

# **Alternatives to Hydraulic Fracturing**

by

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14627

Dissertation submitted in partial  
fulfilment of the requirements for the  
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# **CERTIFICATION OF APPROVAL**

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A project dissertation submitted to the  
Petroleum Engineering Programme  
Universiti Teknologi PETRONAS  
in partial fulfilment of the requirement for the  
**BACHELOR OF ENGINEERING (Hons)**  
**(PETROLEUM)**

Approved by,

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**UNIVERSITI TEKNOLOGI PETRONAS**

**TRONOH, PERAK**

January 2015

## **CERTIFICATION OF ORIGINALITY**

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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**KOSHEKOV SHABERDI**

## ABSTRACT

Hydraulic fracturing is a common stimulation technique which is widely used especially in a North America. It has several positive impacts on economy and energy. However, increasing use of hydraulic fracturing raised some health and environmental concerns, such as large amount of water usage, methane infiltration in aquifers, groundwater contamination, wastewater disposal and air pollution. Requirement of high injection pressure is another challenge. By considering these challenges and limitations, an alternative to hydraulic fracturing is required.

This project aims to review the various alternatives to hydraulic fracturing and to investigate the applicability of laser technology as an alternative to hydraulic fracturing. Laboratory tests were performed using laser machine to analyse the penetration, specific energy and fracture formation of different rock types. For this laboratory study 3 different sandstone, shale and limestone rock samples were used. The properties of sandstone core samples were measured using Poroperm equipment. Each sample were cut into 4 different pieces 2mm, 4mm, 6mm, 8mm using Trimming and Lapping, Polishing machine and exposed to varying laser power.

Highest penetration rate was observed in limestone, followed by Berea gray sandstone, shale, shaly sandstone and Berea yellow sandstone. The range was from 10 ft/hr to 28 ft/hr. High thermal conductivity, low percentage of quartz, high bulk density, dark color and high permeability increase penetration rate and the opposite of these parameters decrease penetration rate. Specific energy of samples were calculated in order to determine efficiency of rock removal. Berea yellow sandstone showed highest specific energy, followed by shaly sandstone, shale, Berea gray sandstone and limestone. Calculated range of specific energy was from 18 kJ/cc to 27 kJ/cc. Lower values of specific energy indicate less energy consumed, hence more efficient.

Laser can penetrate all types of rocks and penetration rate increases with the increase of laser power and decreases with the increase of sample thickness. Specific energy does not change with laser power but under constant laser power it is inversely proportional to penetration rate. Moreover, fractures were observed in sandstone and shale but not in limestone.

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## ABBREVIATIONS AND NOMENCLATURES

|          |                                      |
|----------|--------------------------------------|
| A        | Area (ft <sup>2</sup> )              |
| BG       | Berea gray sandstone                 |
| BY       | Berea yellow sandstone               |
| cc       | Cubic centimetre                     |
| d        | Diameter of laser beam (0.006562 ft) |
| E        | Energy (kJ)                          |
| h        | Sample thickness (ft)                |
| K        | Thermal conductivity (W/m-K)         |
| k        | Permeability (md)                    |
| L        | Length (ft)                          |
| Ls       | Limestone                            |
| P        | Power (W)                            |
| PT (t)   | Penetration time (hr)                |
| PR       | Penetration rate (ft/hr)             |
| SE       | Specific energy (kJ/cc)              |
| Sh       | Shale                                |
| Sst      | Shaly sandstone                      |
| W        | Watts                                |
| $\rho_b$ | Bulk density (g/cc)                  |
| $\phi$   | Porosity (%)                         |

# CHAPTER 1

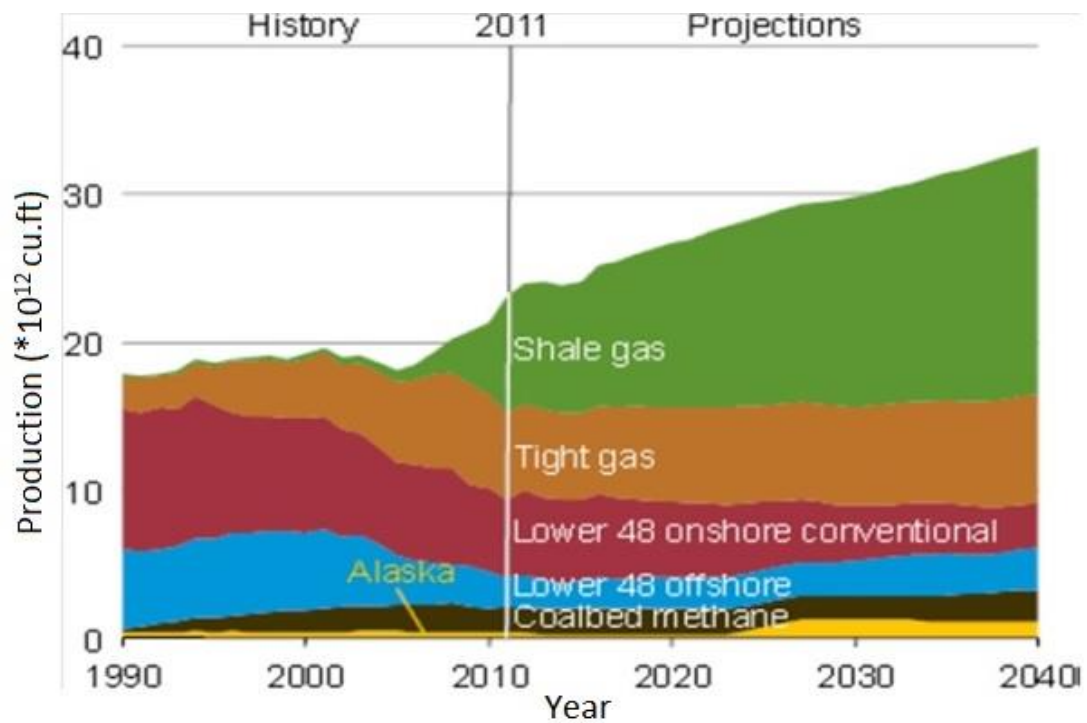
## INTRODUCTION

### 1.1 Project Background

Hydraulic fracturing is the well stimulation technique which is used to extract oil and gas from unconventional and low permeability conventional reservoirs. This is achieved by pumping the fracturing liquid fluid into formation with such high pressure that exceeds the fracture gradient of the rock. Fracturing fluid composed of 90% base fluid, 9.5% proppant and 0.5% chemical additives. Base fluid is usually water but can be other liquids, such as foam, oil, acid, alcohol or emulsion. Proppant is the grains of sand, ceramic or other particulate which keeps the fracture open. Chemical additives helps to reduce the friction, corrosion and bacterial-growth.

Hydraulic fracturing is not new technique; the first experiment was conducted in 1947 and started to be used in 1949. Since after, advances in technology helped improve the technique. In 1968, high volume hydraulic fracturing was started to be used, in which the fracturing volume is larger than the conventional hydraulic fracturing. After the introduction of horizontal wells in late 1980s, hydraulic fracturing started to be commonly used in horizontal wells. Horizontal wells are more effective than vertical wells because they can reach much more resources. The slickwater fluids were introduced in 1997. For these type of fluids, small amount of chemicals are added to increase the flow of fluid. These small amount of chemicals are anti-bacterial agent, corrosion inhibitor and friction reducer, which forms 0.5% of fracturing fluid. Combination of these new techniques, such as high volume fracturing, directional drilling and slickwater fracturing made the application of hydraulic fracturing commercial for high porosity, low permeability shale formations.

Even though the application of hydraulic fracturing is for tight sand, coal beds, shale formations and low permeability conventional reservoirs, its main use is in shale gas extraction. Figure below illustrates the natural gas production in United States by source, 1990 to 2040.



**Figure 1.1: Natural gas production in United States (Source: Sovacool, 2014)**

Figure 1.1 shows that the shale gas production is increasing dramatically. It shows 30% growth rate compared to 2004 which is 4% only. With the increase of energy demand, shale gas is very important as a main source of energy and hydraulic fracturing plays key role in extraction. However, due to its challenges and limitations, there is a tremendous need in search of alternatives to hydraulic fracturing.

## 1.2 Problem Statement

Hydraulic fracturing is common technique for oil and gas extraction from low permeability formations. It was thought best stimulation technique until nowadays. But its increased usage created several challenges and limitations. Major of them are large amount of water usage, requirement of high injection pressure, methane infiltration in aquifers, groundwater contamination, wastewater disposal and air pollution. During treatment from 2 to 10 million gallons of water is required for a single well. To pump such amount of water together with proppant at high pressure into thousands feet of formation is not easy. Fracturing fluid contains many chemicals and some of these chemicals are toxic. These toxic chemicals and methane gas can be contaminated with groundwater through hydraulic connectivity between deep and

shallow formations or through well annulus due to poor cementing and casing. High level of salinity, toxic elements and radioactivity makes wastewater treatment difficult and expensive. During hydraulic fracturing and extraction of shale gases, organic compounds in the shale can be mobilized which causes an air pollution.

### **1.3 Objectives**

The objectives of this project are:

- i. Review various alternatives to hydraulic fracturing.
- ii. Investigate the applicability of laser technology as an alternative to hydraulic fracturing.
- iii. Analyze penetration, specific energy and fracture formation of sandstone, shale and limestone based on laser fracturing.

### **1.4 Scope of Study**

This project focuses on application of laser technology as an alternative to hydraulic fracturing. Sandstone, shale and limestone rock samples will be used for laboratory experiments. Porosity and permeability of sandstone core samples will be measured using Poroperm equipment with the injection of helium gas at 400 psi. Different thickness of samples will be exposed to varying laser power. Penetration time of each sample with different laser power will be recorded in order to calculate penetration rate. From penetration rate, specific energy will be calculated. Also, formation of fracture will be analyzed.



## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Importance of Hydraulic Fracturing

Unconventional reservoirs did not have much importance due to their low permeability which makes their production uneconomical. Suddenly, they become one of the main energy source with advances in hydraulic fracturing. Santamarina (2011) stated that U.S. natural gas coming from shale has increased from less than 1% in 2000, to 25% in 2011. In addition, Hughes (2013) estimated that shale gas production will increase six times from 2011 to 2030. Increase in shale gas production decreases the natural gas prices. According to Coleman (2014), in United States, natural gas prices decreased by 20 % in 2013 compared to 2008.

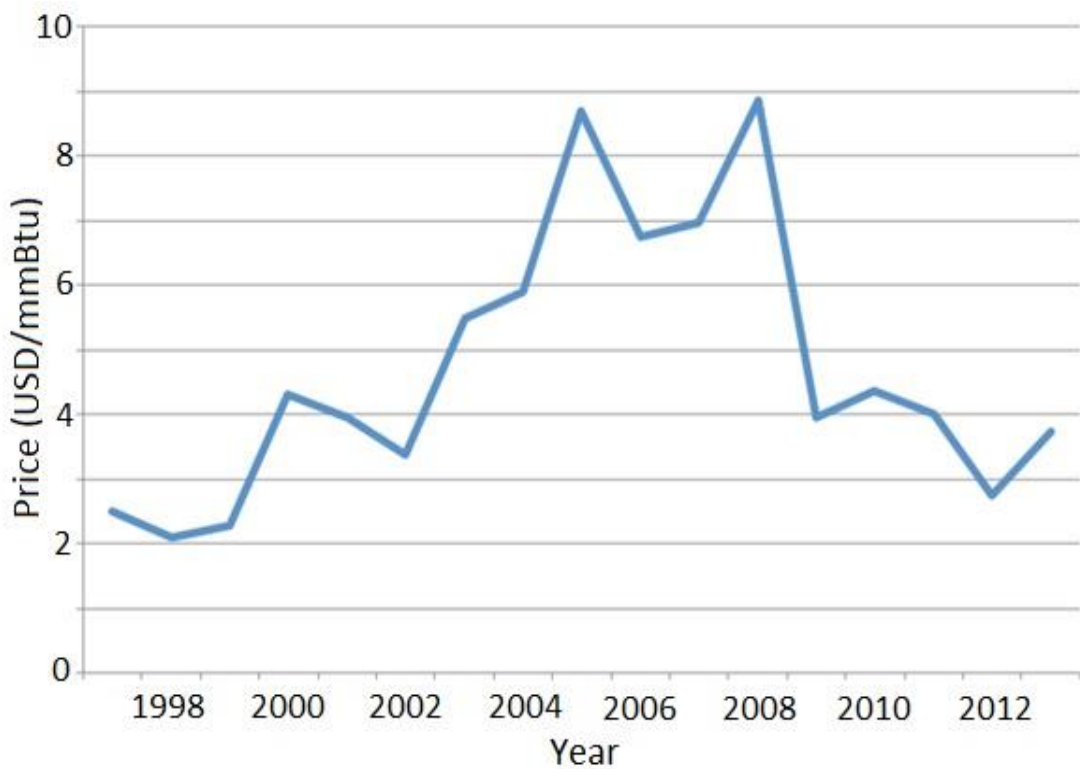


Figure 2.1: Natural gas prices in United States (Source: Coleman, 2014)

## **2.2 Challenges and Limitations of Hydraulic Fracturing**

Besides importance and benefits of hydraulic fracturing, there are some concerns raised which needs to be considered. These concerns are high injection pressure, human health and environmental worries which include large amount of water usage, methane infiltration in aquifers, groundwater contamination, wastewater disposal and air pollution.

Rahman et al (2005) investigated the unsuccessful hydraulic fracturing cases in Australia and they found that requirement of high injection pressure of large amount of water together with proppant is one of main problems encountered. Schmidt (2013) stated that in hydraulic fracturing treatment amount of water required is 3 to 7 million gallons per single well. This means for transportation around 1500 truck trips are required which will cause traffic and road repair issues. Thakur (2012) agreed that amount of water required is high but he mentioned that when compared with water demands of cities, farmers and power plants, this amount is small, only 1.6%.

Vengosh et al (2011) studied the possible contamination of drinking water wells and results showed that the wells located near (<1 km) active fracturing operation had more methane concentration than the wells located away (> 1 km) from these areas. In contrast, Saba and Orzechowski (2011) argued that other parameters could have been accountable for high methane concentration. Vengosh et al (2011) defended their studies and later published a more extensive study.

Environmental Protection Agency was barred from controlling the impact of hydraulic fracturing on ground water. In 2005, fracturing was exempted from Safe Water Drinking Act. These situations and nondisclosure of chemicals used during treatment increased doubts of people on contamination of groundwater. According to Holditch (2012), chemicals used in hydraulic fracturing operation is only 0.5% and do not contain any toxic elements. In contrary, Department of Environmental Conservation released the chemicals and additives which is used during treatment and after that, study of Earthworks (2012) showed some of these chemicals are toxic, such as kerosene, methanol, formal dehyde, hydrochloric acid and sodium hydroxide.

Theodori et al (2014) stated that 70% flowback water which is injected during fracturing operation returns back during few weeks of treatment with produced water that is naturally present in the formation. These waste water contains high amount of salinity, radioactivity and toxic elements makes their disposal challenging. Vengosh et al (2013) pointed out that waste water contains toxic element like barium and salinity can be up to 300 000 mg/l.

Air pollution is another concern of hydraulic fracturing. Shale contains many organic hydrocarbons and during the hydraulic fracturing many chemicals are added that can mobilize and escape to atmosphere. After waste water is collected in surface ponds, organic compounds from water like methanol will be emitted to atmosphere which causes air pollution (Volz et al., 2010). In addition, Colborn et al (2011) expressed that 37% of chemicals used during hydraulic fracturing process is volatile, which has ability to become an airborne.

## 2.3 Alternatives to Hydraulic Fracturing

### 2.3.1 Explosive Fracturing

One of the old method of fracturing the well without using liquid fluid is explosive fracturing that was commonly used between 1860s and 1940s. This method is effective but dangerous. Several problems encountered, such as wellbore damage and safety hazard. Introduction of formation fracturing using propellant were another factor that reduced the use of explosive fracturing. Schmidt et al (1980) stated that propellants have advantages over explosives which they deflagrate rather than detonate.

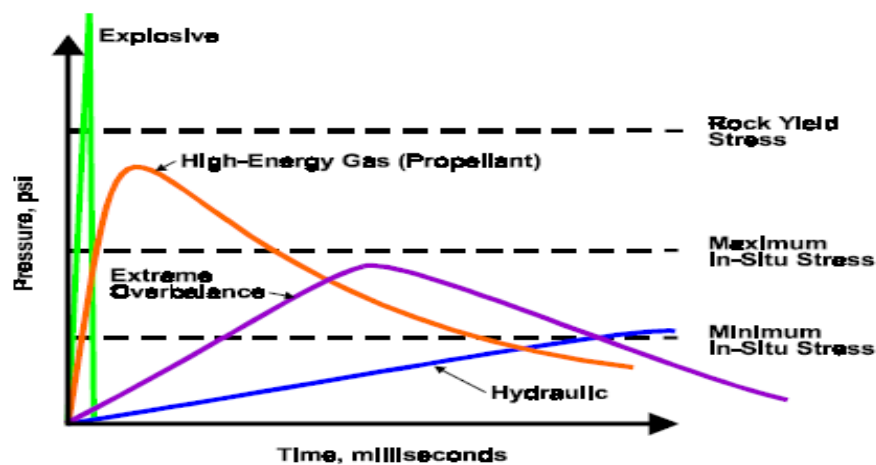


Figure 2.2: Comparison of various fracture stimulation techniques (Source: Advanced Resources International, Inc., 1999)

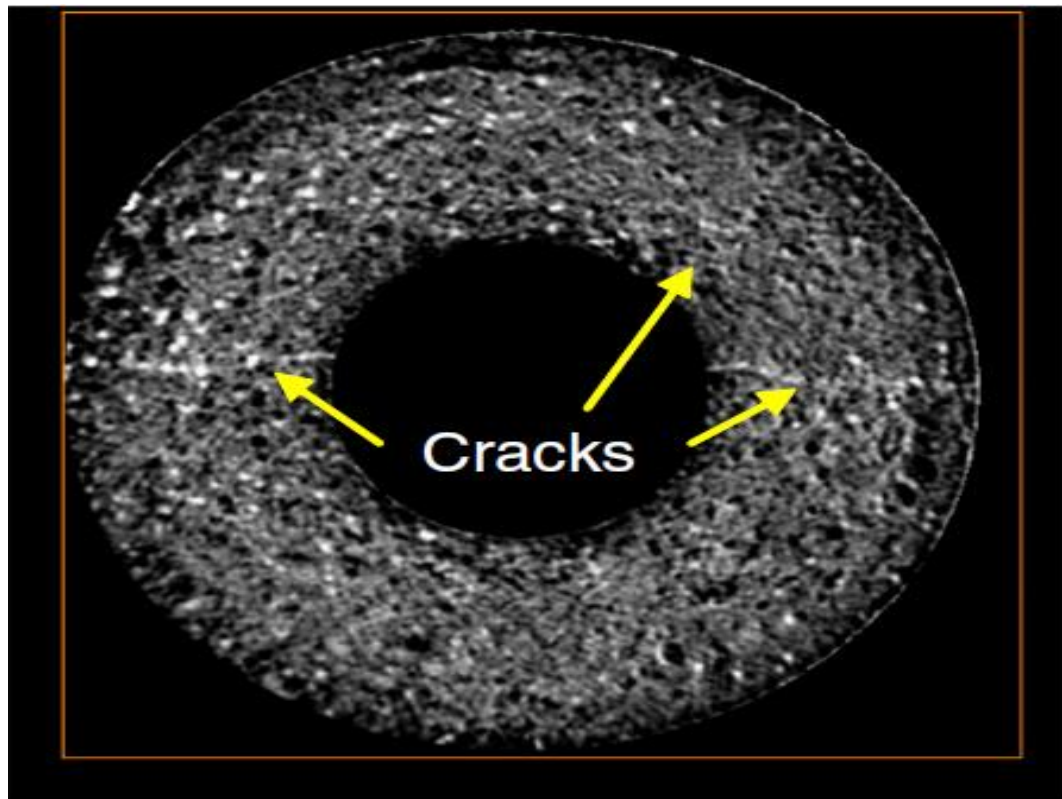
### 2.3.2 Electrical Fracturing

Another alternative to hydraulic fracturing is electrical fracturing that uses induced mechanical loads into rock. Melton and Cross (1967) conducted tests on mine tunnel to analyze the electrical fracturing. Nine horizontal boreholes were drilled at the side of the tunnel. Boreholes were separated from each other by 3 to 129 ft. For the test from 12000V to 20000V voltages were used. After the test, Melton and Cross (1967) concluded that additional experiments are required to accept the feasibility of electrical fracturing because fractures were observed only near distances from borehole.



**Figure 2.3: Piece of electrically fractured shale sample  
(Source: Melton and Cross, 1967)**

Chen et al (2012) studied the effect of electrical fracturing with laboratory experiments. 18 cm long and 12.5 cm diameter cylindrical specimen with 5 cm hole at the middle was immersed in water and electrical shock was applied. Results showed micro fractures near the hole.



**Figure 2.4: CT scan of sample after electrical fracturing  
(Source: Chen et al., 2012)**

Kalaydjian and Goffé (2012) reported that currently this technique is not viable alternative because permeability increases only few meters from wellbore. They also considered electric installations and managements as other challenges.

### **2.3.3 Nitrogen Gas Fracturing**

Abel (1981) stated that nitrogen gas was used for the fracturing of Ohio shales. Ohio shales are encountered between 2 000 ft to 4 000 ft. Production rate of these formations are very low due to their low permeability which ranges from 0.0001 md to 0.01 md. Due to this low production, stimulation technique is needed. He showed 5 wells which was stimulated using nitrogen gas. Summary of results are presented below.

**Table 2.1: Five stimulated Ohio shale wells using nitrogen gas.**

| Well<br>_No | Depth<br>(ft) | N <sub>2</sub><br>volume<br>(scf) | N <sub>2</sub> rate<br>(scf/min) | Surface<br>treating<br>pressure (Psi) | Oil production<br>(bbl/d) |       | Gas production<br>(Mcf/d) |       |
|-------------|---------------|-----------------------------------|----------------------------------|---------------------------------------|---------------------------|-------|---------------------------|-------|
|             |               |                                   |                                  |                                       | Before                    | After | Before                    | After |
| 1           | 2 482         | 370 000                           | 24 600                           | 1 745                                 | New well                  | 85    | —                         | —     |
| 2           | 3 535         | 360 000                           | 28 500                           | 2 495                                 | 26                        | 94    | 46                        | 92    |
| 3           | 3 425         | 720 000                           | 17 760                           | 2 345                                 | 15                        | 50    | —                         | —     |
| 4           | 3 454         | 354 000                           | 27 330                           | 2 545                                 | 26.3                      | 116   | 64                        | 77    |
| 5           | 3 396         | 320 000                           | 24 600                           | 2 380                                 | —                         | —     | 9                         | 830   |

Evans et al (1982) tested nitrogen gas fracturing on Devonian shale series of eastern U.S. For the study Black No. 1 well was used which was offered for research purposes by the owners of the well after decline in production. Nitrogen gas was injected into 1100 ft deep Black No. 1. The well had 7 inch diameter. It was cased up to 1055 ft and perforated between 1000-1030 ft intervals. Stimulation operation lasted 27 minutes and 968 000 scf of nitrogen gas was injected. Wellhead temperature was 115°F and pressure 1 300 psi. Results showed that during 16 minutes of injection, horizontal fracture propagated more than 650 ft. After 16 minutes, fracture started to propagate vertically with the length of more than 330 ft.

Li et al (2000) conducted a laboratory experiment using cement targets to analyze the gas fracturing treatment. 5.5 inch casing with different perforations was inserted inside the target which has 2.6 meters diameter and 1 meter height. After the experiment, results showed that multiple fractures can be achieved using a gas.

Bachman (2010) mentioned that nitrogen fracturing is preferred method for coal seams in the Horseshoe Canyon play in Alberta. Treatment achieved by pumping pressurized nitrogen into formation for the short periods of time from 2 to 4 minutes. Results from both tiltmeter and microseismic images showed the fractures for horizontal and vertical components.

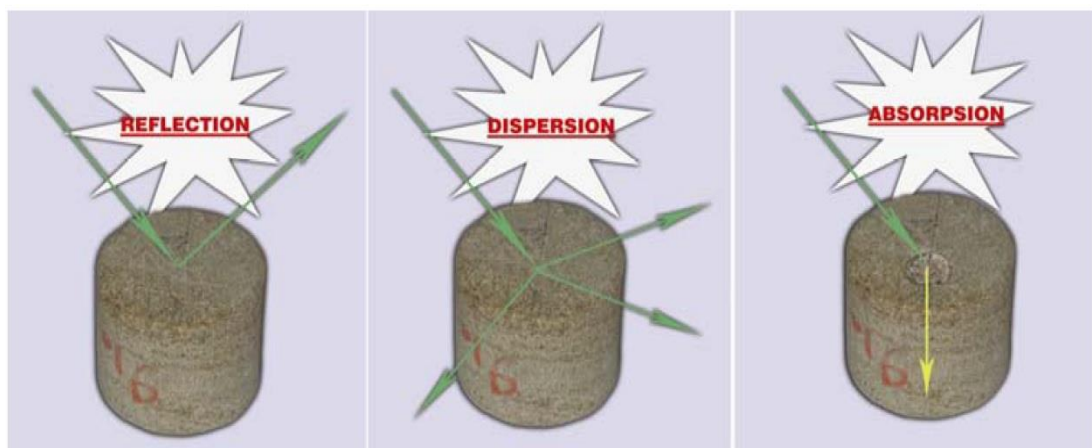
For water sensitive formations, nitrogen will prevent the clay swelling which is one of main problems for slickwater fracturing. However, low density and low viscosity of nitrogen makes it poor proppant carrier and increases the required pumping pressure. Gandossi (2013) stated that application of this technique only for shallow formations.

### 2.3.4 Cryogenic Fracturing

Cryogenic fracturing uses cold fluids to achieve the formation fracture. Even liquid fluid is used in this technique, it is not considered as hydraulic fracturing because injected pressure is lower than the formation rock strength. Unlike other techniques, in this technique pressure is not the main factor which fractures the formation but cold fluids like liquid CO<sub>2</sub> or nitrogen. Mueller et al (2012) presented a method that combines hydraulic fracturing with thermal shock fracturing that is caused by the injection of cold liquid CO<sub>2</sub>. They also indicated that long time is required for the initiation of formation fracturing. Continuous injection of liquid CO<sub>2</sub> is required for several years and production would start after 2 years from the beginning of treatment. Requirement of large quantity of liquid CO<sub>2</sub> is another challenge of this technique.

### 2.3.5 Laser Fracturing

There are 2 methods to destroy rocks namely, mechanical and thermal. Mechanical method is when the induced stress exceeds rock's internal strength. Thermal method is when applied heat exceeds the melting temperature of minerals that are present in the composition of rock. Laser destroys rocks in 3 ways: spallation, melting and vaporizing due to the increase in local temperature. When laser beams radiated to rock surfaces, they will be reflected, distributed and absorbed.



**Figure 2.5: Reaction of laser beams when in contact with rock surfaces  
(Source: Bakhtbidar et al, 2011)**

The laser-rock interaction efficiency is determined due to specific energy (SE). SE is common unit used for laser-rock interaction. It can be defined by Behrmann (1995):

$$SE = \frac{E}{V} \quad (2.1)$$

where,

SE: Specific energy (kJ/cc)

E: Energy input (kJ)

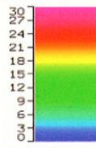
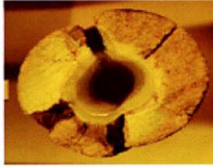
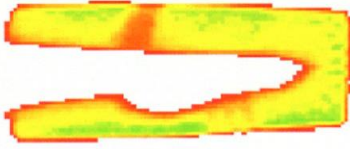
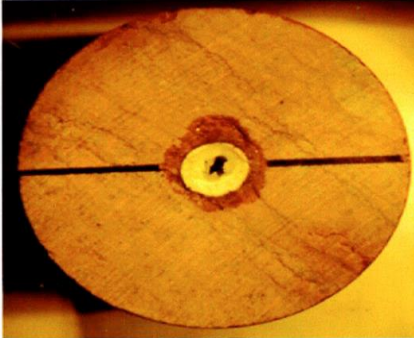
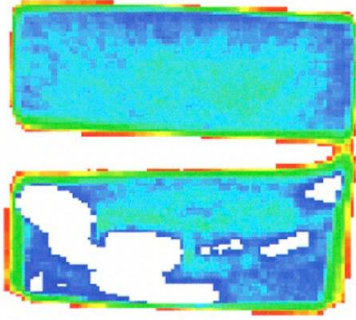


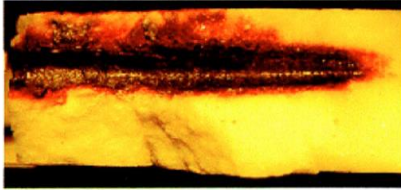
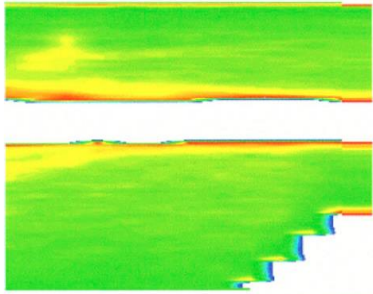
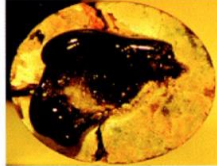
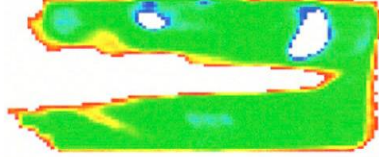

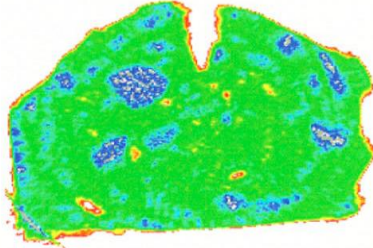
V: Volume removed (cc)

Specific energy shows the energy consumed to remove a cubic centimeter of rock. Lower values of specific energy indicate less energy consumed, hence more efficient and vice versa.

The researches on application of high power laser has been advancing in many areas and formation fracturing is one of them. It has several advantages such as controlling rock phase, shape, depth, diameter and orientation of the hole. These findings are results of several researches.

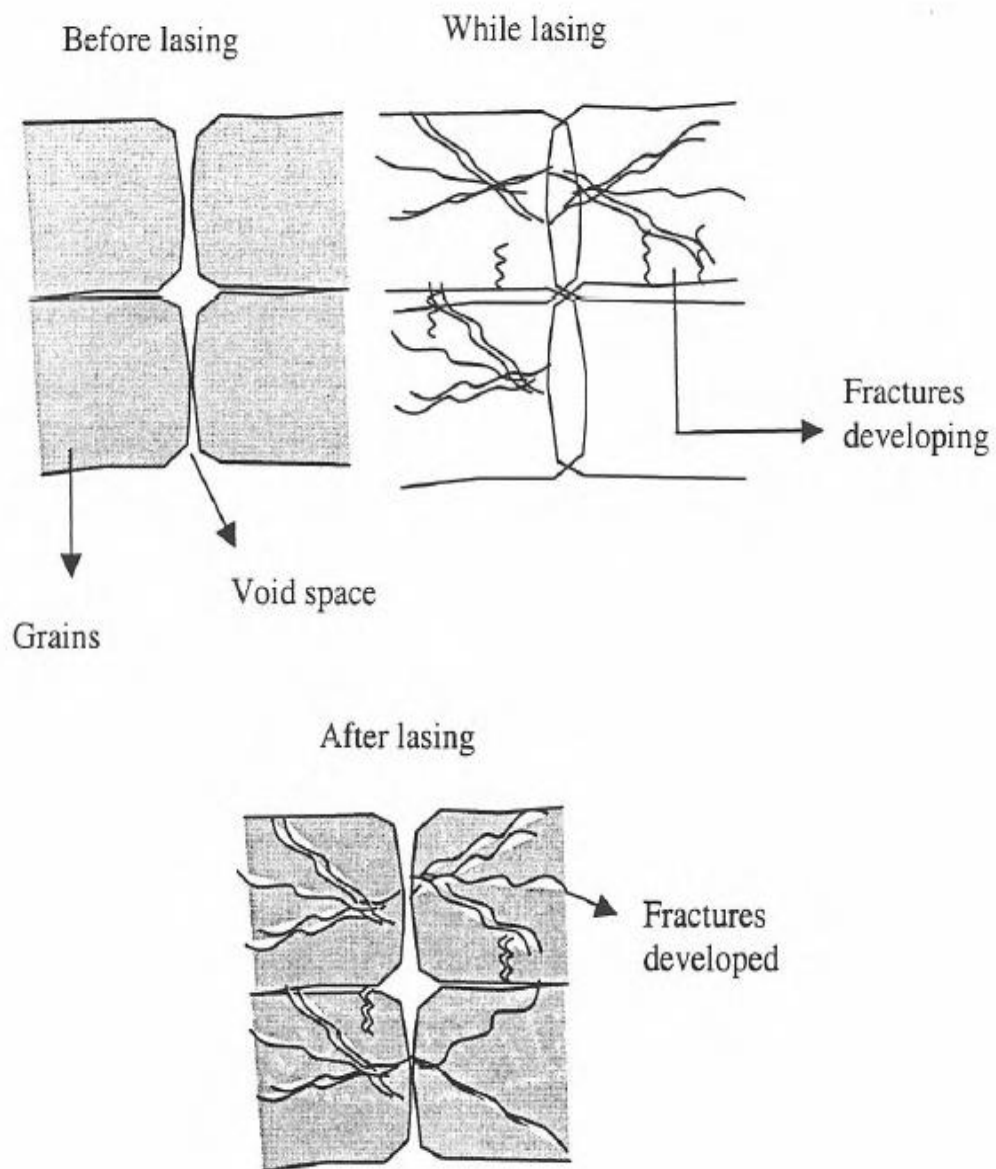
Graves et al (1999) conducted laboratory tests at U.S. Air Force's high power laser research facility using high power Chemical Oxygen-Iodine Laser (COIL). More than 100 rock samples were tested under varying laser power.



| <b>Photographs and CT Scans of<br/>COIL Irradiated Rocks<br/>Laser Beam Diameter = 0.25"</b>   |   |    |
|--|---|---|
| <b>Description</b>   | <b>Photograph</b>   | <b>CT Scan (% Porosity)</b>   |
| <b>Sandstone</b><br>Sample ID: 2SS+2Y1<br>Formation: Mesaverde<br>Core Diameter: 1"<br>Core Length: 2"<br>Duration: 8.0 sec<br>Power: 6.4 kW<br>Penetration: 1.7"                    |    |    |
| <b>Limestone</b><br>Sample ID: LS4T1<br>Formation: Ratcliff<br>Core Diameter: 2"<br>Core Length: 2"<br>Duration: 5.0 sec<br>Power: 6.6 kW<br>Penetration: 2.0"                       |    |    |
| <b>Shale</b><br>Sample ID: 2SH2B<br>Formation: Mesaverde<br>Core Diameter: 1"<br>Core Length: 2"<br>Duration: 7.9 sec<br>Power: 5.6 kW<br>Penetration: 1.8"                          |   |   |
| <b>Salt</b><br>Sample ID: Salt1<br>Source: Surface<br>Core Diameter: 2"<br>Core Length: 4"<br>Duration: 5.8 sec<br>Power: 6.7 kW<br>Penetration: 3.9"                                |  |  |
| <b>Granite</b><br>Sample ID: GR1X<br>Source: Surface<br>Core Diameter: 1"<br>Core Length: 2"<br>Duration: 8.0 sec<br>Power: 6.4 kW<br>Penetration: 1.7"                              |  |  |
| <b>Concrete</b><br>Sample ID: Concrete 1<br>Source: Hanford<br>Sample Length: 6"<br>Sample Width: 6"<br>Sample Height: 4"<br>Duration: 8.0 sec<br>Power: 5.0 kW<br>Penetration: 1.4" |  |  |

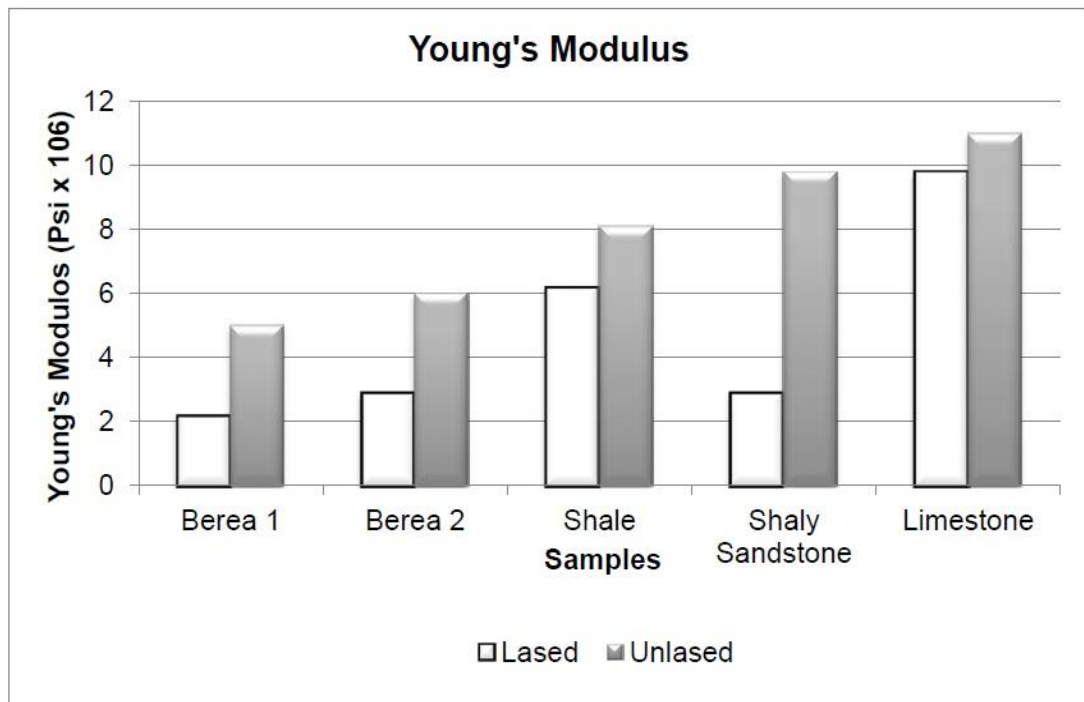
**Figure 2.6: Photograph and CT scan of different lased rocks  
(Source: Graves et al, 1999)**

Batarseh (2001) tested several rock samples using high laser power varying from 2 kW up to 6 kW. Results showed that high power laser can penetrate all rock types regardless of their compressive strength and hardness. Also fractures were observed in sandstone and shale.



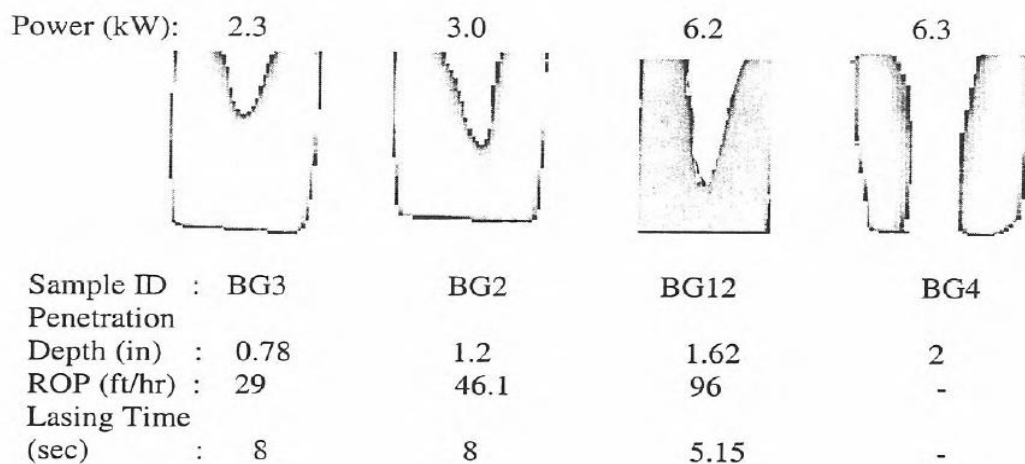
**Figure 2.7: Fracture development before, during and after lasing (Source: Batarseh, 2001)**

Batarseh's study (2001) showed decrease in Young's Modulus of rock after lasing, which means laser reduces the strength of rock. Young's Modulus is the resistance of rock to deformation. According to Batarseh (2001), the reduction in Young's Modulus is due to the fracturing, dehydration and decomposing of some minerals.

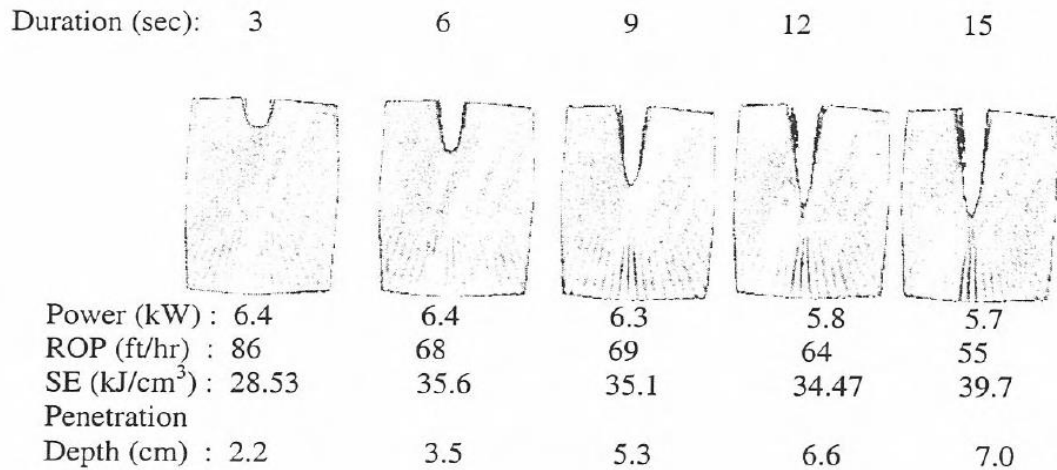


**Figure 2.8: Comparison of Young's Modulus before and after lasing (Source: Batarseh, 2001)**

The length of penetration is directly proportional to lasing time and laser power while keeping diameter constant to optimize the penetration. Batarseh (2001) presented both relationships in his work.

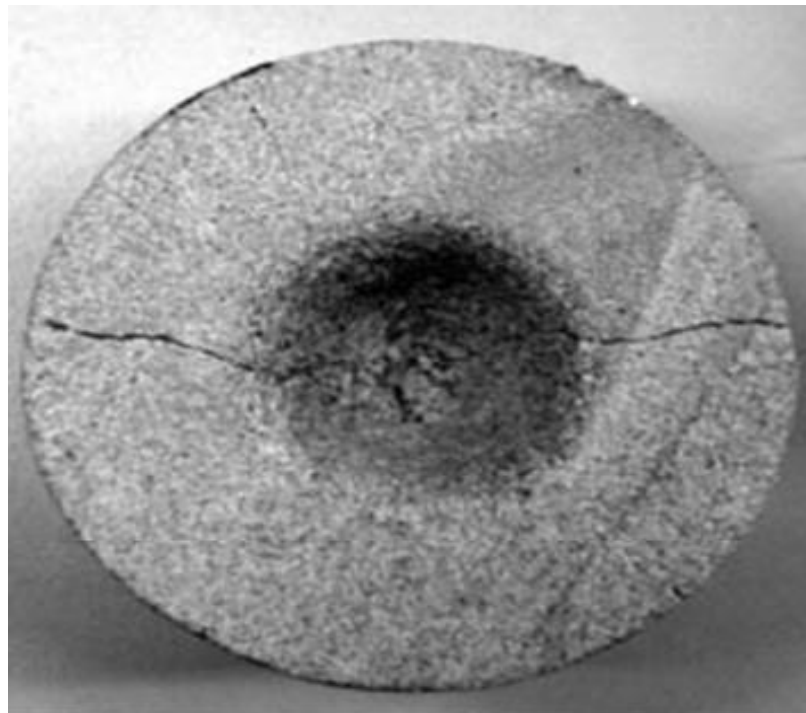


**Figure 2.9: Effect of laser power on penetration depth of Berea sandstone (Source: Batarseh, 2001)**



**Figure 2.10: Effect of lasing time on length of penetration for Berea sandstone (Source: Batarseh, 2001)**

Xu et al (2004) conducted several experiments using 1.6 kW Nd:YAG laser for different sandstone rock samples to see and analyze the formation fracture initiation and length of penetration. From the results it was clear to observe formation fractures.



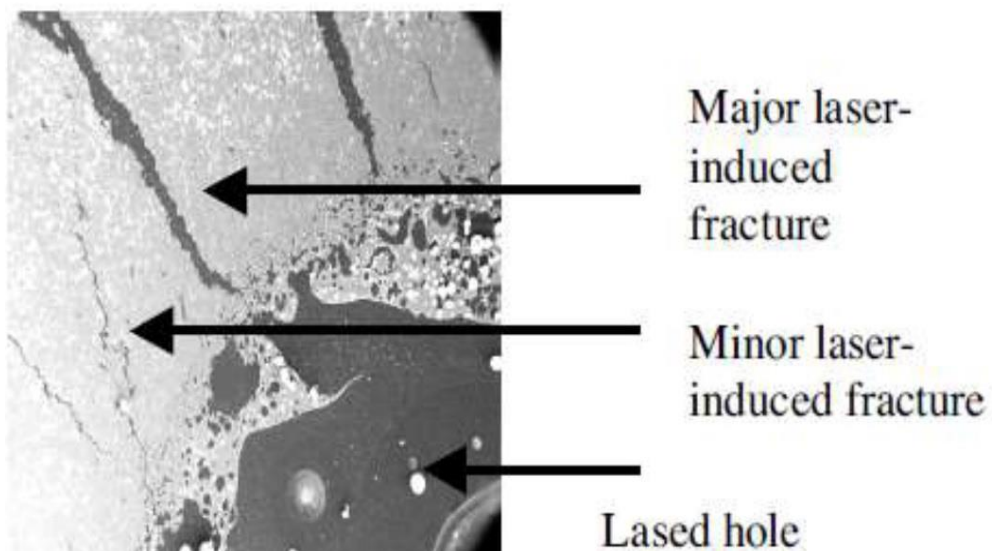
**Figure 2.11: Fracture of sandstone sample exposed to 1.6 kW Nd:YAG laser (Source: Xu et al, 2004)**

According to Xu et al (2004), when sandstone core is exposed to 1.6 kW Nd:YAG laser for 80 seconds, a hole of 25 mm diameter and 100 mm length was penetrated.



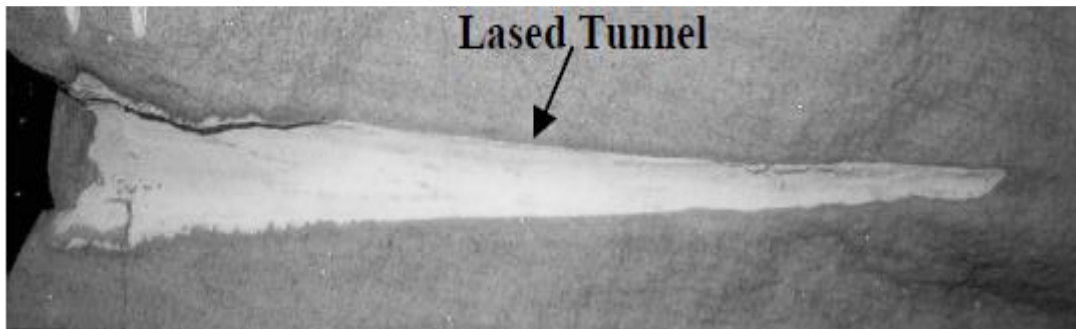
**Figure 2.12: Penetrated sandstone core exposed to 1.6 kW Nd:YAG laser (Source: Xu et al, 2004)**

In addition, Graves and Bailo (2005) presented the results of their study in which it was clear to see fractures from SEM image of shale rock sample.



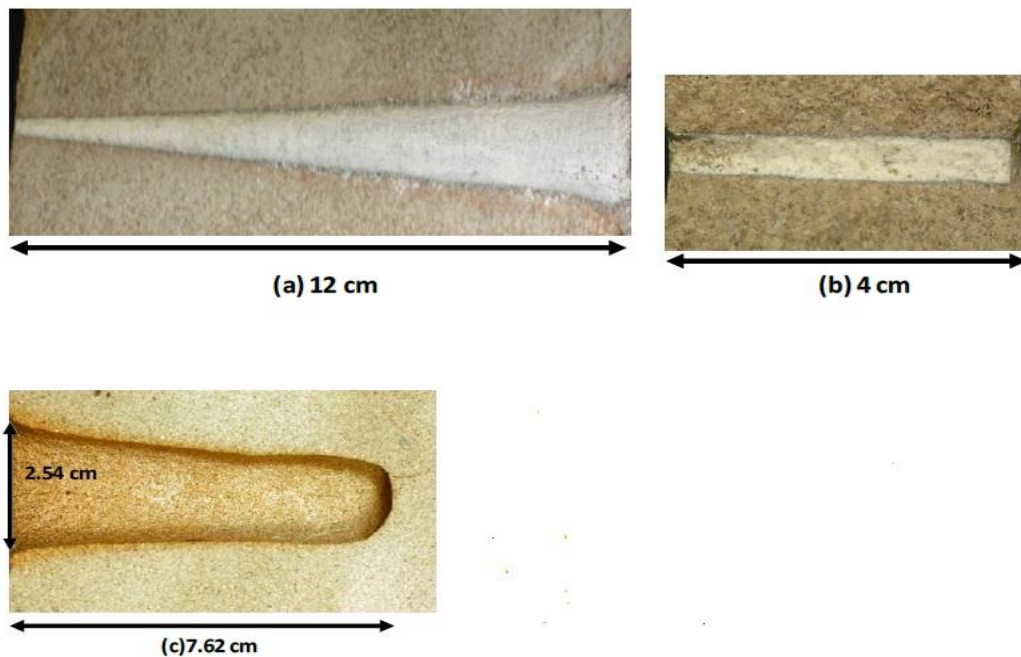
**Figure 2.13: SEM image of lased shale showing fractures (Source: Graves and Bailo, 2005)**

Gahan and Batarseh (2005) showed that a hole with 50 mm diameter and 310 mm length was created when limestone core was exposed to 5.34 kW fiber laser.



**Figure 2.14: Penetrated limestone core exposed to 5.34 kW fiber laser (Source: Gahan and Batarseh, 2005)**

The shape, dimension and diameter of the hole can be controlled by using different types of lenses with different focal points. Conical hole can be generated from focused beam and cylindrical hole can be generated from collimated beam (Iraj, Gahan and Batarseh, 2007)



**Figure 2.15: Different hole geometries of conical (a) and cylindrical (b and c) shapes (Source: Iraj, Gahan and Batarseh, 2007)**

Bakhtbidar et al (2011) conducted laboratory tests using 700W laser for limestone, shale and sandstone. Presented results showed that the 2-3 mm hole was penetrated with 1 cm diameter in 66 seconds.



**Figure 2.16: Penetrated rock samples with laser, left to right: Limestone, shale and sandstone (Source: Bakhtbidar et al, 2011)**

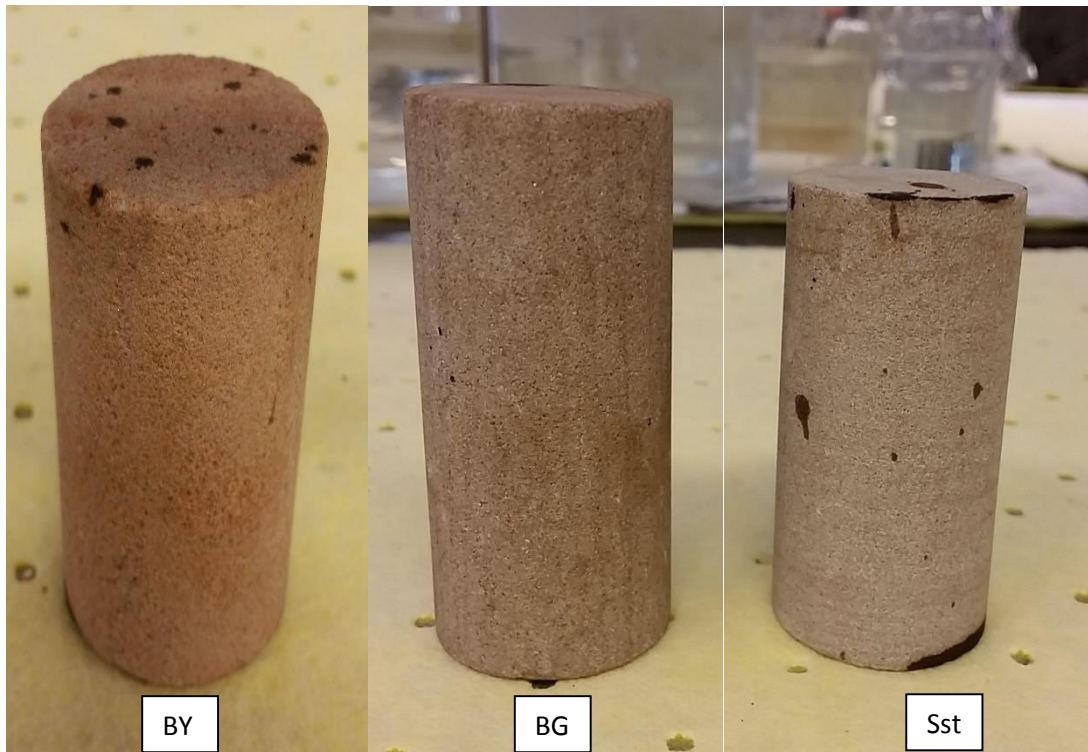
## CHAPTER 3

### METHODOLOGY

#### 3.1 Experimentation

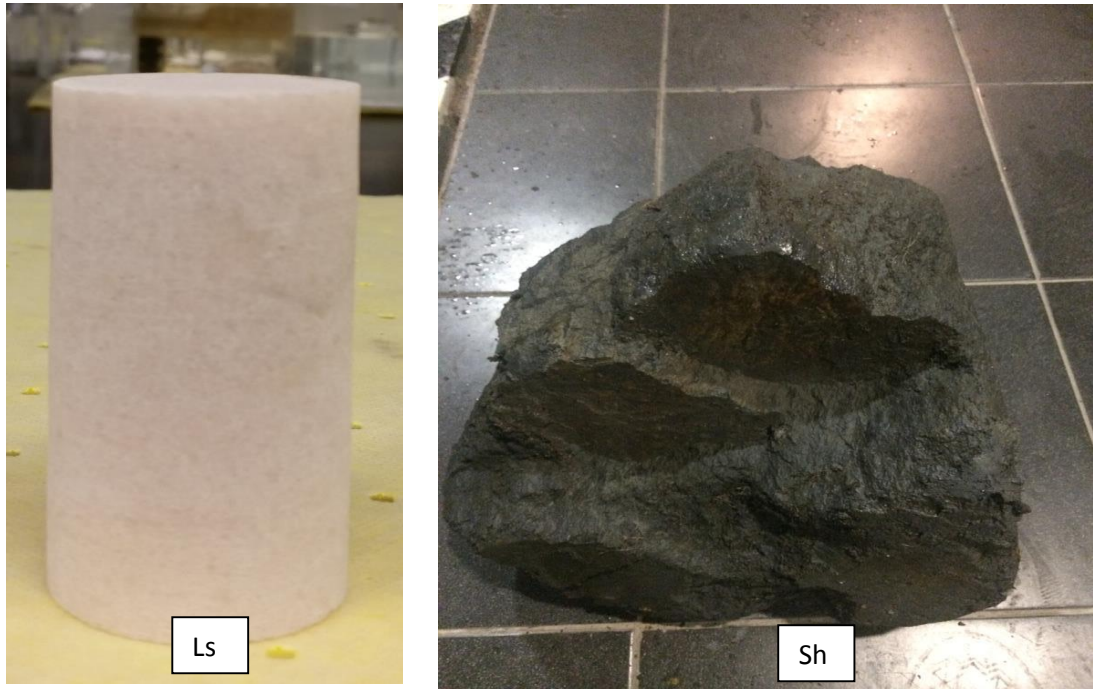
##### 3.1.1 Preparation of Rock Samples

For the laboratory tests Berea yellow sandstone, Berea gray sandstone, shaly sandstone, Shale and Limestone were used. Sandstone and limestone samples were obtained from core analysis laboratory of Universiti Teknologi Petronas (UTP) and shale samples from shale outcrops in Batu Gajah.



**Figure 3.1: Sandstone core samples**





**Figure 3.2: Limestone (left) and shale (right) rock samples**

where,

BY: Berea yellow sandstone

BG: Berea gray sandstone

Sst: Shaly sandstone

Ls: Limestone

Sh: Shale

### **3.1.2 Measurement of Core Sample Properties**

After obtaining rock samples, properties of sandstone core samples were measured using Poroperm equipment by injection of helium gas at 400 psi. These properties are used when analyzing fracture and penetration rate after laser experiment. Procedure of the measurement was as below:

1. Weight and dimensions of first core sample was measured and placed into coreholder.
2. The valves of were opened and pressure increased to 400 psi.
3. New file was opened and “info” sheet was selected.
4. The fields sample ID, diameter, length and weight were filled for each sample.

5. Porosity and permeability were chose for measurement.
6. Measurement was started by clicking “start measure” button.
7. Measurement results were noted.
8. Same operations were repeated for the rest of the samples.



**Figure 3.3: Poroperm equipment**

### 3.1.3 Cutting of Rock Samples

Each rock sample were cut into 4 different pieces with 2, 4, 6, 8 mm size using Trimming Machine. Lapping and Polishing Machine were used to produce precision flat polished surfaces. Procedure of cutting and polishing:

1. Machine were switched on.
2. Specimen was placed and positioned to grinding wheel (cutting line was marked).
3. The wise was fastened.
4. “Start” button was pressed.
5. The table was moved towards the cutting wheel by pushing the front hand wheel.
6. After cutting is finished “Stop” button was pressed and specimen was polished.
7. Same steps were repeated for the rest of the samples.



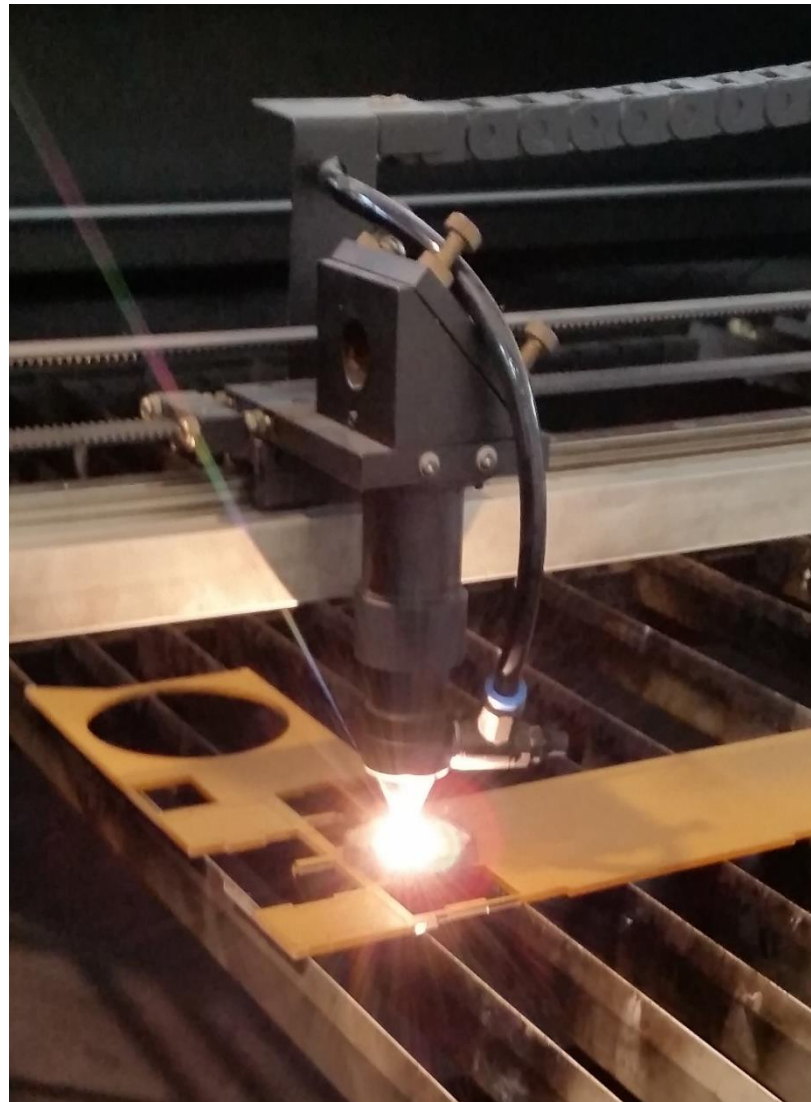
**Figure 3.4: Trimming (left) and Lapping, Polishing (right) Machine.**

### 3.1.4 Penetration of Samples with Laser

Maximum power of the laser is 150W and rock samples were tested with 75W, 90W, 105W, 120W and 135W. Diameter of the laser beam was kept constant as 2mm. Time

taken to penetrate the rock samples with each power was recorded. Procedure of the experiment was:

1. Power supply was switched on.
2. Power pump was switched on and water flow was smooth.
3. First piece of rock sample was put into the machine.
4. 8mm gap was set between rock sample and nozzle of laser.
5. The origin was set and the machine was pre-run.
6. Laser was switched on and the time was measured to penetrate the rock sample with 75W, 90W, 105W, 120W and 135W, respectively.
7. Same procedure was repeated for other pieces of rock samples.
8. Laser, water pump and entire machine were switched off after experiment was completed.



**Figure 3.5: Lasing of samples with laser machine**

### 3.2 Tools/Equipments Required

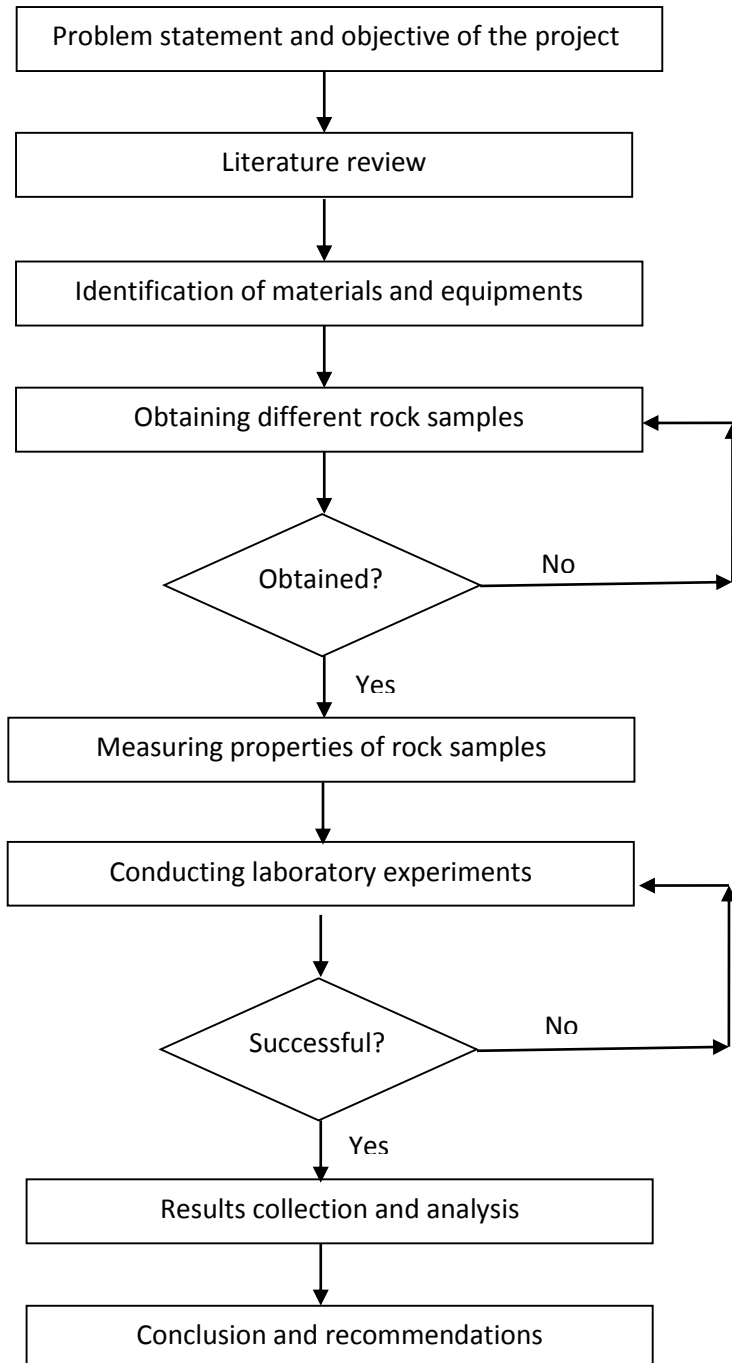
Several tools and equipments will be used to complete this project, the following table shows these tools with brief description about the usage of each tool.

**Table 3.1: List of tools/equipments**

| <b>Tools/Equipments</b>       | <b>Description</b>  |
|-------------------------------|---|
| Rock samples                  | Used to test laser fracturing                                       |
| Caliper                       | Used to measure the thickness, length and diameter of rock samples. |
| Scale                         | Used to measure the weight of core samples                          |
| Poroperm                      | Used to measure properties of core samples                          |
| Helium gas                    | Used to inject into core samples when measuring properties          |
| Trimming Machine              | Used to cut and trim rock samples                                   |
| Lapping and Polishing Machine | Used to produce smooth, flat polished surface                       |
| Laser machine                 | Used to penetrate the rock samples                                  |
| 8mm spacer                    | Used to set 8mm gap between sample and laser nozzle                 |
| Stopwatch                     | Used to record penetration time                                     |

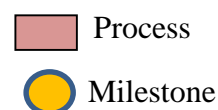
### 3.3 Process Flow Chart

Figure below describes the sequence of work load performed in order to complete the project on time. The parts of the flow chart listed below were performed during Final Year Project 1 and 2 courses.






**Figure 3.6: Flow chart**








### 3.4 Gantt Chart and Key Milestones



**Table 3.2: Gantt chart and milestones for FYP I**

| Details/Weeks                           | 1 | 2 | 3 | 4 | 5 | 6   | 7 | 8 | 9 | 10 | 11 | 12 | 13  | 14   |
|---|---|---|---|---|---|---|---|---|---|----|----|----|---|--|
| Selection of Project Topic              |   |   |   |   |   |   |   |   |   |    |    |    |   |  |
| Research Work                           |   |   |   |   |   |   |   |   |   |    |    |    |   |  |
| Materials and Equipments Identification |   |   |   |   |   |   |   |   |   |    |    |    |   |  |
| Extended Proposal Submission            |   |   |   |   |   |  |   |   |   |    |    |    |   |  |
| Proposal Defence                        |   |   |   |   |   |   |   |   |   |    |    |    |   |  |
| Continuation of Project Work            |   |   |   |   |   |   |   |   |   |    |    |    |   |  |
| Submission of Interim Draft Report      |   |   |   |   |   |   |   |   |   |    |    |    |  |  |
| Interim Report Submission               |   |   |   |   |   |   |   |   |   |    |    |    |   |  |

**Table 3.3: Gantt chart and milestones for FYP II**

| Details/Weeks                                 | 1 | 2 | 3 | 4 | 5 | 6 | 7   | 8   | 9 | 10 | 11 | 12  | 13 | 14  | 15  |
|---|---|---|---|---|---|---|---|---|---|----|----|---|----|---|---|
| Project Work Continues with Laboratory Tests  |   |   |   |   |   |   |   |   |   |    |    |   |    |   |   |
| Progress Report Submission                    |   |   |   |   |   |   |  |   |   |    |    |   |    |   |   |
| Pre-SEDEX                                     |   |   |   |   |   |   |   |  |   |    |    |   |    |   |   |
| Final Report Draft Submission                 |   |   |   |   |   |   |   |   |   |    |    |  |    |   |   |
| Soft Bound Submission of Project Dissertation |   |   |   |   |   |   |   |   |   |    |    |  |    |   |   |
| Technical Paper Submission                    |   |   |   |   |   |   |   |   |   |    |    |  |    |   |   |
| Viva  |   |   |   |   |   |   |   |   |   |    |    |   |    |  |   |
| Hard Bound Submission of Project Dissertation |   |   |   |   |   |   |   |   |   |    |    |   |    |   |  |

## CHAPTER 4

### RESULTS AND DISCUSSION

#### 4.1 Measurement of Sandstone Core Sample Properties

The properties of sandstone core samples were measured using Poroperm and results are presented in Table 4.1. Sandstone core samples had same diameter but different length (Figure 4.1).

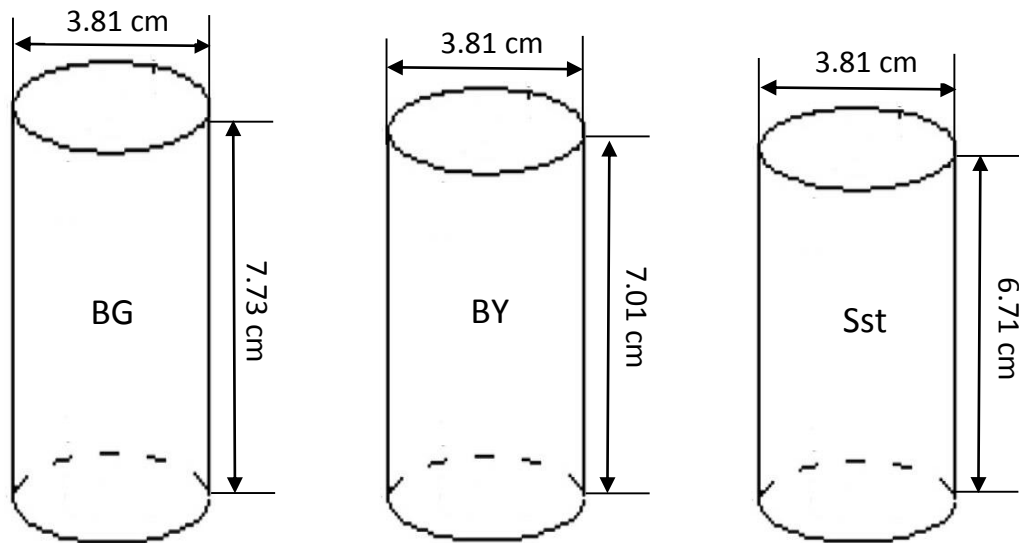


Figure 4.1: Dimensions of sandstone core samples

Table 4.1: Measured properties of sandstone core samples

| Core sample | Grain volume (cc) | Bulk volume (cc) | Pore volume (cc) | Grain density (g/cc) | Bulk density (g/cc) | Porosity (%) | Permeability (md) |
|-------------|-------------------|------------------|------------------|----------------------|---------------------|--------------|-------------------|
| BY          | 63.2              | 79.4             | 16.2             | 2.6                  | 2.06                | 20.4         | 917               |
| BG          | 70.8              | 86.9             | 16.0             | 2.65                 | 2.16                | 18.5         | 138               |
| Sst         | 62.7              | 77.2             | 14.5             | 2.65                 | 2.15                | 18.8         | 39                |

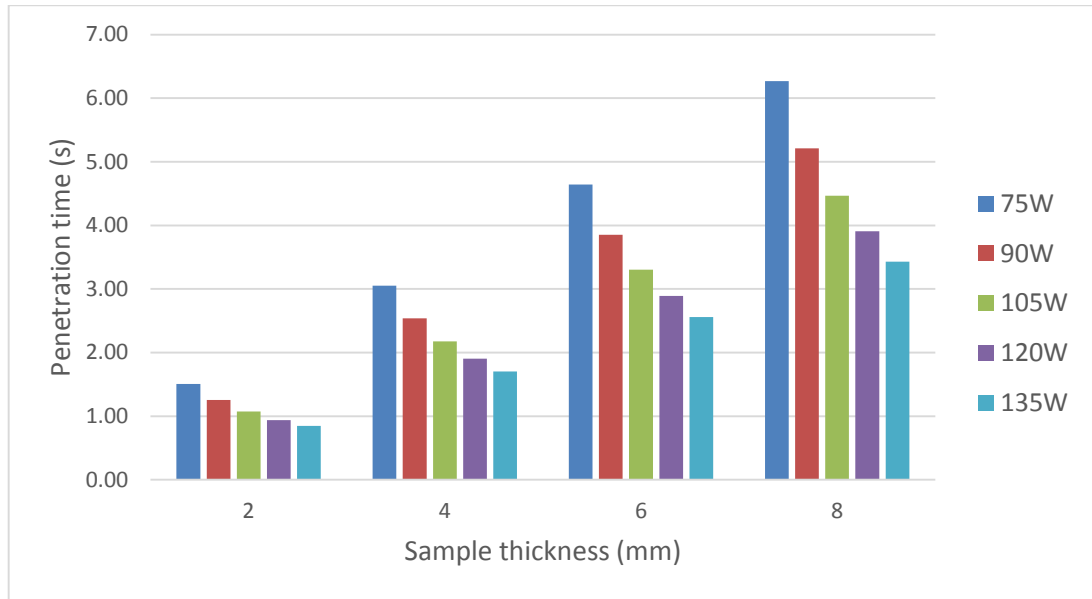
#### 4.2 Effect of Laser Power and Sample Thickness on Penetration Time (PT)

These tests were performed using laser machine. 2mm, 4mm, 6mm and 8mm pieces of each Limestone, Berea gray sandstone, shale, shaly sandstone and Berea yellow sandstone samples were exposed to 75W, 90W, 105W, 120W and 135W laser beam. Results showed that as the laser power decreases and sample thickness increases, penetration time increases for all rock types (Table 4.2-Table 4.6 and Figure 4.2 - Figure 4.6).

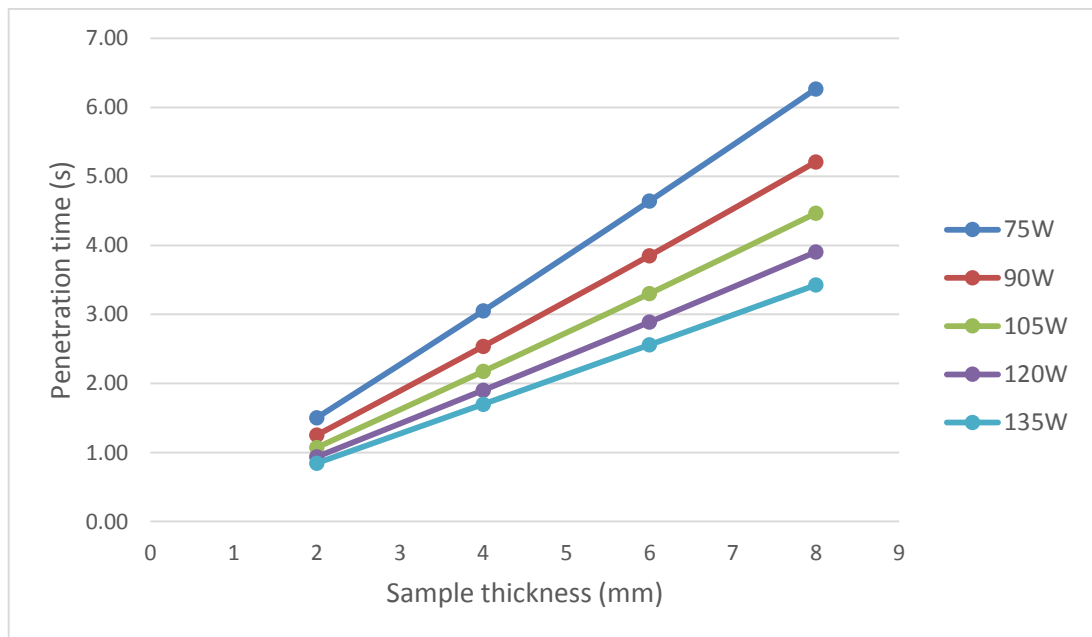


**Table 4.2: Penetration time for different thickness of limestone under varying laser power.**

| Thickness (mm) | Penetration time (s) |      |      |      |      |
|----------------|----------------------|------|------|------|------|
|                | 75W                  | 90W  | 105W | 120W | 135W |
| 2              | 1.50                 | 1.25 | 1.07 | 0.94 | 0.85 |
| 4              | 3.05                 | 2.54 | 2.17 | 1.90 | 1.70 |
| 6              | 4.64                 | 3.85 | 3.30 | 2.89 | 2.56 |
| 8              | 6.27                 | 5.21 | 4.47 | 3.91 | 3.43 |



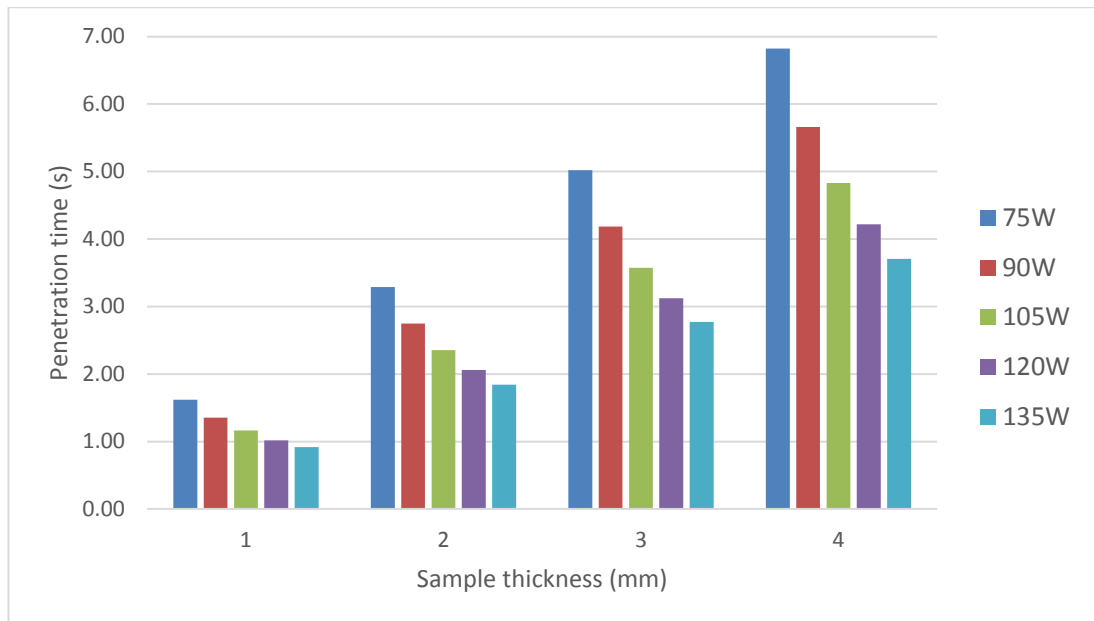
**Figure 4.2a: Effect of sample thickness and laser power on penetration time for limestone.**



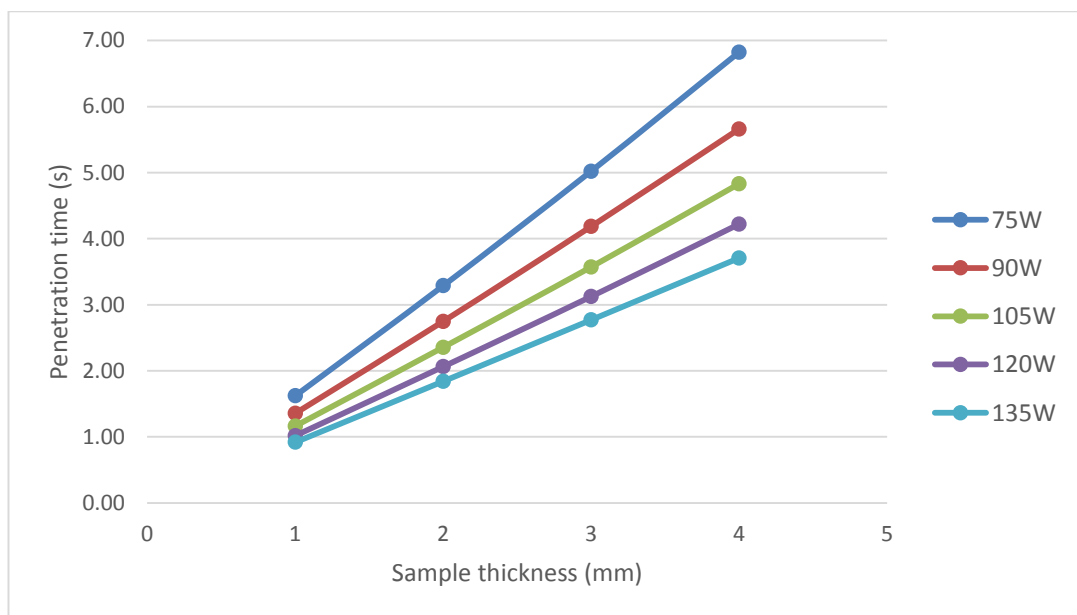
**Figure 4.2b: Effect of sample thickness and laser power on penetration time for limestone.**

**Table 4.3: Penetration time for different thickness of BG sandstone under varying laser power.**

| Thickness (mm) | Penetration time (s) |      |      |      |      |
|----------------|----------------------|------|------|------|------|
|                | 75W                  | 90W  | 105W | 120W | 135W |
| 2              | 1.62                 | 1.36 | 1.16 | 1.02 | 0.92 |
| 4              | 3.29                 | 2.75 | 2.36 | 2.06 | 1.84 |
| 6              | 5.02                 | 4.19 | 3.57 | 3.12 | 2.77 |
| 8              | 6.82                 | 5.66 | 4.83 | 4.22 | 3.71 |



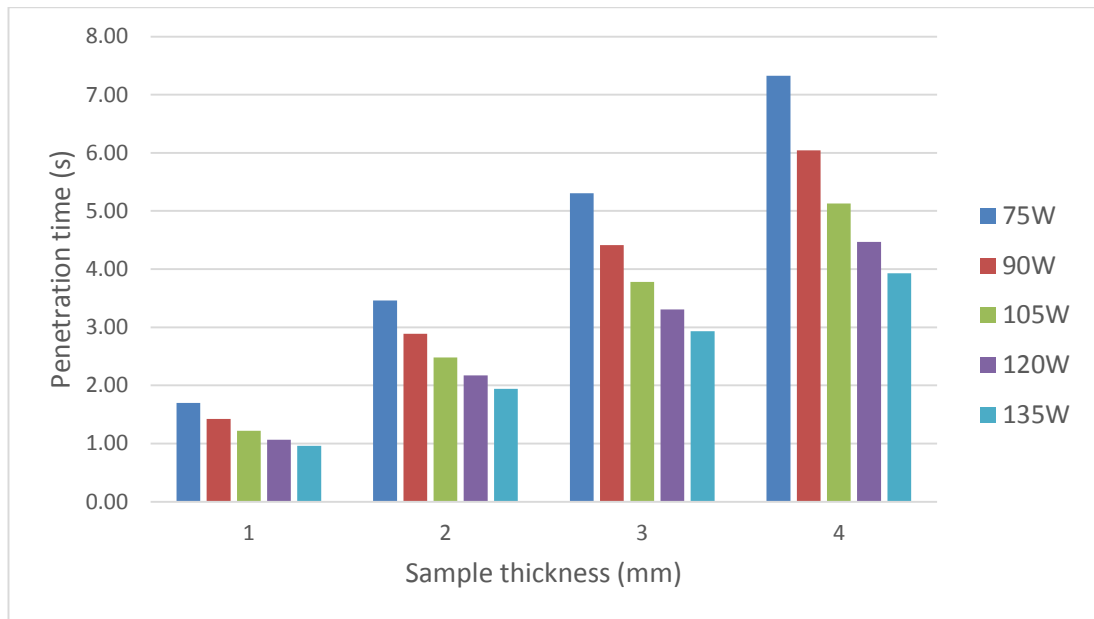
**Figure 4.3a: Effect of sample thickness and laser power on penetration time for BG sandstone.**



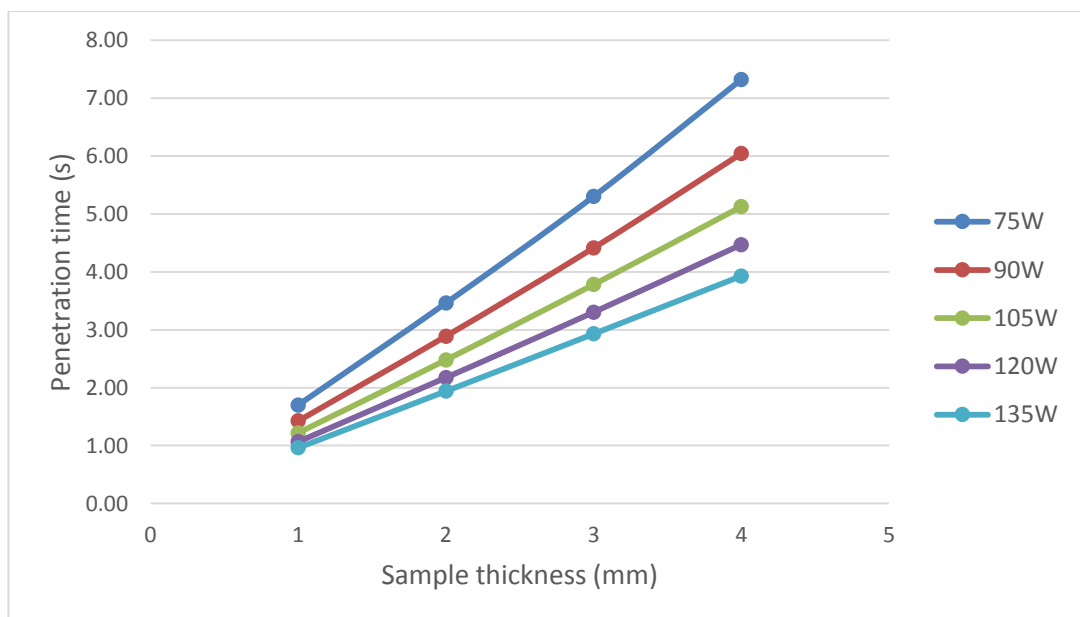
**Figure 4.3b: Effect of sample thickness and laser power on penetration time for BG sandstone.**

**Table 4.4: Penetration time for different thickness of shale under varying laser power.**

| Thickness (mm) | Penetration time (s) |      |      |      |      |
|----------------|----------------------|------|------|------|------|
|                | 75W                  | 90W  | 105W | 120W | 135W |
| 2              | 1.70                 | 1.43 | 1.22 | 1.07 | 0.96 |
| 4              | 3.46                 | 2.89 | 2.48 | 2.17 | 1.94 |
| 6              | 5.30                 | 4.42 | 3.78 | 3.30 | 2.93 |
| 8              | 7.32                 | 6.05 | 5.13 | 4.47 | 3.93 |



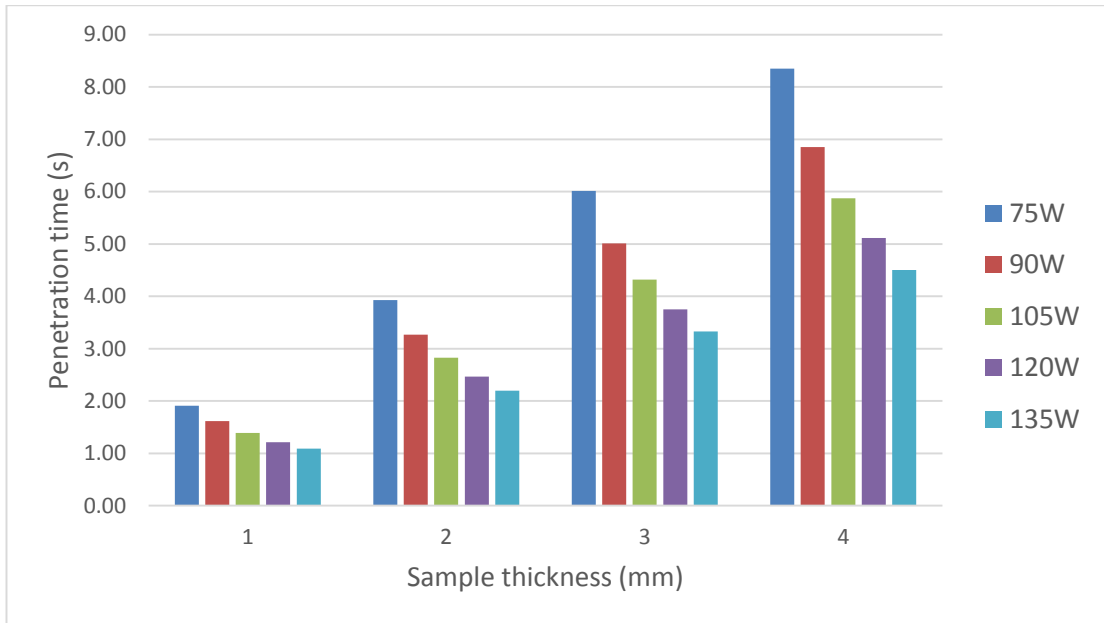
**Figure 4.4a: Effect of sample thickness and laser power on penetration time for shale.**



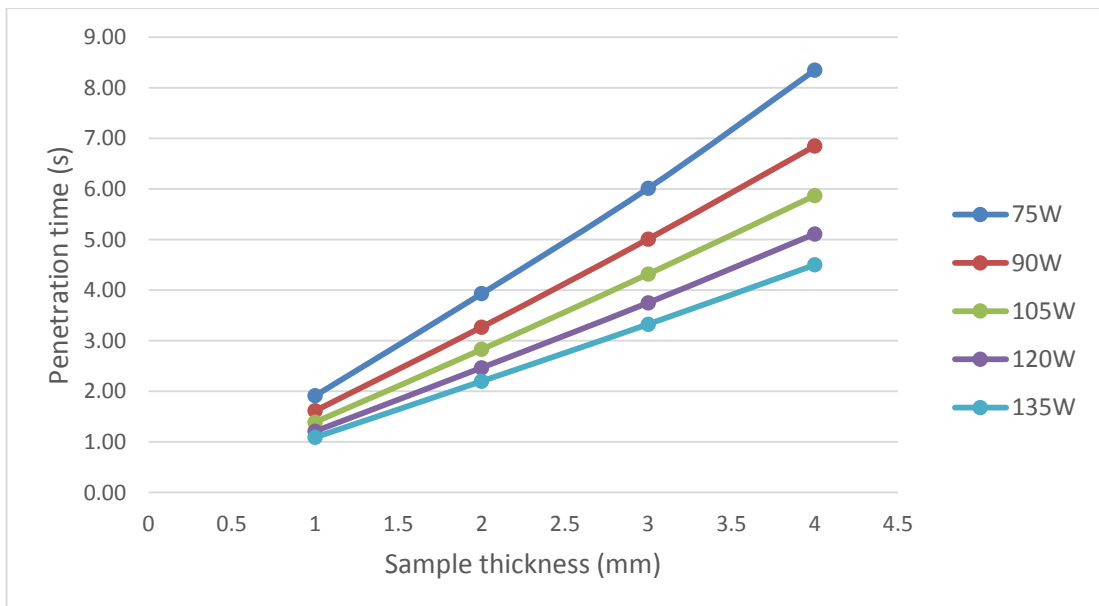
**Figure 4.4b: Effect of sample thickness and laser power on penetration time for shale.**

**Table 4.5: Penetration time for different thickness of Sst sandstone under varying laser power.**

| Thickness (mm) | Penetration time (s) |      |      |      |      |
|----------------|----------------------|------|------|------|------|
|                | 75W                  | 90W  | 105W | 120W | 135W |
| 2              | 1.91                 | 1.62 | 1.39 | 1.21 | 1.09 |
| 4              | 3.93                 | 3.27 | 2.83 | 2.47 | 2.20 |
| 6              | 6.02                 | 5.01 | 4.32 | 3.75 | 3.33 |
| 8              | 8.35                 | 6.85 | 5.87 | 5.11 | 4.50 |



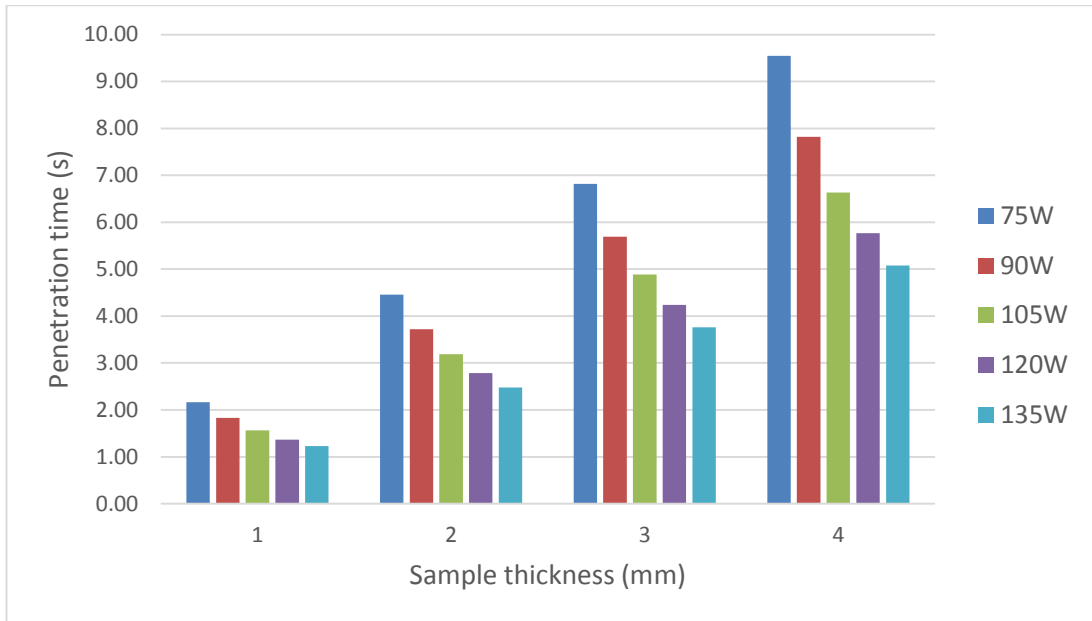
**Figure 4.5a: Effect of sample thickness and laser power on penetration time for Sst sandstone.**



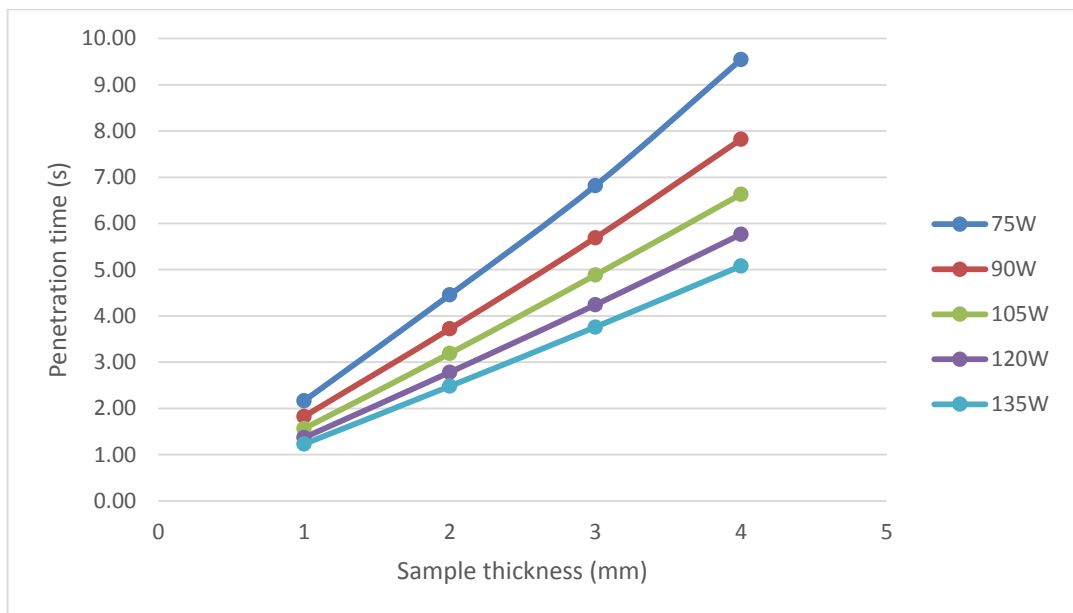
**Figure 4.5b: Effect of sample thickness and laser power on penetration time for Sst sandstone.**

**Table 4.6: Penetration time for different thickness of BY sandstone under varying laser power.**

| Thickness (mm) | Penetration time (s) |      |      |      |      |
|----------------|----------------------|------|------|------|------|
|                | 75W                  | 90W  | 105W | 120W | 135W |
| 2              | 2.16                 | 1.83 | 1.57 | 1.37 | 1.23 |
| 4              | 4.45                 | 3.72 | 3.19 | 2.78 | 2.48 |
| 6              | 6.82                 | 5.69 | 4.88 | 4.24 | 3.76 |
| 8              | 9.54                 | 7.82 | 6.63 | 5.77 | 5.08 |



**Figure 4.6a: Effect of sample thickness and laser power on penetration time for BY sandstone.**



**Figure 4.6b: Effect of sample thickness and laser power on penetration time for BY sandstone.**

### 4.3 Effect of Laser Power and Sample Thickness on Penetration Rate (PR)

Penetration rate of samples were calculated by dividing sample thickness to penetration time (Equation 4.1). The unit of sample thickness were converted from millimeter (mm) to foot (ft) and time from second (s) to hour (hr) in order to present the results in ft/hr.

$$PR = \frac{h}{t} \quad (4.1)$$

where,

PR: Penetration rate (ft/hr)

h: Sample thickness (ft)

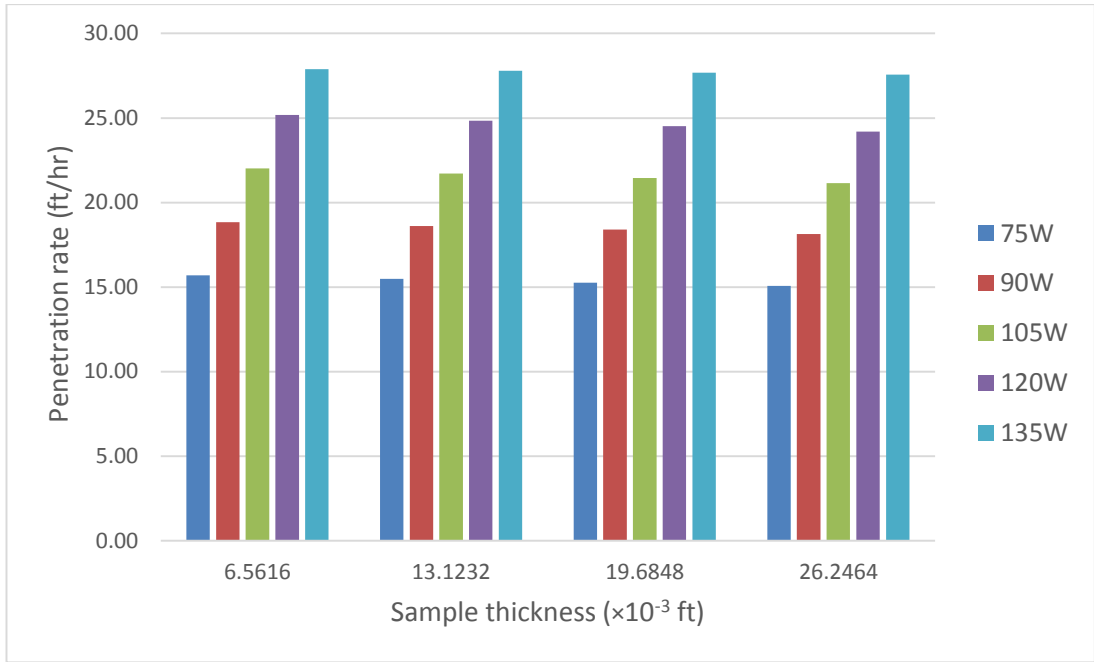
t: Penetration time (hr)

Results indicated that penetration rate increases with the increase of laser power regardless of rock type (Table 4.7 – Table 4.11 and Figure 4.7 – Figure 4.11). More laser power means more heat transfer and less penetration time. As penetration time decreases, penetration rate increases (Equation 4.1). On the other hand, for the constant laser power there is slightly decrease in penetration rate when sample thickness increases (Table 4.7 – Table 4.11 and Figure 4.7 – Figure 4.11). Higher thickness of samples require more penetration time. More penetration time indicate more plasma formation and gases in the lased hole that results to more energy loss. As the hole gets deeper, effect of purging decreases.

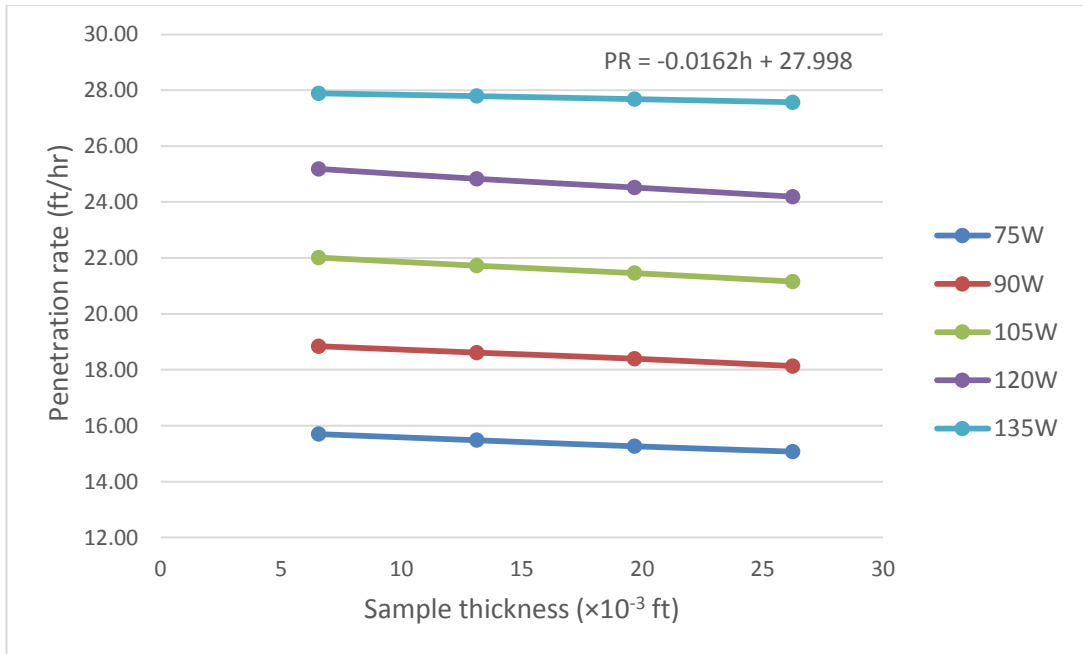
Equation of penetration rate as a function of sample thickness was calculated for each sample which will be used for correlations (Figure 4.7b, 4.8b, 4.9b, 4.10b and 4.11b).

**Table 4.7: Penetration rate of different thickness of limestone under varying laser power.**

| Thickness (mm) | Thickness ( $\times 10^{-3}$ ft) | Penetration rate (ft/hr) |       |       |       |       |
|----------------|----------------------------------|--------------------------|-------|-------|-------|-------|
|                |                                  | 75W                      | 90W   | 105W  | 120W  | 135W  |
| 2              | 6.5616                           | 15.70                    | 18.84 | 22.01 | 25.19 | 27.89 |
| 4              | 13.1232                          | 15.48                    | 18.61 | 21.72 | 24.83 | 27.79 |
| 6              | 19.6848                          | 15.26                    | 18.40 | 21.46 | 24.52 | 27.68 |
| 8              | 26.2464                          | 15.07                    | 18.13 | 21.16 | 24.19 | 27.57 |



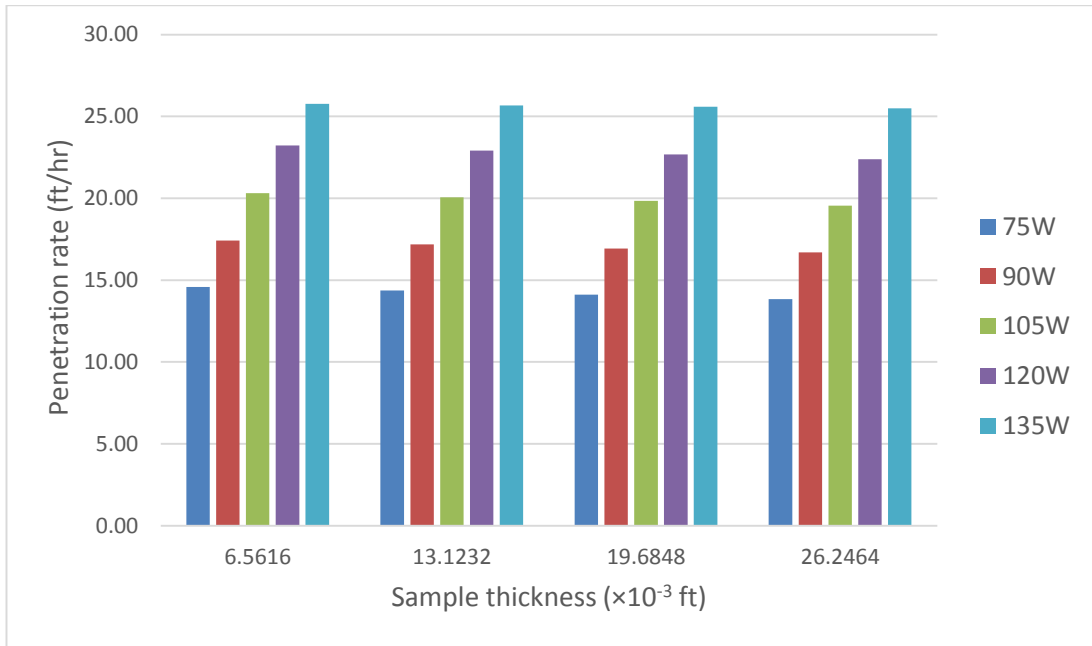
**Figure 4.7a: Effect of sample thickness and laser power on penetration rate for limestone.**



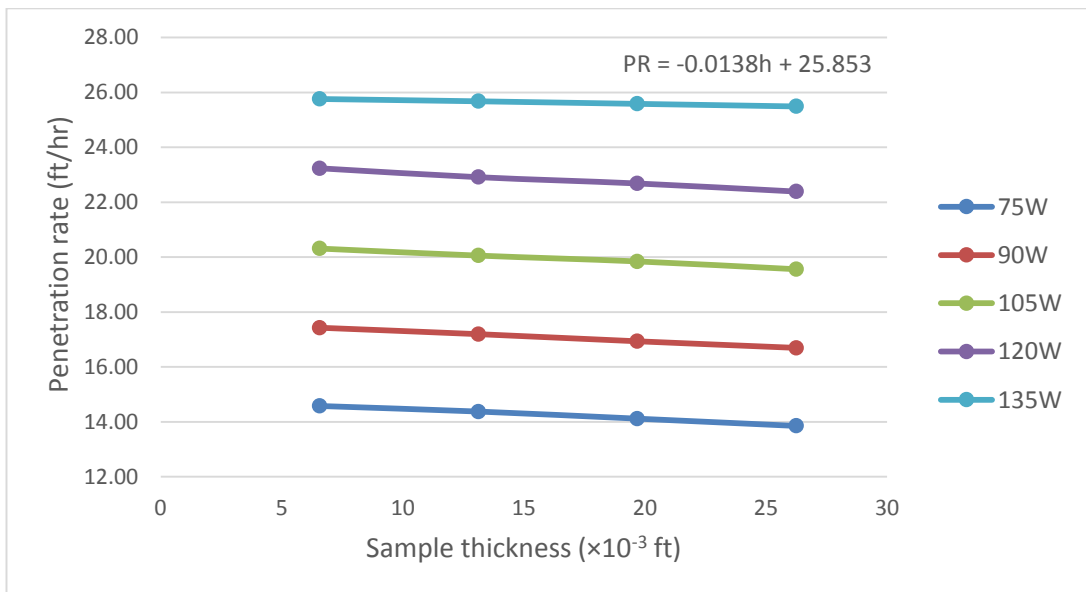
**Figure 4.7b: Effect of sample thickness and laser power on penetration rate for limestone.**

**Table 4.8: Penetration rate of different thickness of BG sandstone under varying laser power.**

| Thickness (mm) | Thickness ( $\times 10^{-3}$ ft) | Penetration rate (ft/hr) |       |       |       |       |
|----------------|----------------------------------|--------------------------|-------|-------|-------|-------|
|                |                                  | 75W                      | 90W   | 105W  | 120W  | 135W  |
| 2              | 6.5616                           | 14.58                    | 17.43 | 20.31 | 23.24 | 25.76 |
| 4              | 13.1232                          | 14.37                    | 17.19 | 20.05 | 22.91 | 25.68 |
| 6              | 19.6848                          | 14.11                    | 16.93 | 19.84 | 22.68 | 25.58 |
| 8              | 26.2464                          | 13.85                    | 16.69 | 19.56 | 22.39 | 25.49 |



**Figure 4.8a: Effect of sample thickness and laser power on penetration rate for BG sandstone.**

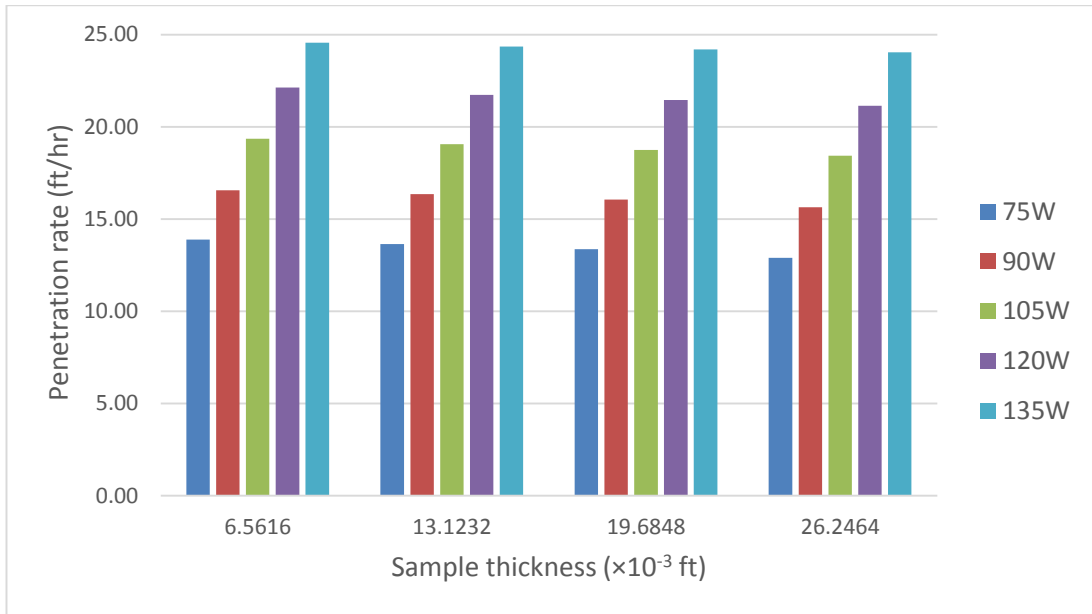


**Figure 4.8b: Effect of sample thickness and laser power on penetration rate for BG sandstone.**

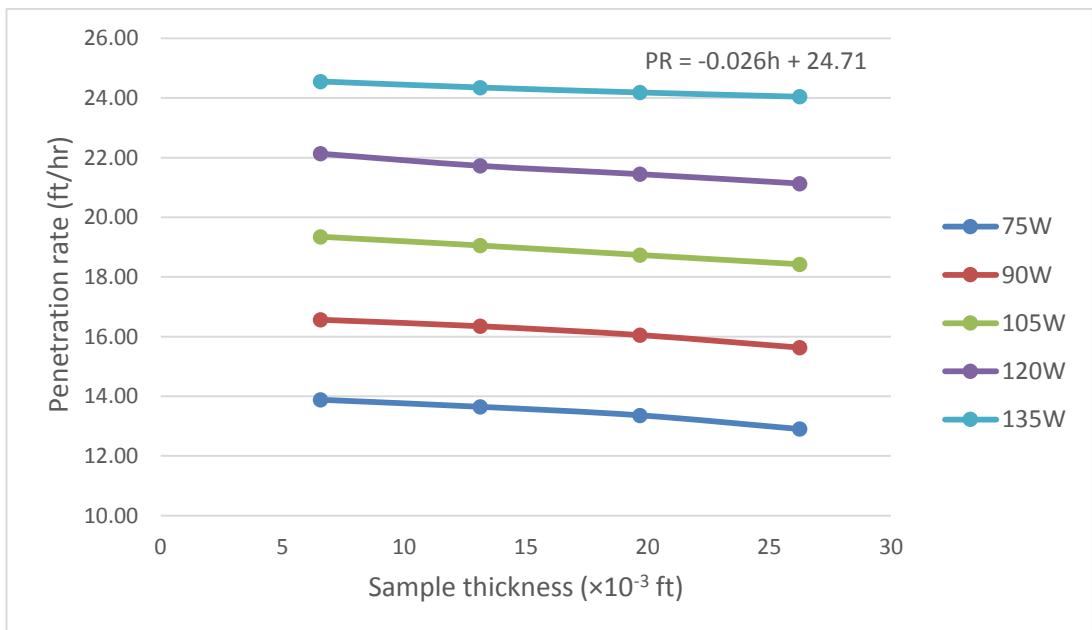


**Table 4.9: Penetration rate of different thickness of shale under varying laser power.**

| Thickness (mm) | Thickness ( $\times 10^{-3}$ ft) | Penetration rate (ft/hr) |       |       |       |       |
|----------------|----------------------------------|--------------------------|-------|-------|-------|-------|
|                |                                  | 75W                      | 90W   | 105W  | 120W  | 135W  |
| 2              | 6.5616                           | 13.88                    | 16.57 | 19.35 | 22.13 | 24.55 |
| 4              | 13.1232                          | 13.65                    | 16.35 | 19.06 | 21.73 | 24.35 |
| 6              | 19.6848                          | 13.36                    | 16.05 | 18.74 | 21.45 | 24.19 |
| 8              | 26.2464                          | 12.90                    | 15.63 | 18.43 | 21.13 | 24.04 |



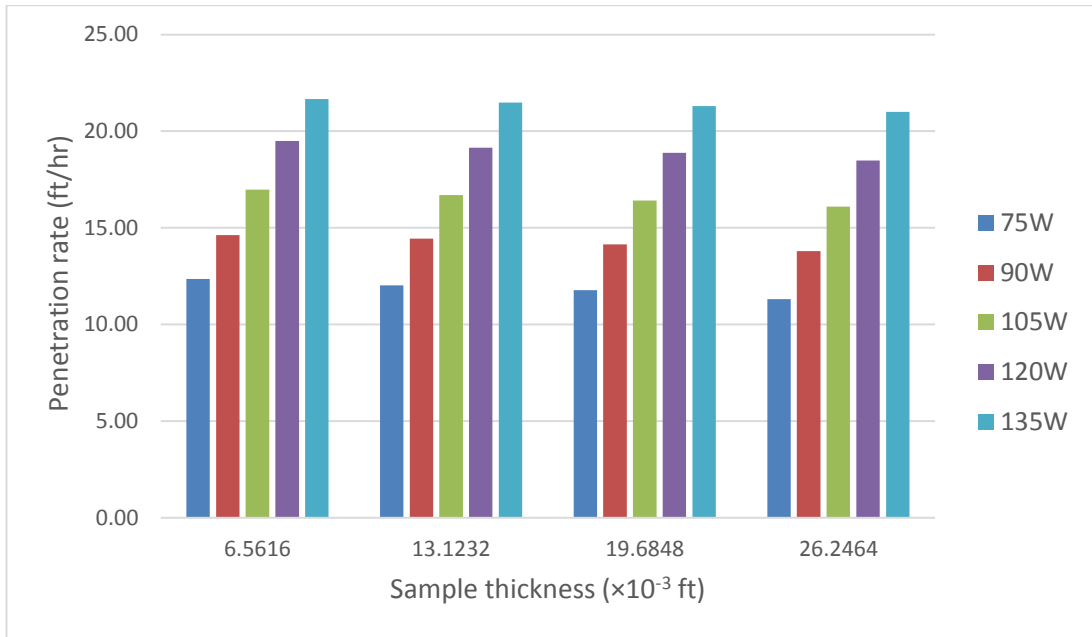
**Figure 4.9a: Effect of sample thickness and laser power on penetration rate for shale.**



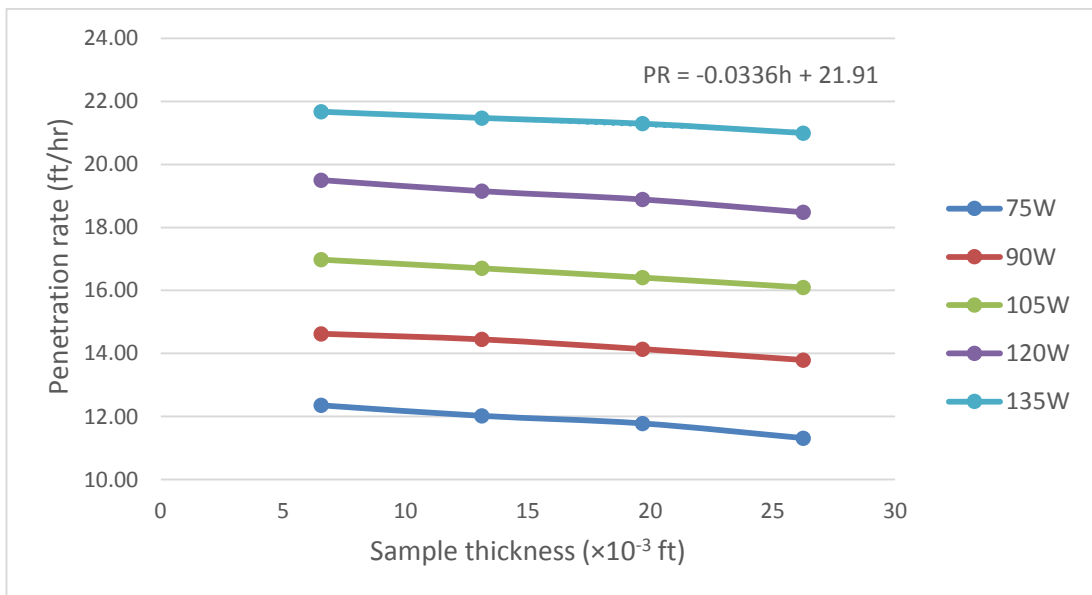
**Figure 4.9b: Effect of sample thickness and laser power on penetration rate for shale.**

**Table 4.10: Penetration rate of different thickness of Sst sandstone under varying laser power.**

| Thickness (mm) | Thickness ( $\times 10^{-3}$ ft) | Penetration rate (ft/hr) |       |       |       |       |
|----------------|----------------------------------|--------------------------|-------|-------|-------|-------|
|                |                                  | 75W                      | 90W   | 105W  | 120W  | 135W  |
| 2              | 6.5616                           | 12.35                    | 14.63 | 16.98 | 19.50 | 21.67 |
| 4              | 13.1232                          | 12.02                    | 14.45 | 16.70 | 19.15 | 21.47 |
| 6              | 19.6848                          | 11.78                    | 14.14 | 16.41 | 18.89 | 21.29 |
| 8              | 26.2464                          | 11.32                    | 13.79 | 16.09 | 18.48 | 21.00 |



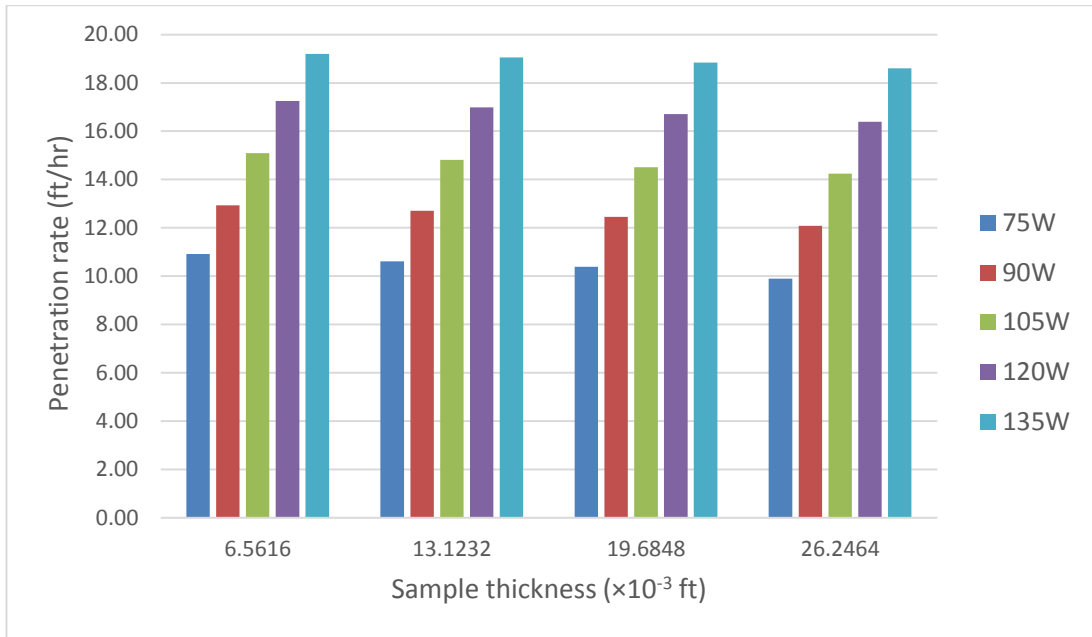
**Figure 4.10a: Effect of sample thickness and laser power on penetration rate for Sst sandstone.**



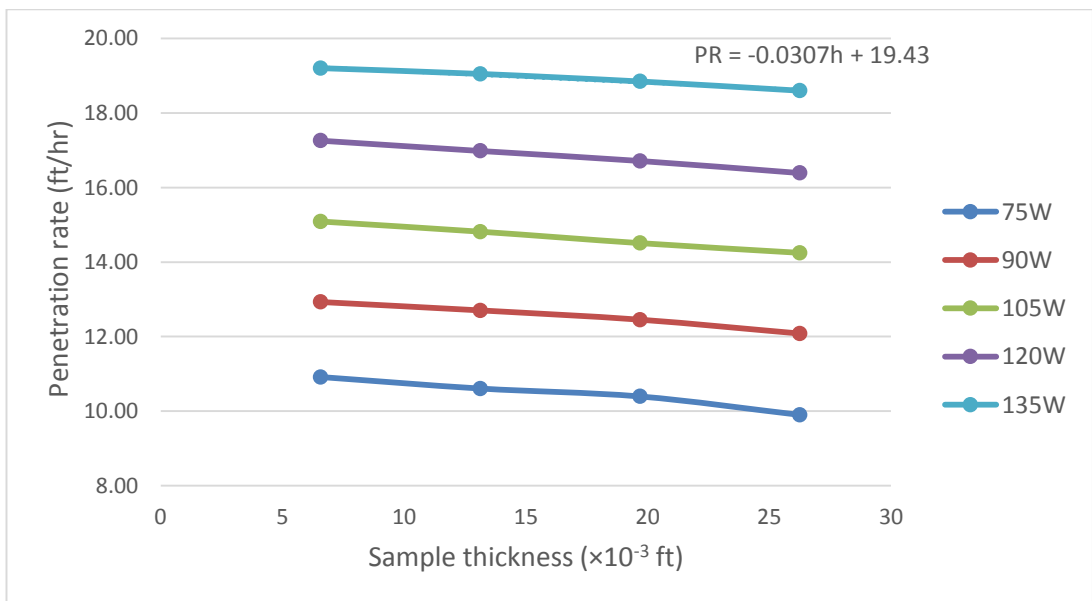
**Figure 4.10b: Effect of sample thickness and laser power on penetration rate for Sst sandstone.**

**Table 4.11: Penetration rate of different thickness of BY sandstone under varying laser power.**

| Thickness (mm) | Thickness ( $\times 10^{-3}$ ft) | Penetration rate (ft/hr) |       |       |       |       |
|----------------|----------------------------------|--------------------------|-------|-------|-------|-------|
|                |                                  | 75W                      | 90W   | 105W  | 120W  | 135W  |
| 2              | 6.5616                           | 10.92                    | 12.93 | 15.09 | 17.26 | 19.20 |
| 4              | 13.1232                          | 10.61                    | 12.70 | 14.82 | 16.98 | 19.05 |
| 6              | 19.6848                          | 10.39                    | 12.45 | 14.51 | 16.71 | 18.85 |
| 8              | 26.2464                          | 9.90                     | 12.08 | 14.25 | 16.39 | 18.60 |



**Figure 4.11a: Effect of sample thickness and laser power on penetration rate for BY sandstone.**



**Figure 4.11b: Effect of sample thickness and laser power on penetration rate for BY sandstone.**

For all samples penetration rate versus sample thickness lines showed linear trend, hence equation of penetration rate as a function of sample thickness can be shown:

$$PR = ah + b \quad (4.2)$$

where,

a = -0.0162 and b = 27.998 for limestone

a = -0.0138 and b = 25.853 for BG sandstone

a = -0.0260 and b = 24.710 for shale

a = -0.0336 and b = 21.910 for Sst sandstone

a = -0.0307 and b = 19.430 for BY sandstone

#### 4.4 Overall Performance

##### 4.4.1 Penetration Rate

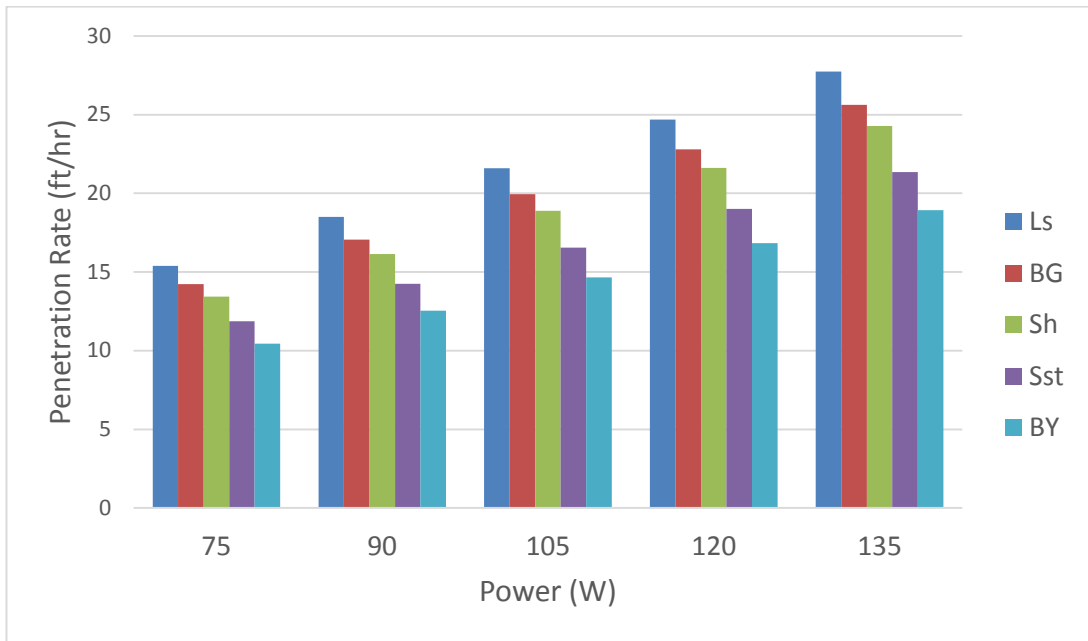
Table 4.12 presents the average penetration rate of each rock sample under different laser power which was calculated using geometric mean method (Equation 4.3).

$$PR_{mean} = \sqrt[n]{PR1 \times PR2 \times \dots \times PRn} \quad (4.3)$$

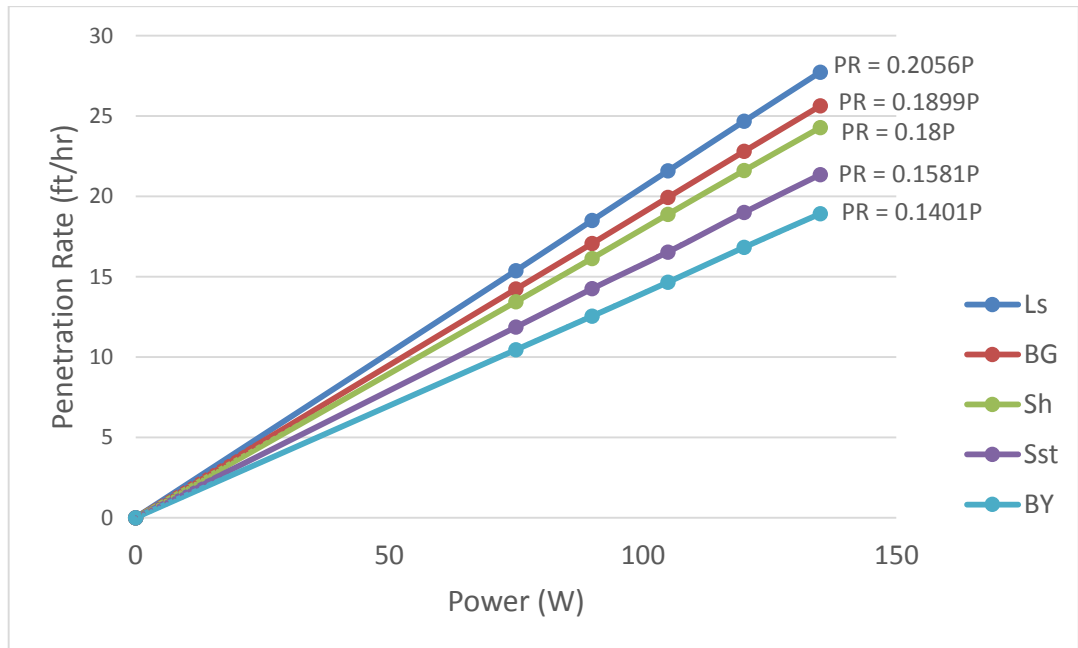
**Table 4.12: Penetration rate of samples**

| Sample        | Penetration rate (ft/hr) |       |       |       |       |
|---------------|--------------------------|-------|-------|-------|-------|
|               | 75W                      | 90W   | 105W  | 120W  | 135W  |
| Limestone     | 15.38                    | 18.50 | 21.59 | 24.68 | 27.73 |
| BG sandstone  | 14.23                    | 17.06 | 19.94 | 22.80 | 25.63 |
| Shale         | 13.44                    | 16.14 | 18.89 | 21.61 | 24.28 |
| Sst sandstone | 11.86                    | 14.25 | 16.54 | 19.00 | 21.36 |
| BY sandstone  | 10.45                    | 12.54 | 14.66 | 16.83 | 18.92 |

Figure 4.12 and Figure 4.13 shows the penetration rate comparison of rock types under each laser power. The highest penetration rate was obtained in limestone, followed by Berea gray sandstone, shale, shaly sandstone and Berea yellow sandstone. Several rock parameters affect on penetration rate. Penetration rate increases with high thermal conductivity, low percentage quartz, high bulk density, dark color and high permeability (Table 4.13). The opposite of these parameters decrease penetration rate.



**Figure 4.12: Penetration rate comparison of rock types at each laser power.**



**Figure 4.13: Penetration rate comparison of rock types.**

From Figure 4.13 equation of penetration rate as a function of laser power can be presented:

$$PR = aP \quad (4.4)$$

where,

a = 0.2056 for limestone

a = 0.1899 for BG sandstone

a = 0.1800 for shale

a = 0.1581 for Sst sandstone

a = 0.1401 for BY sandstone

**Table 4.13: Rock properties that affect penetration**

| Sample | Thermal conductivity (W/m-K) Source (Somerton, 1992) | Quartz (%) Source (Graves et al., 2002) | Bulk density (g/cc) | Color      | Permeability (mD) |
|--------|--|---|---------------------|------------|-------------------|
| Ls     | 1.57   | 10                                      | 2.49                | White      | Very low          |
| BG     | 2.34   | 85                                      | 2.16                | Gray       | 138               |
| Sh     | 3.15   | 46                                      | 2.42                | Black      | Low               |
| Sst    | 1.90   | 75                                      | 2.15                | Light gray | 39                |
| BY     | 2.34   | 90                                      | 2.06                | Yellow     | 917               |

Thermal conductivity is defined as an amount of heat transmitted to unit volume in a unit time. Higher thermal conductivity decreases the amount of minerals melting due to the better diffusion of heat within the rock, and hence penetration rate increases.

Thermal conductivity is directly proportional to permeability and bulk density. This can be seen from the equation below (Somerton, 1992):

$$K=0.6 \times 10^{-3} \rho_b - 5.52\phi + 0.92k^{0.10} + 0.22F - 0.054 \quad (4.5)$$

where,

K: Thermal conductivity (W/m-K)

$\rho_b$ : Bulk density (g/cc)

$\phi$ : Porosity (%)

k: permeability (md)

F: Formation resistivity factor (dimensionless)

Increase in permeability and bulk density increases thermal conductivity which results to the increase of penetration rate. High bulk density indicate less void space as again given by Somerton, 1992 (Equation 4.6); therefore more heat is transferred to solid.

$$\rho_b = 2.65 \times 10^{-3} (1 - \phi) \quad (4.6)$$

Lasing temperatures is high enough to melt quartz and form a glass structure called plasma. Also gas (plume) is produced due to the decomposition of some minerals. These plasma and gases reduce the energy transfer to the rock sample. They absorb a part of laser energy so less energy is transmitted to the rock which results to less penetration rate.

In terms of color, as rock gets darker absorbability increases and reflectivity decreases. Absorbability of the rock is directly proportional to the energy transferred to rock. This direct relation of absorbability and energy transfer increases penetration rate.

The highest penetration rate was observed in limestone. Even though limestone is white in color and has lowest thermal conductivity and permeability, high bulk density and low percentage of quartz are main factors that resulted high penetration rate.

The second highest penetration rate is in Berea gray sandstone. BG has permeability of 138 md which is higher than all rock samples except BY. On the other hand, quartz percentage of BG is lower than BY. Moreover, BG has darker color than Ls, Sst, BY and higher bulk density than Sst and BY. Also thermal conductivity of BG is second largest together with BY.

The third highest penetration rate is in shale which is slightly lower than BG. Shale has highest thermal conductivity, black color, lower percentage of quartz than sandstone and higher bulk density than sandstone. These properties of shale increases penetration rate but its low permeability (compared to sandstone) reduced its penetration rate.

The fourth highest penetration rate was observed in shaly sandstone due to its low thermal conductivity, lower permeability than BG, BY and high quartz percentage than limestone and shale. Also bulk density of shaly sandstone is lower than limestone, Berea gray sandstone and shale.

Berea yellow sandstone has lowest penetration rate even though it has highest permeability and second highest thermal conductivity. This is mainly due to the

highest percentage of quartz and lowest bulk density. Moreover Berea yellow sandstone has bright color compared to shale and Berrea gray sandstone.

In terms of penetration sequence of samples, results are similar to Batarseh (2001) except the switch of Berea gray sandstone with limestone. In his studies BG showed highest penetration rate, followed by Ls, Sh, Sst and BY. This is due to the higher permeability of BG in his studies (500 md compared to 138 md).

In terms of penetration rate, when we compare upscaled penetration rate with previous studies, they are different which is very high (Figure 4.14). This is due to the diameter of laser beam. In previous studies more than 6mm diameter beam was used whereas it is 2mm in our study. It is easier to penetrate using smaller diameter laser because volume of rock removed is less. In calculation of penetration rate diameter of laser beam is not considered. Due to this we can conclude penetration rate is not right parameter to compare unless laser diameter is same.

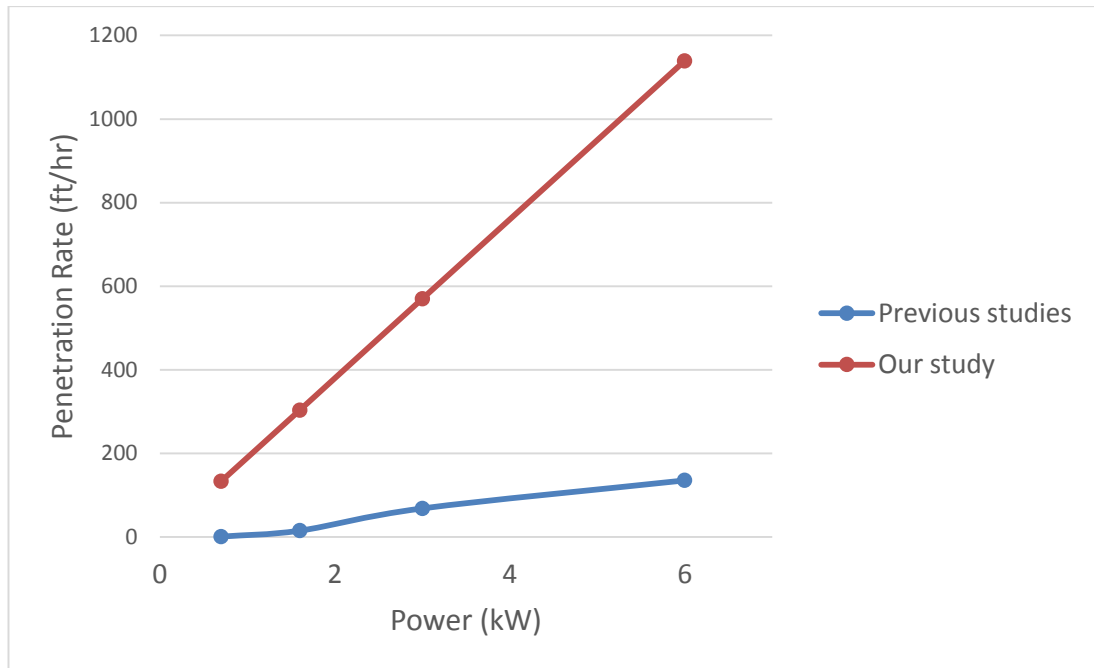
**Table 4.14: Upscaled laser power and penetration rate**

| Sample        | Penetration rate (ft/hr) |       |       |      |
|---------------|--------------------------|-------|-------|------|
|               | 0.7kW                    | 1.6kW | 3kW   | 6kW  |
| Limestone     | 143.5                    | 328.9 | 616.9 | 1232 |
| BG sandstone  | 132.8                    | 303.3 | 569.7 | 1139 |
| Shale         | 125.4                    | 286.9 | 539.7 | 1079 |
| Sst sandstone | 110.7                    | 253.3 | 472.6 | 949  |
| BY sandstone  | 97.5                     | 222.9 | 418.9 | 840  |

**Table 4.15: Penetration rate under different laser power from previous studies**

| Sample        | Penetration rate (ft/hr)                       |  |                                      |                                      |
|---------------|--|--|--------------------------------------|--------------------------------------|
|               | 0.7kW<br>Source<br>(Bakhtbidar et<br>al, 2011) | 1.6kW<br>Source<br>(Xu et al,<br>2004) | 3kW<br>Source<br>(Batarseh,<br>2001) | 6kW<br>Source<br>(Batarseh,<br>2001) |
| Limestone     | –  | –                                      | 52                                   | 115                                  |
| BG sandstone  | 0.54   | 14.76                                  | 68                                   | 135                                  |
| Shale         | –  | –                                      | 33                                   | 110                                  |
| Sst sandstone | –  | –                                      | 30                                   | 93                                   |
| BY sandstone  | –  | –                                      | 28                                   | 75                                   |





**Figure 4.14: Comparison of our study with previous studies**

#### 4.4.2 Specific Energy

For our study, using Equation 2.1 specific energy can be related to laser power and penetration rate (Equation 4.7):

$$SE = \frac{E}{V} = \frac{P \times t}{A \times L} = \frac{P}{\frac{\pi}{4} \times d^2 \times PR} = \frac{3.7596}{ft^2} \frac{P}{PR} \quad (4.7)$$

where,

SE: Specific energy (kJ/cc)

d= diameter of laser beam=0.006562 ft

3.7596: Conversion factor from W to kW, cuft to cc and hr to s.

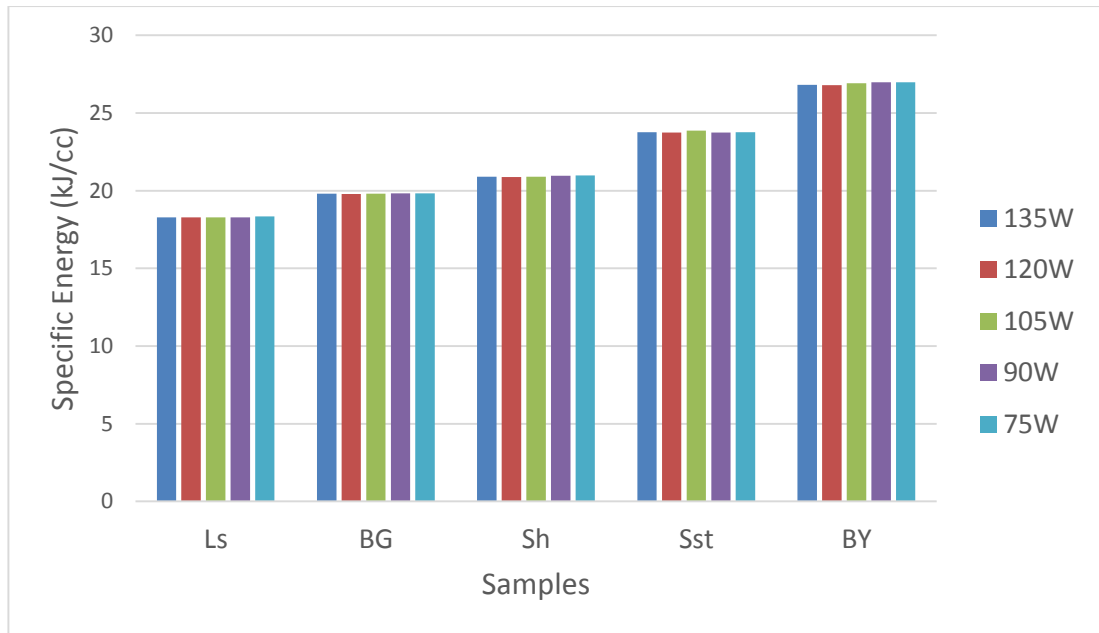
P: Laser power (W)

PR: Penetration rate (ft/hr)

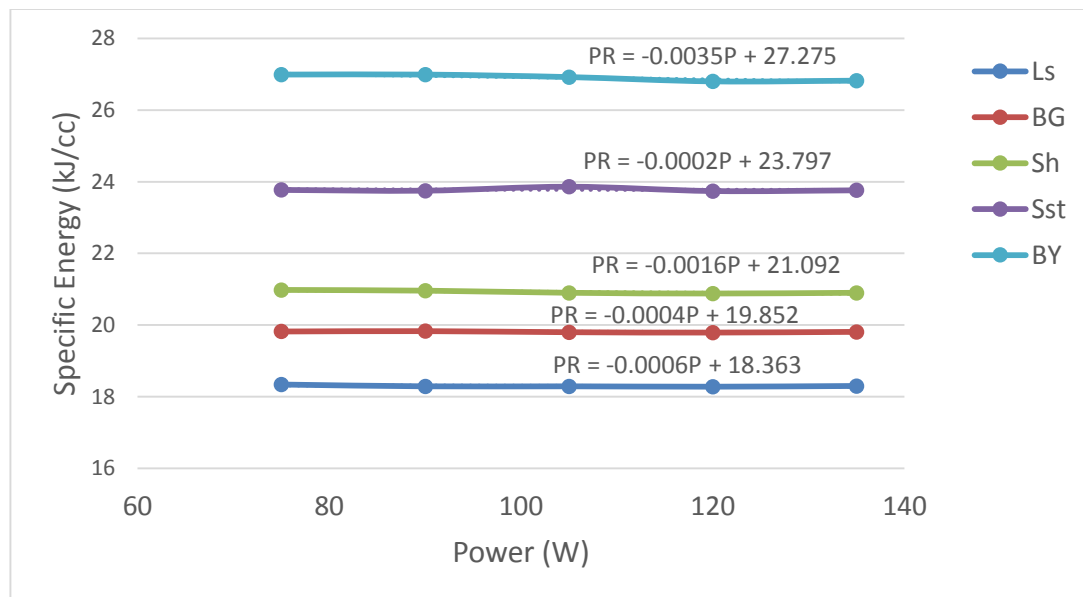
Using Equation 4.7 specific energy of samples were calculated and presented in Table 4.16. Unlike penetration rate, specific energy is similar in each type of rock even at different laser powers (Figure 4.15 and Figure 4.16). On the other hand, at constant laser power specific energy is inversely proportional to penetration rate. It increases with the decrease of penetration rate (Figure 4.17).

**Table 4.16: Specific energy of rock samples**

| Sample        | Specific energy (kJ/cc) |       |       |       |       |
|---------------|-------------------------|-------|-------|-------|-------|
|               | 75W                     | 90W   | 105W  | 120W  | 135W  |
| Limestone     | 18.34                   | 18.29 | 18.29 | 18.28 | 18.30 |
| BG Sandstone  | 19.82                   | 19.83 | 19.80 | 19.79 | 19.81 |
| Shale         | 20.98                   | 20.96 | 20.90 | 20.88 | 20.90 |
| Sst Sandstone | 23.77                   | 23.75 | 23.86 | 23.74 | 23.76 |
| BY Sandstone  | 26.99                   | 26.99 | 26.92 | 26.80 | 26.82 |



**Figure 4.15: Specific energy of samples.**



**Figure 4.16: Specific energy comparison of samples.**

From Figure 4.16 equation of specific energy as a function of laser power was calculated and it can be presented as below:

$$SE = aP + b \quad (4.8)$$

where,

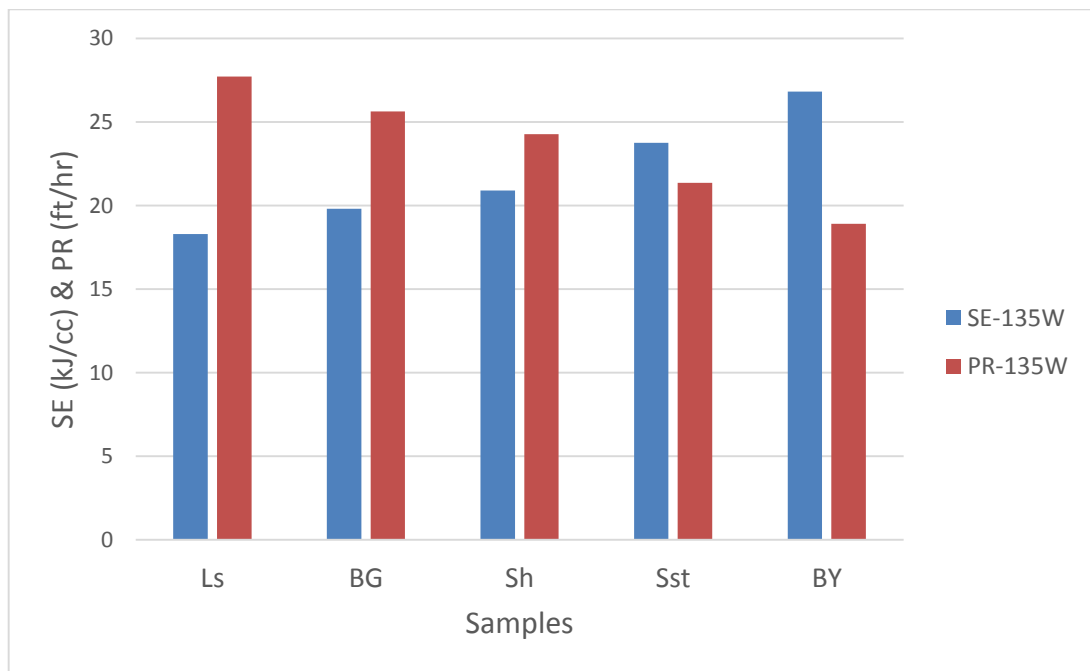
$a = -0.0035$  and  $b = 27.275$  for BY sandstone

$a = -0.0002$  and  $b = 23.797$  for Sst sandstone

$a = -0.0016$  and  $b = 21.092$  for shale

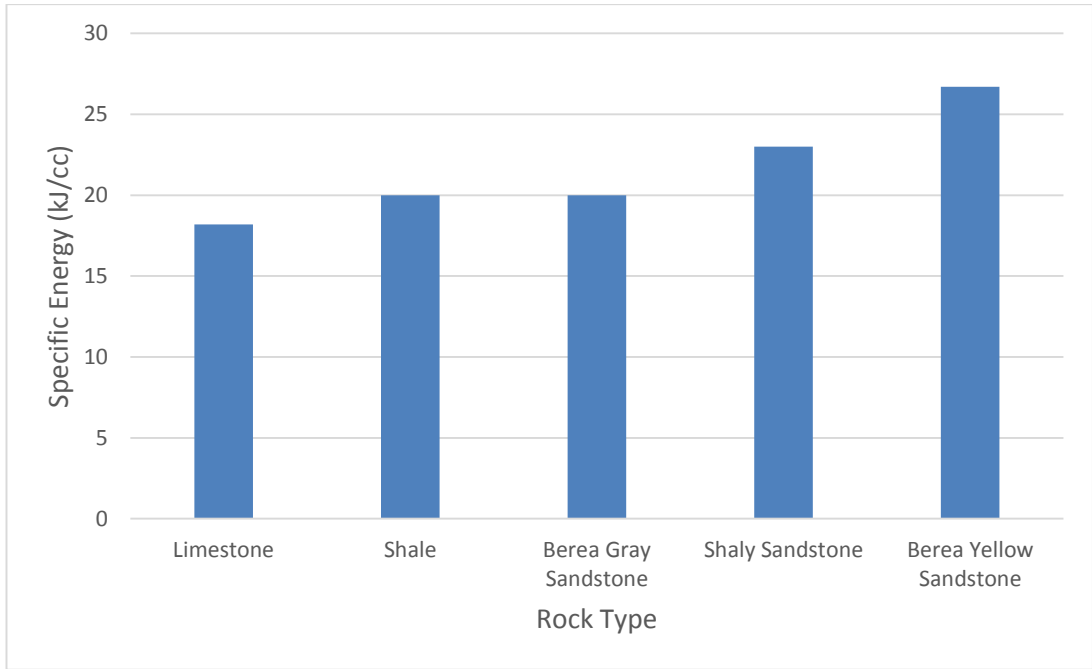
$a = -0.0004$  and  $b = 19.852$  for BG sandstone

$a = -0.0006$  and  $b = 18.363$  for limestone

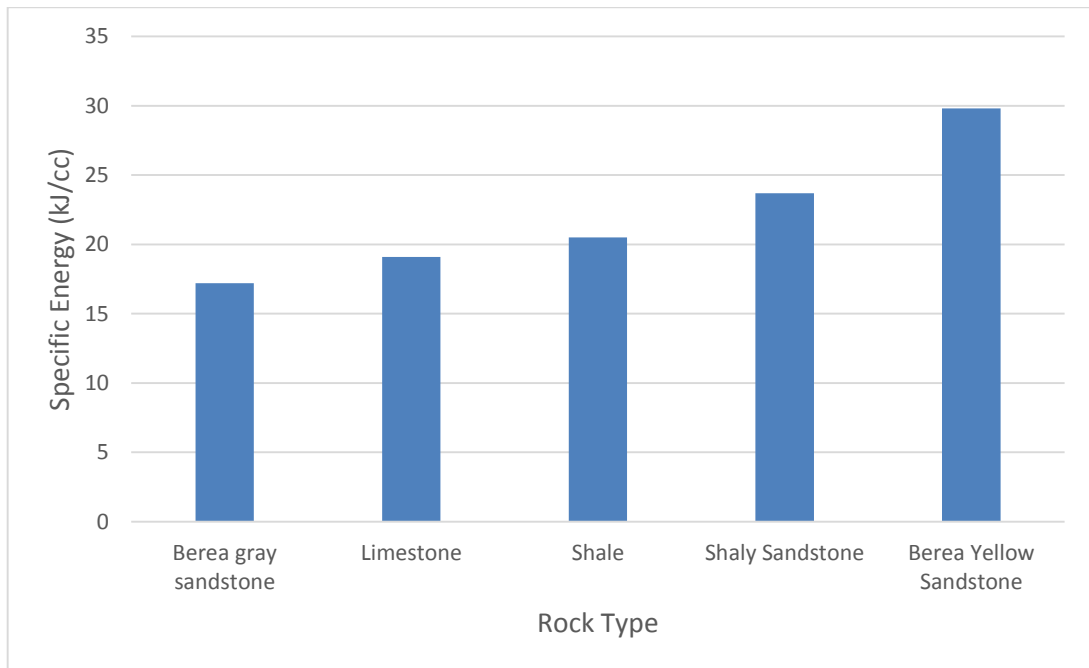


**Figure 4.17: Comparison of specific energy with penetration rate under 135 W laser power.**

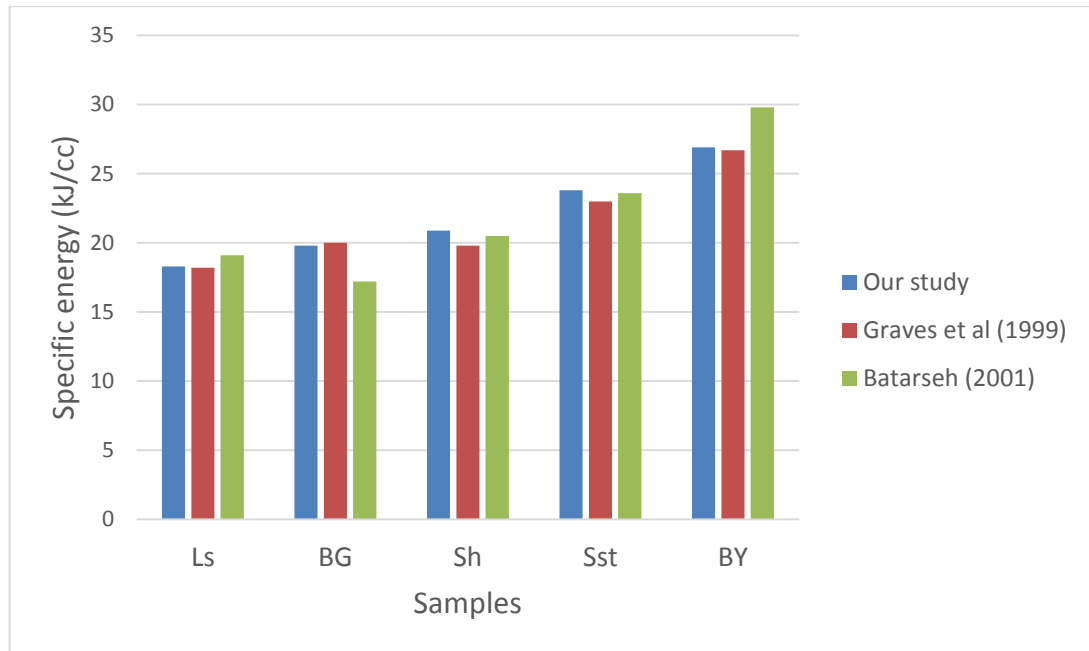
Penetration rate results were compared to previous studies and they were different. When specific energy results are compared, they are similar to Batarseh (2001) for shale and shaly sandstone. Also similarly with Graves et al (1999) for limestone, Berea gray sandstone and Berea yellow sandstone. From here, it can be concluded that same type of rock gives similar specific energy regardless of laser power, laser diameter and penetration rate.



**Figure 4.18: Specific energy of different rock types**  
 (Source: Graves et al, 1999)



**Figure 4.19: Specific energy of different rock samples**  
 (Source: Batarseh, 2001)



**Figure 4.20: Specific energy comparison between different studies**

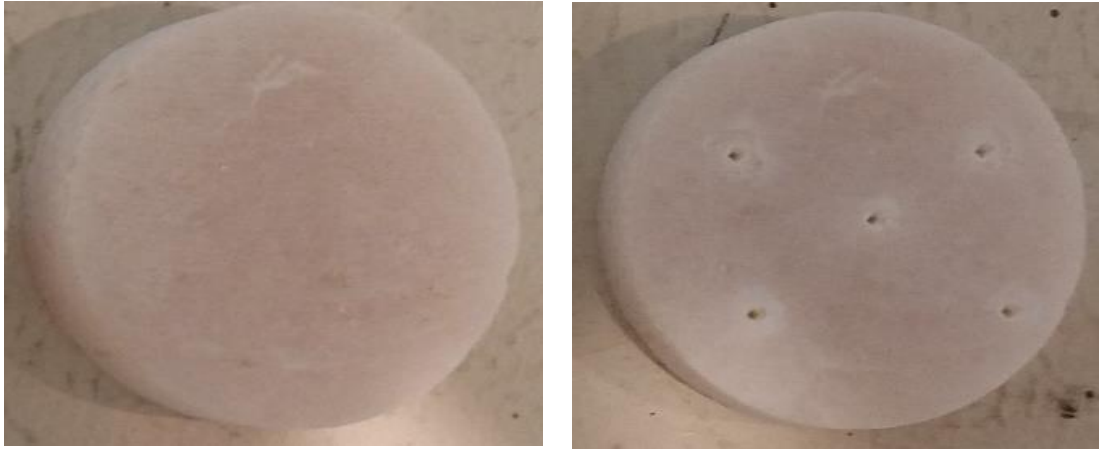
#### 4.5 Fracture Formation Analysis

The fracture behavior is different from one rock type to another. This depends on several parameters such as thermal conductivity and mineralogy.

Increase in thermal conductivity increases fracture formation. At higher thermal conductivity, the rock heats up more efficiently and better temperature distribution within the rocks.

In terms of mineralogy, clays contain water and when subjected to high temperature, water tries to escape in a form of vapor. This increases the volume and pressure in the pore and results to fractures.

Fractures were not observed in limestone similarly with Batarseh (2001) (Figure 4.21). This is because limestone has low thermal conductivity and contains low amounts of clay. On the other hand, sandstone and shale have high thermal conductivity and contain clays. Therefore fractures were observed in sandstone and shale after lasing similar to Batarseh (2001), Xu et al (2004) and Graves and Bailo (2005). Moreover, after lasing color of sandstone and shale became brighter due to high thermal conductivity and efficient temperature distribution within rock (Figure 4.22, Figure 4.23, Figure 4.24 and Figure 4.25).



**Figure 4.21: 8mm limestone before (left) and after (right) lasing.**



**Figure 4.22: 8mm Berea gray sandstone before (left) and after (right) lasing.**



**Figure 4.23: 8mm shale before (left) and after (right) lasing.**



**Figure 4.24: 8mm shaly sandstone before (left) and after (right) lasing.**



**Figure 4.25: 8mm Berea yellow sandstone before (left) and after (right) lasing.**

## **CHAPTER 5**

### **CONCLUSION AND RECOMMENDATIONS**

#### **5.1 Conclusion**

Alternatives to hydraulic fracturing were reviewed and applicability of laser technology was investigated as an alternative to hydraulic fracturing. Laboratory tests were performed and results were encouraging. Results showed that laser beam can penetrate different types of rocks. Penetration rate increases with the increase of laser power and decreases with the increase of sample thickness. Different types of rocks have different penetration rate. Highest penetration rate was observed in limestone, followed by Berea gray sandstone, shale, shaly sandstone and Berea yellow sandstone. High thermal conductivity, low percentage of quartz, high bulk density, dark color and high permeability increase penetration rate and the opposite of these parameters decrease penetration rate. Specific energy of samples were calculated in order to determine efficiency of rock removal. Unlike penetration rate, specific energy does not change with laser power but under constant laser power it is inversely proportional to penetration rate. Berea yellow sandstone has highest specific energy, followed by shaly sandstone, shale, Berea gray sandstone and limestone. Fractures were observed in sandstone and shale. However, no fractures were observed in limestone due to low thermal conductivity and low amounts of clay and quartz.

#### **5.2 Recommendations**

Some recommendations can be put forward for future research and development of laser technology application in hydraulic fracturing. Firstly, field tests should be conducted to analyze the applicability of laser technology. Secondly, high power lasers should be used to compare results from this research. Thirdly, tests should be conducted for more types of rocks including granite, salt and etc. Fourthly, tests should be conducted using different diameter of laser in order to determine optimum specific energy. Fifthly, laser power and temperature should be correlated with rock types in order to understand the power needed to melt or evaporate the rock samples. Moreover, the change of rock behavior after lasing should be analyzed from Field Emission



Scanning Electron Microscopy (FESEM). Last but not least, the methods of laser fracturing, ways of delivering laser radiation, the economics, reliability, durability safety and environmental considerations should be taken into account.

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## APPENDICES

### APPENDIX A: Shale Outcrops



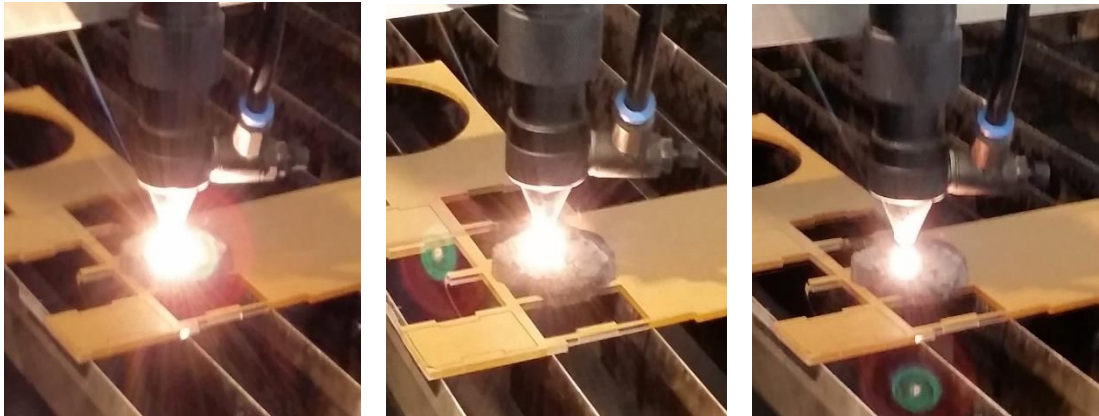
**Figure A.1: Shale outcrops in Batu Gajah**

### APPENDIX B: Laser Machine



**Figure B.1: 150 W laser machine which was used in the laboratory experiment**

### APPENDIX C: Reaction of Laser Beams at Different Times



**Figure C.1: Reflection (left), Dispersion (middle) and Absorption (right) of laser beams at different times.**

### APPENDIX D: Interior View after Lasing



**Figure D.1: Interior view of 8mm sandstone after penetration**