are hopeful that field experimentation will soon follow. If successful, the door will have opened further to other remote site laser applications. ♦

References

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