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ABSTRACT

The search for water, minerals and most importantly evidence of life on other objects of our solar system will require access to the subsurface for sampling and in situ investigations. Drilling is therefore needed for this task, but present drilling technologies on Earth will be difficult to apply on such objects. Therefore, some novel alternatives will be needed for successful drilling. This work focuses on one promising method introduced by Zaptec AS, which is plasma channel drilling (PCD), where a rock is fragmented with high voltage pulses. The PCD process require an isolating medium for its operation, usually water, around the electrodes (drill bit). Very fast high voltage pulses are applied to the rock surface, causing the rock to fail electrically. The electrical breakdown creates a channel of plasma in the rock, which by thermal expansion causes mechanical fragmentation. This work seeks to investigate the feasibility of the PCD process in extra-terrestrial environments and to check the possibility of using compressed gas instead of water which has been used and proven effective on Earth. Furthermore, an attempt to optimize the field around the Zaptec drill head was done with Comsol Multiphysics software.

The difference in breakdown strength between rocks and fluid is crucial, hence the breakdown strength is reviewed, calculated with the Paschen law and compared to estimate the feasibility of PCD when using the atmosphere of planets and other objects as drilling fluid. Several related subjects are also briefly discussed, like the challenges and successes of drilling on other solar system objects and some of the many high voltage mechanisms that happens in sparking. Past and ongoing drilling technologies for space applications are also reviewed. PCD seems feasible on Titan which has similar breakdown strength as Earth but unlikely on Mars with a breakdown strength of only 0.74 kV/cm. Asteroids and comets and Europa which is essentially vacuum present the best environment for PCD. The use of gas as drilling fluid seems highly unlikely but will require further research in to that area of study.

DEDICATION

This thesis is dedicated to Akosua Asamoah Boateng my beautiful baby girl who was born at the most critical moment of this work and to Jaden Asamoah Boateng for his inspiration.

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I express my sincere gratitude to God for giving me the needed strength and wisdom to complete this project. I would like to express my profound appreciation to professor Per Amund Amundsen my supervisor for the opportunity given me to do this thesis and for his support and technical advice during this research project.

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Table of Contents

List of Figures

List of Tables

Chapter 1 INTRODUCTION

Drilling is an important and integral activity in the very existence of our everyday life as humans. Drilling is the act of removing material from a body of material with a drill i.e. the process of boring holes in solid materials. The applications of drilling are enormous which span from production of oil, drinking water, attaching surfaces, soil sampling, etc.

Over the years several types of drills and drilling systems have been developed with the most common ones being rotary drills and drilling systems. These equipment, comes in different shapes and sizes for specific purpose and job type. About ten million drills are estimated to be sold every year (Zacny, et al., 2009).

The objectives and type of surface being drilled, largely determines the type of drill, drilling system and/or technologies needed. The gun drill is use for drilling long, straight holes in metals (sometimes, to produce gun barrels). The ultra sound/sonic “gopher” is used for drilling icy surfaces and an electric hand drill, to drill small holes in walls, and so on (Bar-Cohen, et al., 2009).

Future in-situ planetary resource utilization and characterization, as well as the scientific search of water and life on other parts of the solar system, will require access to the subsurface and hence drilling is required. But the extra-terrestrial environment poses greater challenges to existing drilling technologies used on Earth. The challenges include, very high temperatures as on Venus (737 K) and very low temperatures as on Europa and Titan (93.7 K).

In addition, potential missions may require sampling at very low gravity as is found on asteroids and comets, high pressure environments such as on Venus (90.8 atm) as well as harmful radiations on bodies such as Europa. The remoteness of these sites or environment may make it difficult to transport massive/heavy drilling systems used on Earth which can achieve depth that maybe needed for effective subsurface sampling and investigation (Hoftun, et al., 2014).

The traditional drilling technologies used on Earth will be difficult to apply in space mainly because of the above-mentioned factors and constraint requirement in equipment mass, volume, power and the reliance on gravity and the continuous circulation of liquid water-based or oil based drilling fluids (Hoftun, et al., 2016; Zacny, et al., 2009)

New and innovative technologies will have to be developed to accomplish the ambition of deep drilling on such environment because early drilling tools which were used on the moon, may not be useful anymore (Bar-Cohen, et al., 2009). Below are two images of successful drilling systems on the moon.

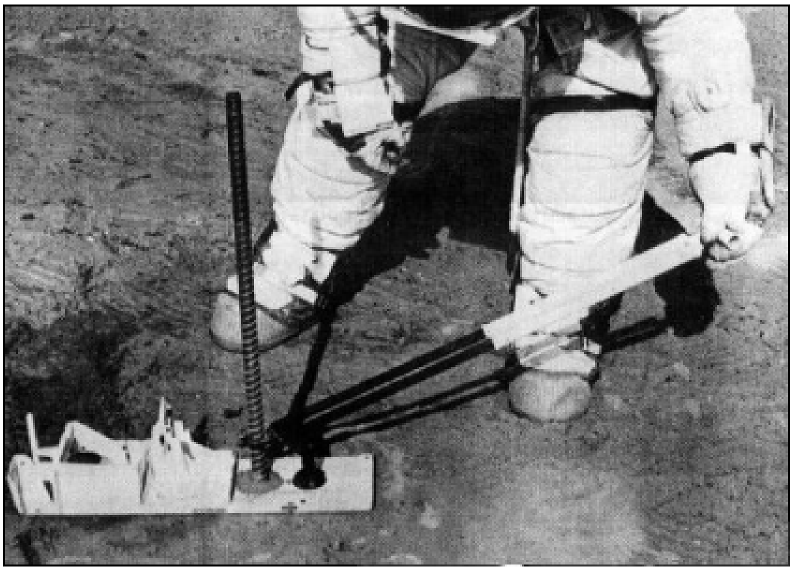


Figure 2.1: Apollo Luna surface drill (ALSD) (Zacny, 2013)

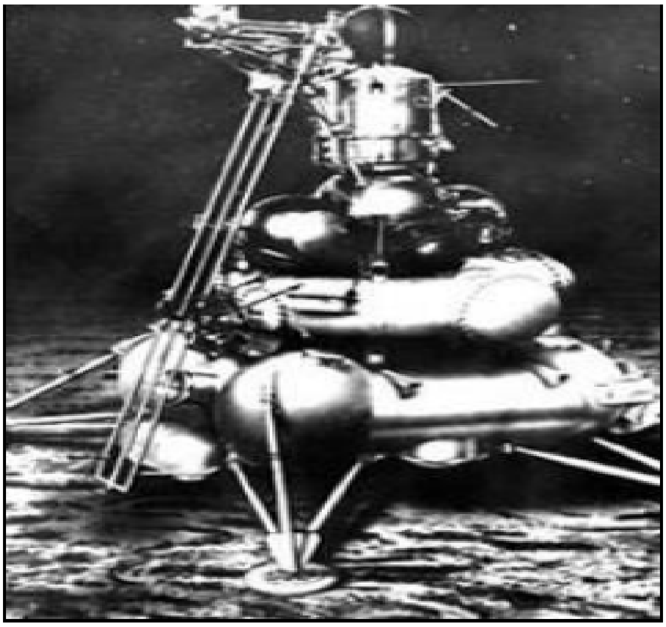


Figure 2.2: Soviet Lunar drill (Zacny, 2013)

There have been significant advances for low temperature applications, such as the Ultrasonic/Sonic Driller/Corer (USDC) which was demonstrated to drill at temperatures as low as 93 K. The technologies for high temperature applications are still limited but a USDC-based high temperature sampler is under development by NASA, to operate in the temperature range of Venus (Shrout, et. al., 2004).

This work, inspired by a project carried by Zaptec AS. in 2015, seeks to look at an alternative drilling method to the well-known conventional methods. The technology under development is plasma deep channel drilling which seek to achieve the following: high drilling energy efficiency, continuous drilling process without replacement of mechanical parts, constant casing diameter and effective transport of disintegrated rocks (Hoftun, et al., 2016).

This technology is primarily addressed to drilling on Earth for oil and gas, geothermal energy, and mining industries (GA-Drilling, 2014), but this work goes beyond the primary aim and seek to investigate the possibility of its application on other solar system objects for scientific research purposes.

Plasma deep channel drilling is a technology where high voltage spark goes through rock by delivering high voltage many times per second to an electrode assembly in contact with the material body. Fragments of the rock are transformed into plasma which expands into the surrounding rock and eventually cause it to fragment and fracture. Much energy is not needed to produce these electrical pulses “lightning”, “it all depends on how often you want it to ignite” (Hoftun, et al., 2014; McGregor, et al., 2007). Experimental trials of plasma drilling showed that the method is feasible, and achieved 7.5 metres per hour in sandstone.

1.1 PROBLEM DEFINITION AND OBJECTIVES

The exploration of the solar system in search for past and present life, will require access to the subsurface. Exploration target for potential future missions includes bodies that have had, or have water near the surface including Mars and Europa. Asteroids and comets are rich in metals and other minerals, they are believed to hold the key to the mysteries regarding the formation of the Earth.

Getting access to the subsurface of these objects will require drilling but the drilling technologies used on Earth may not be useful. Plasma channel drilling is among several drilling technologies being developed for space exploration and in situ analysis of our Solar System. The technology has been done on Earth and works with water as drilling fluid.

This work seeks to:

1. Investigate the feasibility of plasma channel drilling technology on extra-terrestrial environments.
2. Investigate the possibility of using gas as drilling fluid, since water and other liquids will add weight to the drilling system and might not be welcome on a very low pressure and very low temperature environments.
3. Attempt to optimize the configuration of the Zaptec drill bit to push the plasma channels in the rock instead of short-circuiting through the drilling fluid.

Chapter 2 PLASMA DRILLING

An electrical discharge or spark results from the creation of a conducting path between two points of different electrical potential with the higher or positive potential as the anode, and the lower, or negative potential as the cathode (Calvert, 2002).

The names anode and cathode, which has Greek origin, were given by Michael Faraday, with help from classical scholar William Whewell, when studying electro chemistry and electrical discharges in the 1830's (Cobine, 1958; Calvert, 2002).

The study of electrical discharges, is from the advent of vacuum pumps and sources of electrical current in the middle of the 19th century. It was generally studied as a problem or limitation to electrical circuits, where the spark is not wanted. The discharge is permanent, if the supply of electrical charge is continuous, but temporary otherwise (Calvert, 2002).

Most often, the medium is a gas, typically the atmosphere, and with a large potential difference, from a few hundred volts to millions of volts. Electric sparks have been studied as far back as the 18th century, to understand the phenomenon of lightning (Mollet, et al., 2017).

Apart from laboratory discharges which takes place in partially-evacuated tubes, there are also electrical discharges in nature. Lightning, aurora borealis, and similar phenomena are examples which may results from high potentials of static electricity. With the advent of technology, interesting and fascinating examples such as arc welding, corona discharge on high-tension lines, fluorescent lamps, neon advertising signs, neon and argon glow lamps, and vacuum tubes have become useful applications of sparks (Calvert, 2002).

From the 1950's on, has been a field of active research to generate high-pressure pulses with sparks in liquids for impact crushing of different brittle solid materials such as rock particles. In the last decades drilling based on the use of pulsed electric power has been intensively investigated to overcome some of the challenges accompanied with conventional mechanical and explosive drilling systems (Timoshkin, et al., 2003).

2.1 Methods of Spark Drilling

Electro hydraulic drilling, electric discharge machining, and plasma channel drilling are few of recently developed spark discharge drilling systems. This chapter seek to review the above technologies.

2.1.1 Electrohydraulic Shockwave Drilling

An electrohydraulic technique of pulverizing rock was tested by Svedberg in 1905 to produced colloidal metallic suspensions by capacitor discharge in liquids (Kitzinger, et al., 1992). In this method, an electrical spark is created between two electrodes at the drill head, immersed in dielectric fluid. A pulse of electricity at high peak power is passed through the spark between the electrodes (Gutsol, 2013). A rapidly expanding plasma is formed and subsequently creates a shock wave. These powerful shock waves travel through the fluid and is guided to crush the rock within the body of rock to be drilled.

A medium with very low compressibility is needed to effectively transport the shock wave; preferably water or mud. A gas or mixture of gases will not work. Drilling into the rock is achieved by repeating the shock wave 10 – 50 times per second (Tetra, 2017). Here, the difficulty of focusing the shockwave onto the material may result in waste of energy and ultimately in a poor drilling rate. To prevent this waste, a method of focusing the shock wave to a focal region of the rock to be drilled using a “shock wave reflector” has been proposed in Gutsol, (2013).

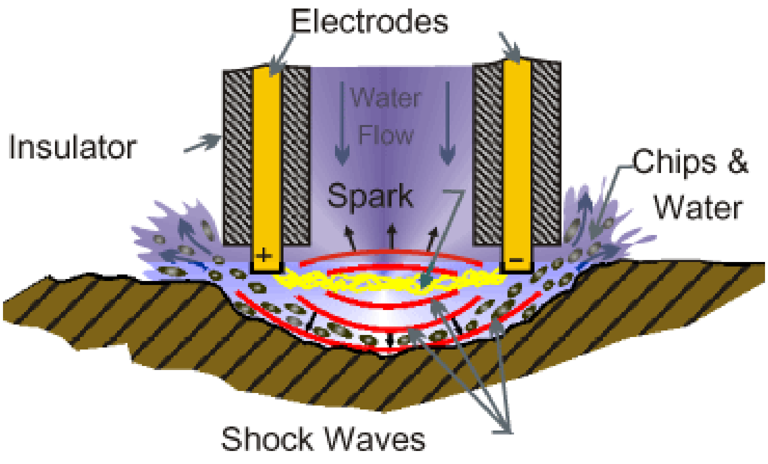


Figure 2.1: Underwater plasma shock wave (Tetra, 2017)

2.1.1.1 Applications of electrohydraulic drilling

Electrohydraulic drilling technology can be used to drill wells for extracting oil and gas, water, and other materials from the Earth.

Tetra Corporation have invested approximately $9.4 billion over the past 17 years to develop its electrohydraulic technology and protected the process with several patents (Tetra, 2017). Some of the developments and patents include:

- The invention and demonstration of focused shockwave drill technology
- Development of low-frequency, high efficiency under-water plasma acoustic sources
- Developing electrohydraulic deep drill
- Electrohydraulic pressure wave projectors
- Portable electrohydraulic mining drill

Plasma Sound Source (PSS), may be used as a source of powerful sonar pulses underwater. Electric charges stored in large high-voltage bank of capacitors, creates underwater spark discharge upon release, producing high-pressure plasma and vapour bubble. The expansion and collapse of the plasma and vapour bubble produce a loud sound with frequency between 20 and 200 Hz, useful for both seismic and sonar applications (Sheriff, 2002).

In the medical front, the technology is developed to be used for a non-invasive treatment of urinary calculosis (kidney stones) and biliary calculi (gallbladder or liver stones) using an externally applied, focused, high-intensity acoustic pulse procedure known as Extracorporeal Shock Wave Lithotripsy (ESWL). The stones are broken into smaller pieces for an easier passage through the urinary tract and subsequently from the body (Thompson, et al., 2015).

2.1.2 Electric Discharge Machining (EDM)

Electric discharge machining (EDM), also known as spark erosion machining is among the most extensively used non-conventional material removal processes. It was first observed by the English chemist Joseph Priestly in 1770, when electrical discharges eroded electrode parts in his experiments (Babu, et al., 2016).

Two Soviet researchers, the Lazarenko brothers, during the Second World War developed a machining process that formed the basis for modern EDM (Waukesha, 2017). They developed a system for machining hard metals by vaporising the materials from the surface. At the same period three Americans, Harold Stark, Victor Harding, and Jack Beaver developed an EDM process for removing broken drills and taps from hydraulic valves. This became the foundation for vacuum tube EDM machines (Ho, et al., 2003).

The EDM process is based on removing materials from a workpiece with a series of repeated electrical sparks between an electrode and the workpiece immersed in a dielectric fluid (Jameson, 2001). The thermal energy which accompany the process, creates a plasma channel with extreme temperatures of about 8000 to 12000 degrees Celsius, melting and vaporizing almost anything in the process. The entire process is controlled and the sparks are localized to affect only the surface of the workpiece (Ho, et al., 2003).

Using thermal energy to machine electrically conductive parts regardless of hardness, EDM has unique advantages in the manufacture of mould, die, automotive, aerospace and surgical components (Babu, et al., 2016).

Since there is no direct contact between the electrode and the workpiece, EDM eliminate the problem of mechanical stresses, chatter and vibrations during machining. The method allows tool steels to be hardened before machining, hence, the problems of dimensional variability, which are characteristic of post-treatment are avoided. Additionally, electrodes as thin as 0.1 mm diameter are being used to drill holes in curved surfaces at steep angles without problems (Waukesha, 2017).

The use of EDM is steadily expanding, limited only by the relatively prohibitive cost and low manufacturing speed of this method. EDM is among the most accurate manufacturing processes available for creating complex shapes and patterns within parts and assemblies today. But it was not until the advent of Computer Numerical Control (CNC) in the 1980s, that EDM received tremendous improvements in the efficiency of machining operation (Ho, et al., 2003).

CNC have since then facilitated a total automated EDM process, from inserting the electrodes in the tool changer to a finished and polished cavity or cavities. The advantages of EDM over the years have seen the technology being intensely sought for by the manufacturing industries, yielding enormous economic benefits and great research interests (Babu, et al., 2016).

2.1.2.1 Categories of EDM:

Wire EDM

Wire EDM uses a thin single-strand metal wire (used as the electrode) submerged in de-ionised water, to cut through metals using heat and electrical sparks (Kumar, et al., 2015). The wire is usually made of brass or stratified copper, between 0.1 and 0.3 mm diameter. It is fed from a spool through the workpiece guided by a microprocessor, which eliminate the need for pre-shaped electrodes and gives it the ability to cut intricate and delicate shapes. (Waukesha, 2017).

Extrusion dies and blanking punches are very often made by wire EDM from metal that is difficult to cut. Cutting is always through the entire workpiece. Wire EDM can be extremely accurate with almost no rough edges generated. (Waukesha, 2017; Kumar, et al., 2015).

Die Sinker EDM

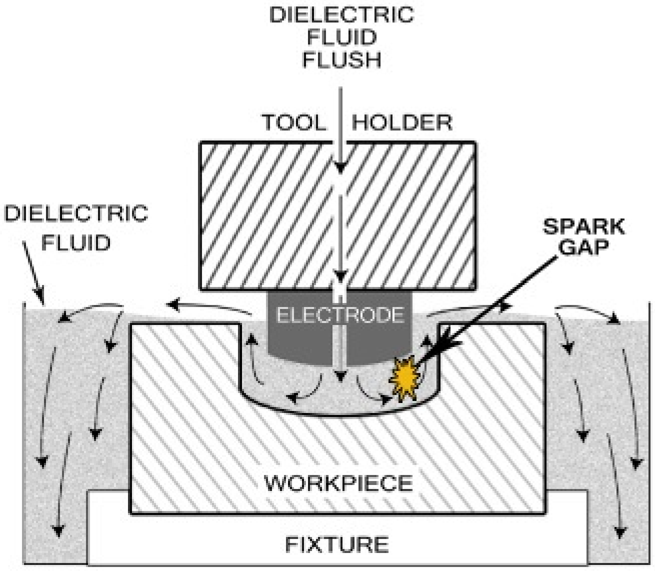


Figure 2.2: Die sinker EDM process (Kemplon, 2015)

In this process, the electrode has the shape of a die, and will carve the workpiece to its complementary shape. Both the electrode and workpiece are submerged in an insulating liquid such as oil or, other dielectric fluids. The electrode and workpiece are connected to a suitable power outlet which generates electrical potential between the two parts. A plasma channel is formed and dielectric breakdown occurs in the fluid initiating a spark, as the electrode approaches the workpiece (Dibitonto, et al., 1989; Eubank, et al., 1993).

These sparks occur in vast numbers at seemingly random locations between the electrode and the workpiece (Jameson, 2001). As the base metal is eroded, the spark gap subsequently increases, the machine automatically lowers the electrode so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup (Ferri, et al., 2008; Kumar, et al., 2015). These controlling cycles are sometimes known as "on time" and "off time" (Semon, 1975; Kumar, et al., 2015).

2.1.3 Plasma Channel Drilling (PCD)

In addition to the above-mentioned processes, an efficient and recently investigated type of electric pulse drilling, and the main technology being investigated by this work, is plasma channel drilling. Recently some commercial applications have begun to emerge (Biela, et al., 2009). GA Drilling with headquarters in Slovakia have developed and patented their plasma drill invention, PLASMABIT. The technology according to GA Drilling (2017), could enable massive time and cost saving when compared to most existing drilling technologies.

This method induces high voltage pulses of microsecond duration with electrodes close to, or in contact with the material formation to generate elongated plasma channels in the material body, which expand rapidly following electrical breakdown of the material and causing efficient fracture and fragmentation of the rock formations (Timoshkin, et al., 2004; Hoftun, et al., 2014).

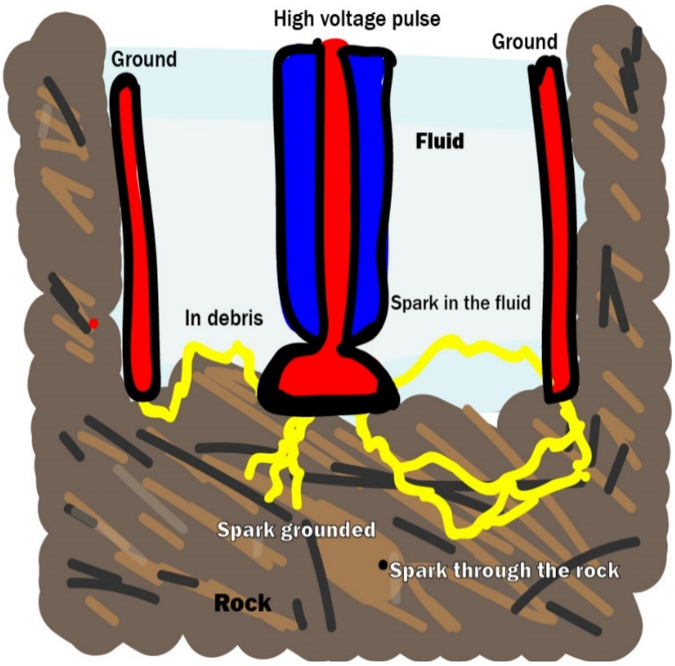


Figure 2.3: High voltage, low power sparks delivered through an electrode assembly.

2.1.3.1 Mechanism of Plasma Channel Drilling (PCD)

High voltage pulses of microsecond duration are delivered to an electrode assembly close to, or in contact with the rock. A highly destructive short lived electrical plasma channel is created, which cause localized fracture and fragmentation to the rock structure, ahead of the electrode assembly. The process takes place in the presence of dielectric fluid, preferably water or transformer oil (Hoftun, et al., 2016; Timoshkin, et al., 2004).

The rock is fractured and fragmented through (1) an excited sonic impulse/pressure wave that breaks the rock surface like discussed before; and (2) a discharge channel created inside the rock structure that vaporizes a micro part of the rock. The diameter of the channel increase from several micrometres to several hundred micrometres due to the expansion of the plasma channel. The expansion takes place during the first hundreds of nanoseconds after the electrical breakdown (Hoftun, et al., 2016).

The plasma-channel seeks out the path of least resistance through the rock and hence breakdown occurs at the weakest parts of the rock where fewer chemical bonds needs to be broken (McGregor, et al., 2007). The expansion of the discharge channel acts like a piston on the surrounding material, creating an efficient and tailored drilling action with different angular or radial orientation which eliminates the need for rotary drill bit (Timoshkin, et al., 2004).

2.1.3.2 Drilling Fluid

The drilling fluid in the PCD process has a multipurpose function. Due to differences in the electrical properties of the rock and dielectric fluid, it behaves as a superior electrical insulator which increase the chance of the conducting plasma channel going through the bulk of the rock (Timoshkin, et al., 2004).

The breakdown strength of water is greater than most rocks (sandstone, shale, or marble), for high-voltage pulses with a rise time of about 0.5-0.8 s or less. Hence rock mostly fail electrically before the water. According to experiments by Timoshkin, et al., (2004), there is no significant difference in the breakdown effect between the rock and the drilling fluid when water is replaced with oil. Both water and transformer oil have low conductivity, hence gives high efficiency of the plasma channel (McGregor, et al., 2007). The breakdown voltage of various materials will be discussed in detail in the subsequent chapters.

The drilling fluid also serves the purpose of removing drill cuttings and functions as drilling lubricant. The fluid is supplied by high pressured pump through metal tubes which form part of the design, to flush out drill cuttings from the borehole (Timoshkin, et al., 2004).

Using water as drilling fluid has been experimented and proven to work. The use of gas has proven more challenging and is still under investigation. Zaptec AS, presented a method of drilling on Mars, Asteroids, and the moons of Mars by plasma channel drilling. In their work, compressed CO_2 is one of the proposed fluids for cuttings removal (Hoftun, et al., 2016).

2.1.3.3 Detailed description of the drill head

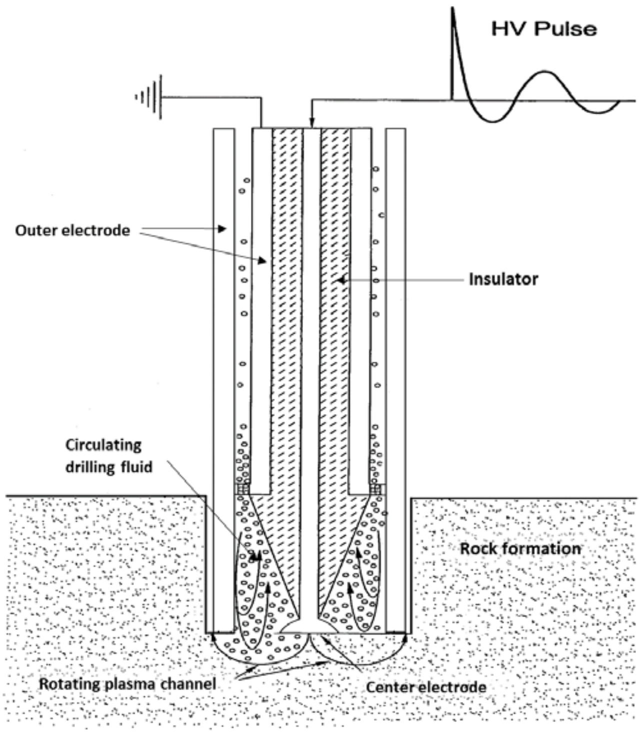


Figure 2.4: Schematic representation of the drill head (Timoshkin, et al., 2003)

Different materials are used for the electrodes in the drill head with the most preferred one being stainless steel (Timoshkin, et al., 2004). The material is chosen to optimize the lifetime and increase the overall reliability of the drill head. The components and configuration of the electrode assembly may also vary, depending on the type of bore to be created.

In the work presented by Timoshkin, et al., (2004), a high-voltage disc electrode was used as the centre electrode with a grounded cup-like electrode as the external electrode. To prevent electrical breakdown between the electrodes, an insulator, made of gas-filled nylon surrounds the internal electrode. A drill head of 35mm diameter internal electrode and 50 mm diameter external electrode with an inter-electrode spacing of about 7mm was used for most of the drilling tests undertaken by researchers in the University of Strathclyde, Glasgow (McGregor, et al., 2007).

An annular inter-electrode gap is provided by this type of configuration which promotes the formation of the plasma in any position within the gap. Self-rotation of the plasma occurs during the drilling process, eliminating the need for mechanical rotation (Timoshkin, et al., 2004).

2.1.3.4 Laboratory Test of the PCD Drill

McGregor & Turnbull (2007) carried out drilling tests, using two separate miniature PCD drills. The drills had 35mm and 50mm internal diameters. Samples of soft yellow sandstone and medium hard yellow sandstone were drilled. A 33kV output voltage and an HV pulses with an energy of 163 J were delivered to the drills. The results are shown in the table below

Table 1: Results of drilling with 35mm and 50mm PCD drills (McGregor, et al., 2007)

	SOFT SANDSTONE		**MEDIUM HARD SANDSTONE**	
	35 mm drill	**50 mm drill**	**35 mm drill**	**50 mm drill**
Drilling rate (cm/min)	15-16	9	5	2
			8	4

The 35mm drill achieved a drilling rate of more than twofold compared with the 50mm drill.

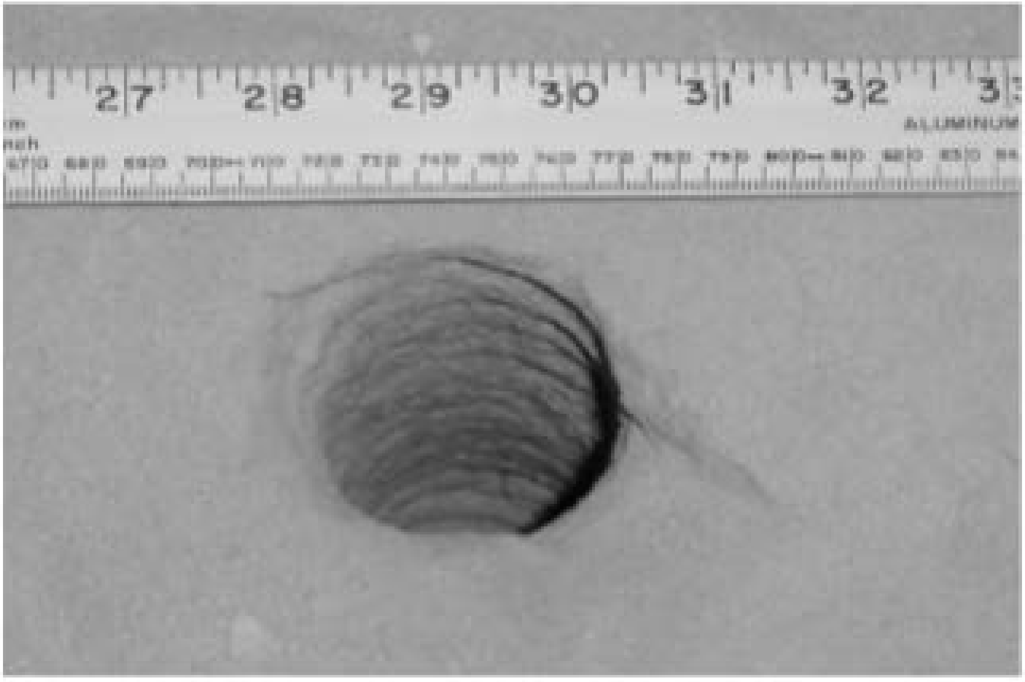


Figure 2.5: 50 mm hole drilled in yellow sandstone with PCD (Timoshkin, et al., 2003)

2.1.3.5 Power

Theoretically, the efficiency of the drilling process is maximized when voltages as high as possible are applied to electrodes to cause the rock to suffer breakdown before the fluid. (Timoshkin, et al., 2004) However, the maximum operating voltage of the system is practically restricted to less than 50 kV (McGregor, et al., 2007).

Table 2: Specific Energy For Drilling (McGregor, et al., 2007).

Pulse Repetition Rate (PPS)	**Specific Energy, Jcm^{-1}**	
	61 J/pulse	122.5 J/pulse
5	No data	474
10	803	581
15	781	589
20	937	859

Chapter 3 DRILL HEAD ELECTRIC FIELD

Plasma drilling has been done using water as drilling fluid. The possibility of using gas has been investigated by Zaptec but proved challenging. The following numerical simulations are performed to gain better understanding of the electric field around the drill bit. During the various simulations and calculations, numerous results were obtained, which aims at explaining most of the procedure and relevant theories.

3.1 Simulated Results

The Comsol multi-physics software was employed for the simulation (Comsol-Multiphysics, 2017). The simulations were made to: (1) verify if varied materials and fluid will influence the electric field in the rock. (2) try and optimize the geometry of the drill bit by changing the electrode configuration. The geometry chosen (figure 2.4) for the simulations correspond to the Timoshkin (2003) drill bit that was tested.

The simulations were employed to calculate and visualize the static electric field generated by the drill head before the plasma channel opens

3.1.1 Using water as drilling fluid

Water has dielectric constant of 80.6, which is greater than most rock with maximum dielectric permittivity of 5. For electrical pulses with rise times less than half a microsecond, water has values of critical breakdown field greater than those for rock, so the rock fails electrically before the water. Joule heating of the plasma formed in the breakdown channel results in extremely rapid expansion of the plasma column. The breakdown strength of water is hugely greater than that of the rock. Hence sparks initiated at the tip of the center electrode will go into the rock. Water is the ideal drilling fluid and is proven effective but this work investigates the possibility with gas.

Another problem with water is that it would freeze at the temperature of Mars and Europa. There is an ongoing research to develop ionic fluids that do not freeze at low temperatures. It might therefore be possible to use these in drilling operations on extra-terrestrial objects. (Hoftun, et al., 2014). Alternatively, it might also be possible to use a small amount of water around the drill head by heating it.

3.1.2 Dielectrics

A dielectric is a material that resist the flow of electric charges when applied through them but are polarized after shifting slightly from their average equilibrium positions. Thus, positive charges are displaced towards the field and negative charges shift in the opposite direction and thereby creating an internal electric field that reduces the overall field within the dielectric material itself (Serway, et al., 2013).

Dielectrics conduct electricity poorly, but can support electrostatic fields efficiently. Most dielectric materials are solid with examples including porcelain (ceramic), mica, glass, plastics, and oxides of various metals. Some fluids can also serve as good dielectric materials. Dry air, distilled water, and vacuum are examples of very efficient dielectrics (Bain, et al., 2017).

A dielectric begins to conduct current if the voltage across it is too great (electrostatic field becomes too intense), the phenomenon is known as *dielectric breakdown* (Deshpande, 2012; Devasahayam, et al., 2017).

The breakdown condition can reverse itself at voltages below the critical point in gas and liquid but usually permanent in solids. In components that use gases or liquids as the dielectric medium, this condition reverses itself if the voltage decreases below the critical point. But in components containing solid dielectrics, dielectric breakdown usually results in permanent damage (Devasahayam, et al., 2017).

3.1.3 Dielectric Constant

Maxwell "described the appearance of opposing charges on the two ends of a discontinuous circuit as being an electric displacement, measured as charge accumulation per unit area, Q/A, in coulombs per square meter" (Zhdanov, 2009). He then postulated a constitutive equation relating the amount of displacement to the applied electrical force. This is represented in differential notation as;

$$D = \varepsilon E \tag{3.1}$$

ε is the dielectric permittivity which has a well-defined value even in the absence of matter. That is 8.854 x 10^{-12} Farads/meter in free space. The constant is the ratio of the dielectric material’s ability to carry an alternating current to that of vacuum (Ren, et al., 2012). It can be expressed as

$$\varepsilon = {}^{\varepsilon_s}/_{\varepsilon_o} \qquad (3.2)$$

ε_s is the static permittivity of the material and ε_o is permittivity of vacuum.

Dielectric constant is greatly influenced by temperature, moisture levels, electrical frequency, and density (Nelson, 1981). Substances with a low dielectric constant include a perfect vacuum, dry air, and dry gases such as helium and nitrogen. Ceramics, distilled water, paper, mica, polyethylene, and glass have moderate dielectric constants, with metal oxides, in general, having high dielectric constants (Deshpande, 2012).

3.1.4 Using CO_2 as drilling fluid

Figure 3.1 below, shows simulation results of the drill bit using CO_2 as drilling fluid. The upper side is filled with CO_2 $\varepsilon_r = 1$, on the lower side rock $\varepsilon_r = 5$, a voltage of 35 KV is supplied to the centre electrode with the outer as the return path (ground).

CO_2, was used because of it abundance in the Martian and Venusian atmosphere. The dielectric permittivity of carbon dioxide as most gases is approximately 1 and essentially the same as vacuum.

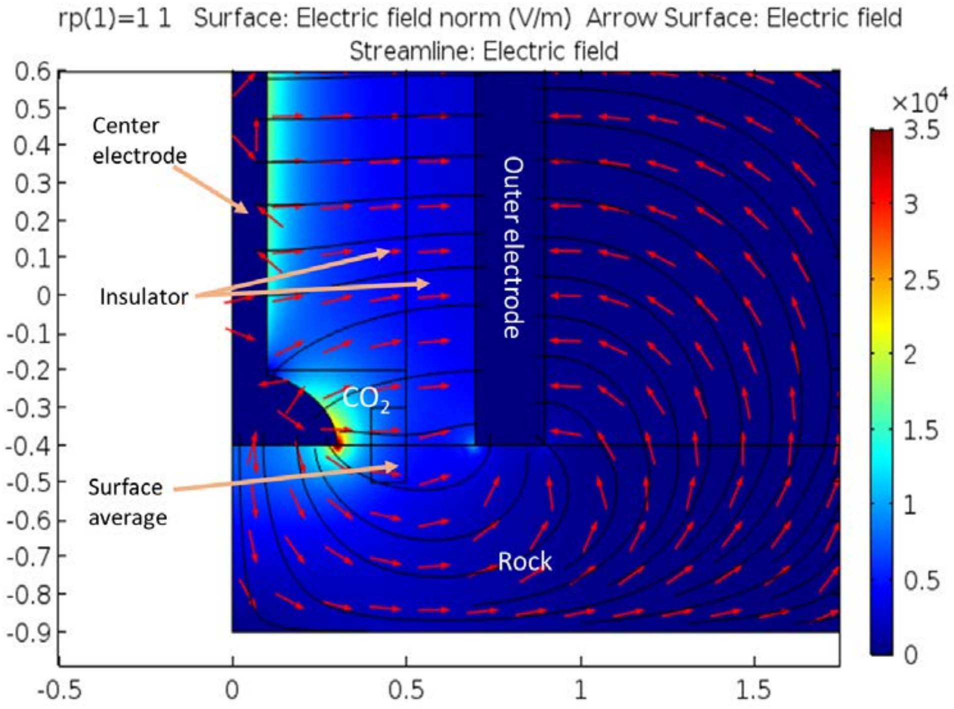


Figure 3.1: Half-section, rotational symmetry view of electric field around the drill head. Drilling fluid is CO2.

The breakdown voltage of CO_2 is very low but I couldn't find experimental data for the specific mars conditions. According to (Stumbo, 2013) is about 0.54 ± 0.02 kV for 0.5 torr cm.

We performed the calculation of the breakdown voltage in mars conditions in the next chapter and anticipate the results is at about 740 V for electrode gap of 1 cm.

This voltage is much smaller as compared with that of the rock (granite = 8.5-11 kV/m) (Nimmagadda, et al., 2014) and for 1 cm gap we have 1860 V (assuming linearity of breakdown voltage with electrode gap in solids). This simply means that even with higher electric field, surface average of 6130.8V/m in the rock and 7326.0V/m in the CO_2 gap, the sparks go through CO_2 rather than the rock. Comparable results were obtained for N_2 drilling, since the permittivity of CO_2 and N_2 are approximately the same.

The dielectric strength of gases is usually lower than that of the rock to be drilled, thus the spark forms in the gas. However compressed gas could be used as drilling fluid. (Hoftun, et al., 2014)

3.1.5 Channelling the Sparks Downward, by Using Insulators

To force the sparks to go down the rock, the strength of the electric field in the rock should be improved significantly or field in the fluid must be decreased. Insulators with high dielectric permittivity and significantly high breakdown voltage were used in the following simulations. Example of such insulator is dielectric ceramic (BaSmTi) (Morgan, 2013) with a dielectric constant of 76.5. A wide range of insulators with different permittivity is available in commercial activities.

The figures below show simulations of the drill bit electric field with an insulator between the two electrodes, having dielectric permittivity ranging from 5 to 100. The drilling fluid used is CO_2.

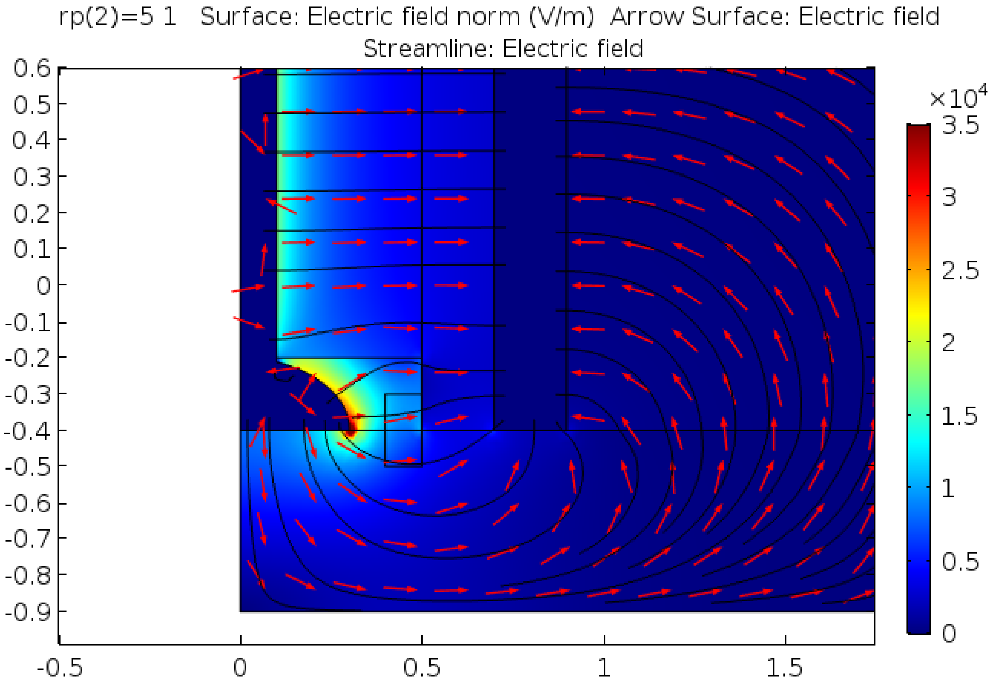


Figure 3.2: Half-section, rotational symmetry view of electric field for insulator with (εr = 5)

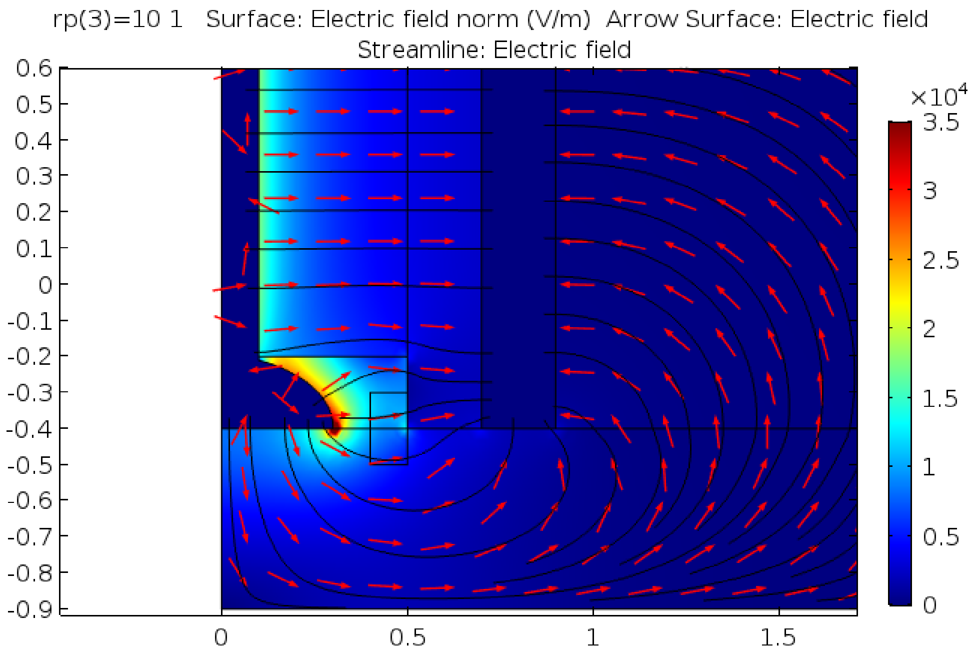


Figure 3.3: Half-section, rotational symmetry view of electric field for insulator with ($\varepsilon_r = 10$)

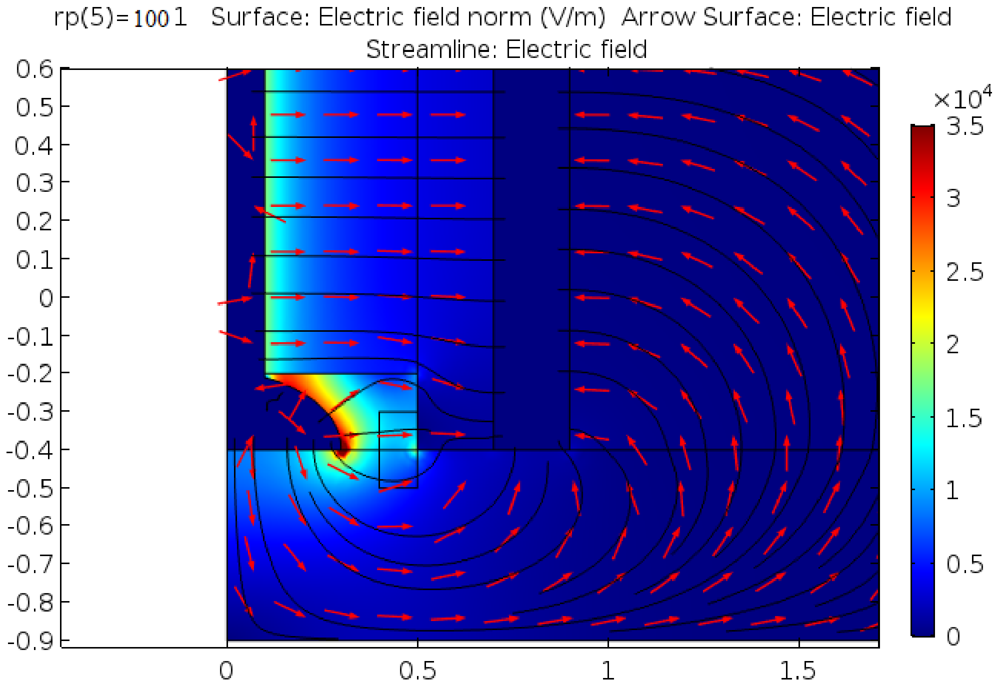


Figure 3.4: Half-section, rotational symmetry view of electric field for insulator with (ε_r = 100)

The electric field, surface average in the rock and in the gap for each of the above simulations were measured and tabulated below. The electric field in the rock increased slightly between $\varepsilon_r = 1$ and $\varepsilon_r = 10$; from 6130.8 V/m to 7365.5 V/m. but unfortunately the electric field in test area occupied by the dielectric fluid also increased, cancelling any gain.

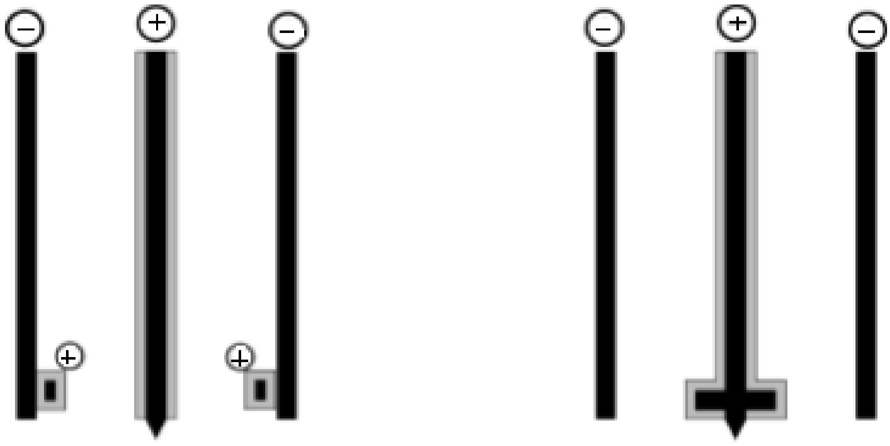
Other configurations of insulators can be tried, and should be possible to increase the difference in electric field between the rock and the gap.

Table 3: Electric field surface average for rock and gap in V/m

Dielectric constant (ε_r)	Electric field in rock V/m	Electric field in gap V/m	Field rock/ field gap
1	6130.8	7326.0	0.837
5	6902.0	9677.8	0.713
10	7365.5	10409	0.708
100	8230.1	11460	0.718

3.1.6 Channelling the sparks down by shaping the electrodes

If it is possible to shape the electric field so it has a weaker radial component, the spark can be forced to go downward inside the rock, rather than radially through the CO_2. That is, if the plasma channel of the spark starts forming at the tip of the centre electrode. This configuration can be achieved by placing an insulated conductor ring with the same voltage as the centre electrode, either near the outer electrode (figure 3.9a) or to sandwich the centre electrode (figure 3.9b) and insulated by the same material as the centre electrode.



(a) (b)

Figure 3.5: Electrode configuration with ring attached to: (a) outer electrode (b) centre electrode (Pattarini, et al., 2016)

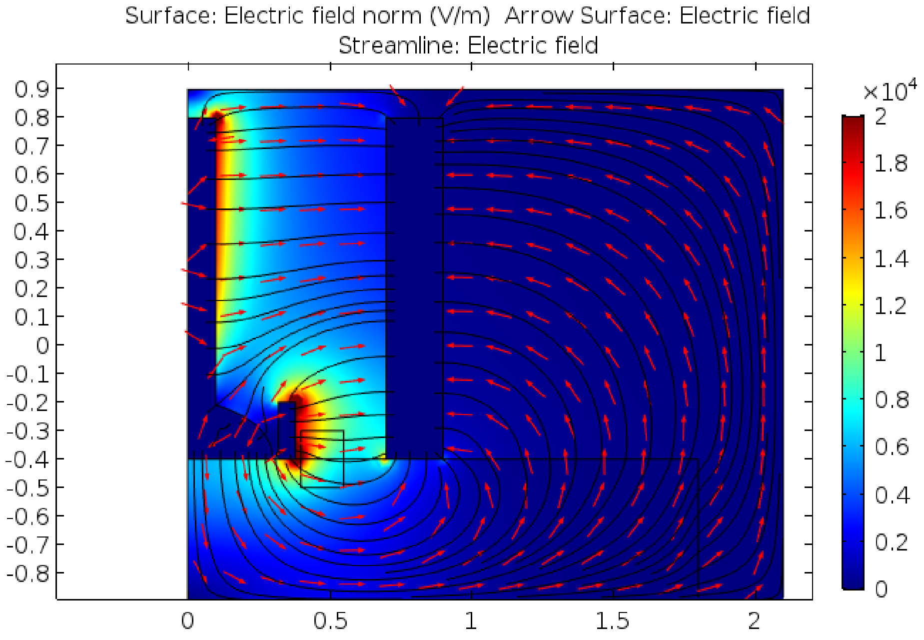


Figure 3.6: Electrode configuration with an insulated conductor ring attached to centre electrode

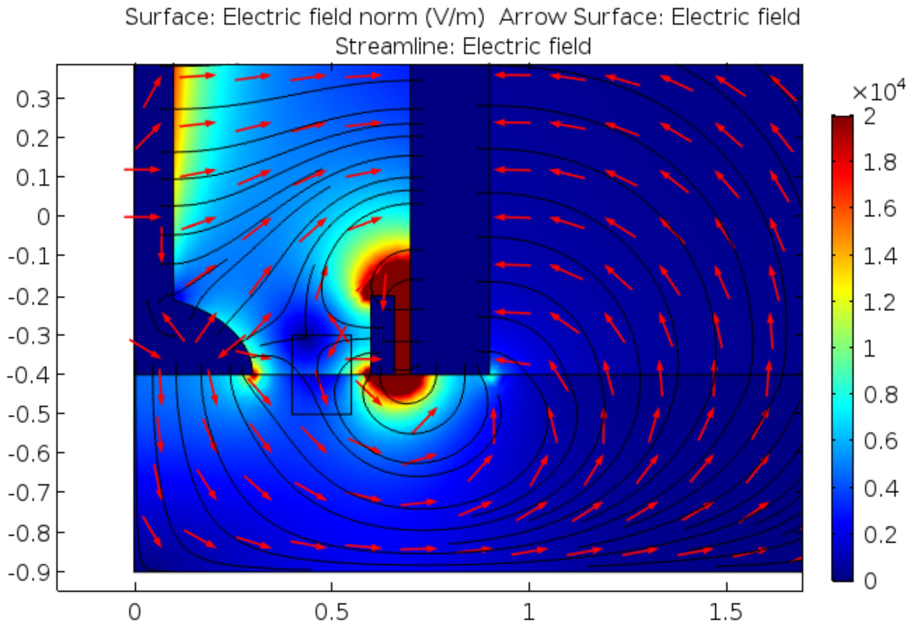


Figure 3.7: Electrode configuration with an insulated conductor ring attached to outer electrode

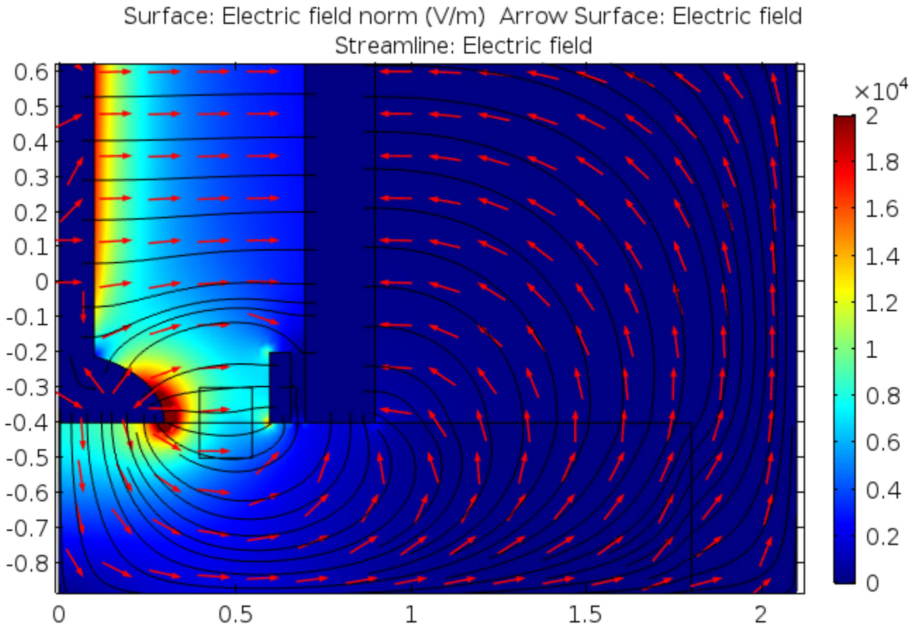


Figure 3.8: Electrode configuration with a conductor ring attached to the outer electrode inverse polarity

The system seems delicate and add complexity to the drill bit, but can effectively forc the spark into the rock. The inner ring type looks simpler and more robust. The simulated results of the two configurations (figure 3.10 and figure 3.11) seems to increase the downward field in to the rock but unfortunately, also increase the gap field. The position of the ring can be varied to get optimal results, and other configurations can be tried as well.

Table 4: Electric field surface average in rock and gap for ring configuration

Configuration	Electric field in rock V/m	Electric field in gap V/m	Field rock/ field gap
Inner ring	8895.3	12584	0.71
Outer ring	3600.7	3706.3	0.97
Outer ring inverse polarity	6464.7	8173.1	0.79

The relative difference in dielectric properties with the gas having less dielectric permittivity and less dielectric strength as compared to the rock, might make plasma drilling with gas extremely difficult. However, the use of powerful insulators and complex configurations gives slightly improved downward electric field into the rock. Overall, it was possible to optimize the drill but the gain seems low.

Several other different configurations were tried but with little progress. The most viable solution to the problem is to use a fluid with high breakdown voltage; therefore, I will review in the next chapter the breakdown voltage of materials and specially gases, to understand if there exist conditions at which breakdown voltage of the gas is higher than of the rock, like in the success of water PCD.

3.1.7 Cuttings Removal

Compressed CO_2, N_2 and CH_4 can be circulated to remove drill cuttings from the borehole, as suggested by (Hoftun, et al., 2014) for drilling on Mars.

The PCD process will be carried out under low energy levels, hence the cuttings are expected to be very fine. In Mars conditions, 1 gram of gas can potentially lift out over 3 kg of cuttings from a hole.

Removing such fine cuttings under Mars conditions with ambient pressure of 5 torr may well be an easy task. In an experiment conducted by (Zacny, et al., 2005), most cuttings were flushed out of the borehole with a pressure as low as of 30 torr.

With considerably low amount of power (few Watts), the Martian atmosphere can be compress to a useful pressure between the consecutive gas blasts.

Chapter 4 ELECTRICAL BREAKDOWN

This chapter introduces the fundamental concepts of electrical breakdown and how the various concepts discussed explain the subject of plasma channel drilling. The purpose is not to elaborate the details of all the subjects in electrical breakdown but to build a foundation that will introduce most of the terms required to adequately understand the subject matter of this thesis. The plasma drilling process has been proven effective with water; we however want to test the feasibility of drilling with a gas instead and estimate the breakdown strength for gases in the atmosphere of other planets.

Electrical breakdown occurs when the voltage applied across an electrical insulator exceeds the breakdown voltage. Hence the insulator become electrically conductive. The phenomenon may occur in solids, liquids, gases, and vacuum. The breakdown mechanism for each of these media is different. (Tesla, et al., 2016)

4.1 Electrical Breakdown in Solids and Liquids

4.1.1 Solids

Breakdown in solids causes permanent damage and materials do not recover their dielectric strength even after the applied voltage is removed. The breakdown of rocks usually is as a result of the porous (gas voids) nature of the material (Lisitsyn, et al., 1999). The breakdown strength of granite is approximately 8.5 – 11 kV/mm (Nimmagadda, et al., 2014).

Breakdown in solids is grouped in to various mechanisms which include (Wadhwa, 2007; 2014):

- Intrinsic or ionic breakdown
- Electromechanical breakdown
- Breakdown due to treeing and tracking
- Thermal breakdown
- Electrochemical breakdown

Breakdown of solids is a wide subject treated in textbooks like Wadhwa, (2007).

4.1.2 Liquids

Liquids may recover partially their dielectric strength after breakdown when the applied voltage is removed. Water for example recovers its original state after breakdown.

Breakdown in liquids may be classified into:

1. Breakdown in pure liquids (electronic breakdown):

The breakdown process in pure liquids is similar to that in gases and the electric strength is very high of the order of 1 MV/cm. At higher electric field above 100 kV/cm, conduction increases and more electrons are emitted, hence breakdown occurs (Lucas, 2001; Wadhwa, 2007)**.** Breakdown of pure liquids are very high.

Table 5: Breakdown strengths of pure liquids (Wadhwa, 2007)

Liquid	Breakdown strength in MV/cm
Benzene	1.1
Hexane	1.1 – 1.3
Nitrogen	1.6 – 1.88
Oxygen	2.4
Silicon	1.0 -1.2

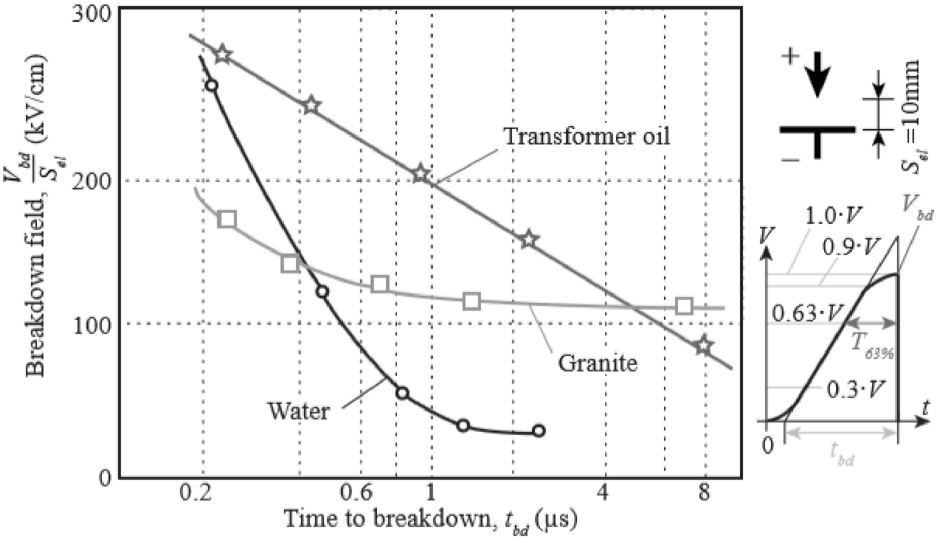
2. **Breakdown in impure liquids**

The dielectric strength in liquids is affected by impurities such as gas bubbles, suspended particles etc. In commercial liquids, the types of breakdown mechanism are (Wadhwa, 2007; Lucas, 2001):

- Suspended particle mechanism
- Cavitation and bubble mechanism
- Thermal mechanism
- Stressed oil volume theory

The physical breakdown mechanism of both solids and liquids are complex and outside the scope of this work. We, however treat in detail the mechanism in gases, with the

Townsend avalanche mechanism. Figures 5.1, present the breakdown strength of various rocks, water and transformer oil.



S_{el} = electrode distance

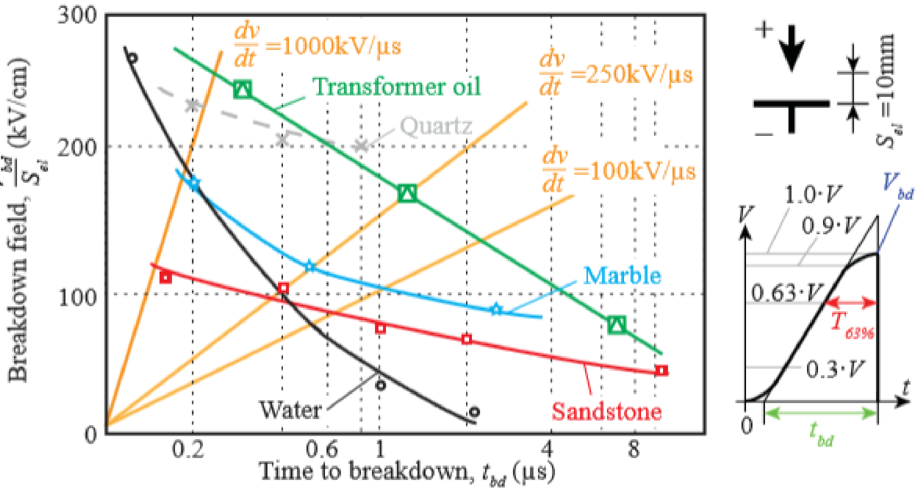


Figure 4.1: Breakdown field-time characteristics liquids and rocks (Hobejogi, 2014)

In figure 4.1, the breakdown voltage of the parameters was studied for different high voltage pulse rise time. That is another computation of the breakdown mechanism and working with rise time is another option for making PCD feasible.

4.2 Electrical breakdown in gases

4.2.1 Townsend Avalanche

At a current conduction order of 10^{-10} A/cm and at normal temperature and pressure gases are excellent insulators (Wadhwa, 2007).

When no electric field is applied, a state of equilibrium exists in the gas between the state of electrons and positive ions generation due to the decay process (Wadhwa, 2007). However, this equilibrium state is disturbed when high electric field is applied.

J. S. Townsend first studied the current generated in gases between two parallel electrodes and discovered that the current increased proportionally as the voltage is increased and then remains constant, at I_s which corresponds to the saturation current (Mytnikov, 2012). At higher voltages, the current increases exponentially due to ionization of gas by electron collisions. As the gap voltage increases from zero to V_1 the current increases linearly. For a gap voltage between V_1 and V_2 the current remains constant at a value I_s. See figure 4.2 below.

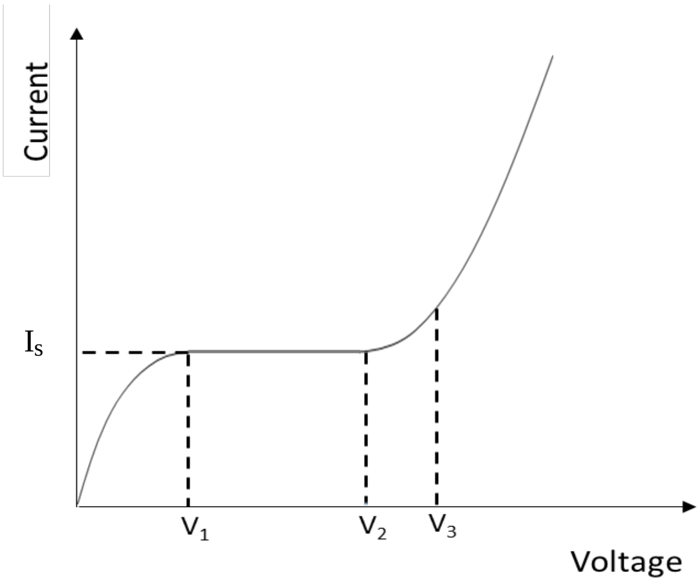


Figure 4.2. Current – Voltage relationship of gas

Townsend introduced a coefficient α known as the Townsend's first ionization coefficient which he defined as the number of electrons produced by one electron per unit length of path in the direction of the field. Using Townsend's first ionization coefficient, the incremental increase of electrons is given as:

$$dn = \alpha n \, dx \qquad (4.1)$$

Where, n is the number of electrons at a distance x away from the cathode. Integrating this

equation over the distance, d, from cathode to anode gives

$$n = n_o e^{\alpha d} \tag{4.2}$$

Where, n_o is the number of primary electrons generated at the cathode.

Hence in terms of current at the anode

$$I = I_o e^{\alpha d} \tag{4.3}$$

Where I_o, is the current leaving the cathode and $e^{\alpha d}$, the electron avalanche; that is the number of electrons produced by one electron in travelling from cathode to anode.

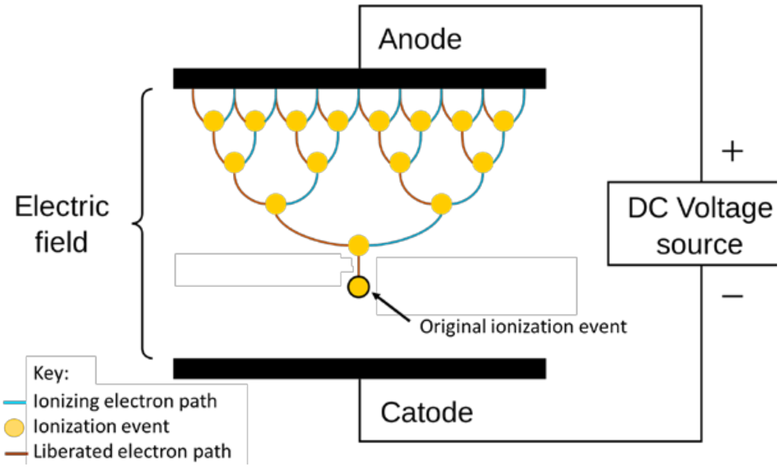


Figure 4.3: Visualisation of a Townsend Avalanche (Wikipedia, 2017)

The first ionization coefficient α is dependent on the electron energy distribution in gases, which depends only on the ratio of the applied electric field, E and the gas pressure, P (i.e. $\frac{E}{P}$).

Therefore, α can be written as

$$\alpha = \mathrm{P\,f}\left(\frac{\mathrm{E}}{\mathrm{P}}\right) \tag{4.4}$$

The dependence between $\frac{\alpha}{P}$ and $\frac{E}{P}$ has been confirmed experimentally and f is a function to be determined experimentally or by models. Several other secondary processes contribute to the breakdown process. Some of these include secondary electrons produced at the cathode by positive ion impact, secondary electron emission at the cathode by photon impact, and ion impact ionization of the gas. To account for these processes the Townsend second ionization coefficient, γ, was introduced. The steady state current equation accounting for both Townsend coefficients, can be rewritten as

$$\mathrm{I} = \mathrm{I_o}\frac{e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \tag{4.5}$$

Here γ may represent one or more possible mechanisms ($\gamma = \gamma_i + \gamma_{ph} + \ldots$). Typical values of γ in electrical discharges are 0.01 to 0.1 (Fridman, et al., 2004). Values for γ are highly dependent on the work function of the material. Low work function of the cathode surface will produce more emission. The value of γ is relatively small at low values of $\frac{E}{P}$ and higher at greater values of $\frac{E}{P}$. This is to be expected, since at high values of $\frac{E}{P}$ there will be a greater number of positive ions and photons with high energies sufficient to cause ionization upon impact on the cathode surface (Wadhwa, 2007).

4.2.2 Townsend Breakdown Mechanism

Townsend breakdown mechanism is the ignition of self-sustained current in a gap controlled by secondary emission from the cathode (Fridman, et al., 2004).

In attempting to account for the ionization required for the initiation of a self-sustained electrical discharge, Townsend developed a theory of the electric spark (Neuman, 1929).

While the cumulative ionization of the gas at high fields by electrons constitutes part of the mechanism of the spark, Townsend has shown that for a self-sustained discharge it is essential for electrons to be liberated from the cathode (Wadhwa, 2007).

As the voltage between the electrodes increases, the current at the anode increases per equation (4.5), and we can see that the current growth is beyond control and breakdown occurs when

$$1 - \gamma(e^{\alpha d} - 1) = 0.$$

If $e^{\alpha d} \gg 1$, then:

$$1 - \gamma e^{\alpha d} = 0 \tag{4.6}$$

When $\gamma e^{\alpha d} < 1$, the discharge is non-self-sustained (i.e., when the voltage is reduced the current starts decreasing and extinguish when the source is removed) and when $\gamma e^{\alpha d} > 1$, the discharge is a self-sustained one (i.e. even if the voltage is reduced the current does not decrease and maintains itself). Secondary electron photoemission also accounts for self-sustained discharged (Panneerselvam, 2017; Wadhwa, 2007).

Since $e^{\alpha d} >> 1$, the anode current is equal to the external current. Once the spark is initiated, a plasma channel opens dramatically the resistance but in practice it is limited by the resistance of the external circuit and the voltage drop across the gap.

4.2.3 Paschen's Law (Sparking Potential)

The Paschen law is an equation that gives the voltage necessary to start a discharge or electric arc between electrodes in a gas as a function of pressure and gap length. This voltage is known as the breakdown voltage of the gas (Wadhwa, 2007).

Substituting equation (4.5) into (4.6) gives an analytic expression for breakdown voltage for uniform field gaps with respect to pressure and gap length.

$$e^{f\left(\frac{E}{P}\right)Pd} = \frac{1}{\gamma} + 1 \tag{4.7}$$

Taking the logarithm of both sides of (4.7) gives, (Wadhwa, 2007).

$$f\left(\frac{E}{P}\right)Pd = ln\left(\frac{1}{\gamma} + 1\right) = K$$

For a uniform field, V_B = Ed, the voltage between the electrodes. Hence:

$$\boldsymbol{V_B = K(Pd)} \tag{4.8}$$

Equation (4.8) shows that for a given gas and electrode material, the breakdown voltage of a uniform field gap is a unique function of the product of gas pressure and the gap length. This is known as Paschen's law and the curve that explain this relation is the Paschen curve.

From numerical and theoretical analysis, equation 4.4 can be written in the form (Schnyder, 2013),

$$\alpha = \mathrm{AP}e^{\left(-B\frac{E}{P}\right)} \tag{4.9}$$

Where A and B are parameters determined experimentally and found to be roughly constant over a restricted range of $\frac{E}{P}$ for a given gas. Equation (4.6) can be rewritten as:

$$\alpha\mathrm{d} = \ln\left(1 + \frac{1}{\gamma}\right) \tag{4.10}$$

Substituting equation (4.10) by (4.9), gives:

$$\mathrm{AP}e^{\left(-B\frac{E}{P}\right)}d = \ln\left(1 + \frac{1}{\gamma}\right) \tag{4.11}$$

$$\frac{-BP}{E} = ln\left[\frac{ln\left(1 + {}^{1}/_{\gamma}\right)}{APd}\right] = \ln\left[\ln\left(1 + {}^{1}/_{\gamma}\right)\right]ln[APd]$$

Substituting E $= \frac{V}{d}$ and simplifying we have:

$$\mathrm{V_B} = \frac{BPd}{\ln(APd) - \ln[\ln(1 + \frac{1}{\gamma})]} \tag{4.12}$$

Where V_B is the breakdown voltage in Volts, P is the pressure in Pascals, d is the gap distance in meters, γ is the secondary electron emission coefficient at the cathode, A is the saturation ionization in the gas at a field $\frac{E}{P}$ and B is a normalization constant.

Equation 4.12 is commonly used for the breakdown voltage and it would be used to estimate the breakdown voltage of various atmospheres in the section that follows. A diagram showing Paschen curve for various gases using the equation (4.12) is shown in figure 4.3

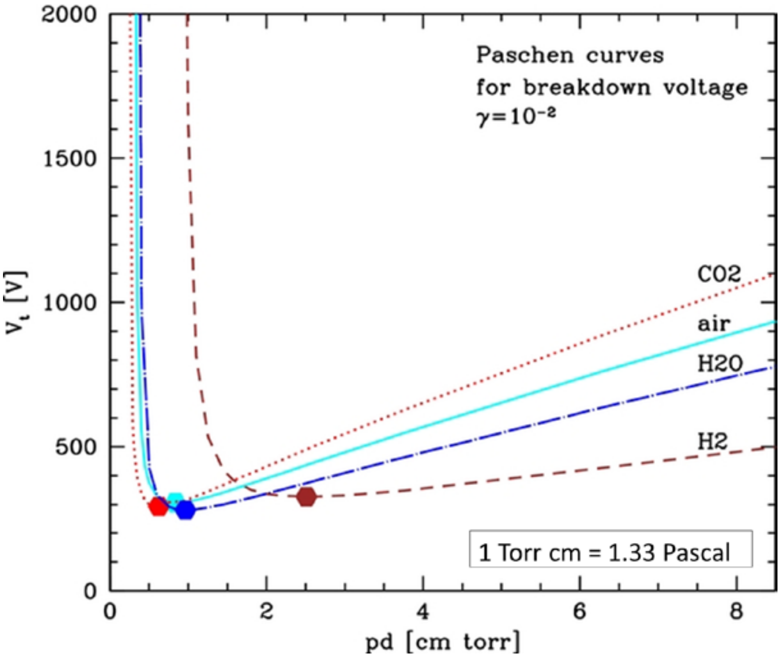


Figure 4.4: Paschen curve for different gases (Helling, 2013)

Note that there exists a minimum sparking potential (V_{bmin}) at a (Pd) min value.

$$V_{bmin} = 2.72\,\frac{B}{A}ln\left(1+\frac{1}{\gamma}\right) \tag{4.13}$$

This V_{bmin} can be explained qualitatively by considering the efficiency of ionization. For $Pd > (Pd)\ min$, electrons crossing the gap make more frequent collisions than at (Pd) min, but the energy gained between collisions is less, which results in a lower ionization level for a given gap voltage. For Pd < (Pd)min, electrons crossing the gap make less frequent collisions than at (Pd)min. Therefore, (Pd)min corresponds to the highest ionization frequency (Wadhwa, 2007). Values of (Pd) min and their corresponding V_{bmin} for some gases are given in the table below.

Table 6: Minimum Sparking Constants for Various Gases (Wadhwa, 2007; Lucas, 2001).

Gas	Pd(min)	V_{bmin} volts
H_2	1.05	230
N_2	0.65	240
Air	0.55	325
CO_2	0.57	420
He	4.0	155
O_2	0.70	450

4.3 Breakdown Voltage Using the Paschen Law

The breakdown voltage for the various planets and other solar system objects is estimated using the Paschen Law. The surface properties of some selected planets and other objects are outlined in table 9 in chapter 5.

4.3.1 Estimating breakdown voltage for the Mars application

The atmosphere of Mars is 96% CO_2 plus other gases, with an average surface pressure P = 0.0063 atm and temperature T = 210 K (- 63 ºC). Assuming the atmosphere was filled with pure CO_2, the breakdown voltage could be estimated with equation (4.12)

But the value of A for Mars conditions can be estimated from equation 4.14 (Berzark, et al., 2006);

$$\mathrm{A} = \frac{\sigma_n}{\mathrm{k}\, T_n} \qquad 4.14$$

Where, σ_n is the electron collision cross section, k is Boltzmann's constant and T_n is the temperature of the neutral atoms.

From table 7, the values of parameters A and B at standard temperature and pressure for CO_2 are as follows; A = 20 $cm^{-1}Torr^{-1}$ and B = 466 $Vcm^{-1}Torr^{-1}$. The unit used for pressure in the following calculations is Torr (1 Torr = 0.00131atm).

Table 7: Values of parameters A and B for different gases (Fridman, et al., 2004).

Gas	A ($cm^{-1}Torr^{-1}$)	B ($Vcm^{-1}Torr^{-1}$)	$\frac{E}{P}$ range ($V\ cm^{-1}Torr^{-1}$)	V_i (volts)
H_2	5	130	150-600	15.4
N_2	12	342	100-600	15.5
Air	15	365	100-800	—
CO_2	20	466	500-1000	12.6
He	3	34	20-150	24.5
Hg	20	370	200-600	—

Parameter A is recalculated for Mars with temperature - 63°C (210 K) as follows;

$$AT_n = \frac{\sigma_n}{\mathrm{K}} = \text{constant} \tag{4.15}$$

$$A_{Mars}T_{Mars} = AT_n \tag{4.16}$$

Where A_{Mars} is the parameter A in Mars conditions, T_{Mars} is Mars temperature and T_n in Kelvin. Hence;

$$A_{Mars} = \frac{\mathrm{A}T_n}{T_{Mars}} = \frac{20\ x\ 298}{210} = \mathbf{28.38\ cm^{-1}\ Torr^{-1}}$$

The Townsend second ionization coefficient γ, can be estimated from equation (4.13) as;

$$\gamma = \frac{1}{e^{\frac{AV_{bmin}}{B\times 2.72}}} \tag{4.17}$$

For CO_2,

$$\gamma_{CO_2} = \frac{1}{e^{\frac{20\ x\ 420}{466x\ 2.72}}} = \mathbf{0.0013}$$

Breakdown voltage of CO_2 in Mars conditions with d = 1cm is therefore;

$$V_{B_{Mars}} = \frac{466\ x\ 4.79\ x 1}{\ln(28.38\ x\ 4.79\ x\ 1) - \ln[\ln(1 + \frac{1}{0.0013})]} = \mathbf{739.58\ V}$$

From the above calculation, the breakdown of Mars’ atmosphere is very small and the problem of sparking in the gas is much more severe in Mars conditions than on Earth. The breakdown voltage of the rock is likely to be the same as that in earth’s conditions.

The procedure was repeated for Earth, Venus and Titan, and the results are shown in the table below

Table 8: Breakdown Voltage of the atmosphere of some planets and objects in the Solar System for d = 1 cm.

Object	Gas	A_{object} (cm^{-1} $Torr^{-1}$)	γ_{gas}	Breakdown Voltage V_B (kV)
Venus	CO_2	8.09	0.0013	2840
Earth	Air	15.00	0.0050	36
Mars	CO_2	28.38	0.0013	0.7
Titan	N_2	38.16	0.0452	40

The breakdown voltage of Titan is slightly higher than that of Earth and present a very good atmosphere for plasma drilling. Venus with a breakdown voltage of 2.84 MV presents the best atmosphere for plasma drilling.

4.4 Breakdown in vacuum

In a vacuum of the order 10^{-5} torr, breakdown due to an electron avalanche is not possible since electrons cross the inter-electrode gap without any collision. Formation of vacuum arc is because of cold emission from the micro spikes on the surface of the cathode (Wadhwa, 2007).

In ideal conditions, experimentally vacuum breakdown strength is up to $3*10^7$ V/cm. Electrons that create the spark must all be torn away from the electrode but the breakdown is reduced to about 10^5 by several secondary factors, such as electrode microscopic geometry and surface chemistry; the material of the electrode and its surface contaminations being the most crucial factors and varies a lot.

The breakdown mechanism can be classified as cathode-type or anode-type depending on the electrode that first experience thermal instability which initiate the emission (Ilic, et al., 2011). The breakdown which result from this process is a thousand times greater than gas breakdown. This result from the fact that the mean free path for electrons in vacuum is large compared to in gas (Wadhwa, 2007).

The Moon and Europa, present an almost vacuum atmosphere in the order of 10^{-10} torr and 10^{-9} torr respectively. Asteroids and Comets do not have any atmosphere and exist in a deep or perfect vacuum. Since the breakdown strength in vacuum is very high, plasma drilling will be best practise on these objects and the issue of sparks found in the gap should not affect those conditions.

Chapter 5 REVIEW OF PLANETS AND DRILLING SYSTEMS

This chapter seeks to introduce you to the various solar system objects outlined in this work. Emphasis would be on the *atmosphere*, the *rock type*, *regolith*: - the layer of unconsolidated solid material covering the bedrock of planets, and past and on-going investigated drilling systems needed for sampling and in-situ analysis on the various planets/objects.

The table below summarizes the rocks and fluid of planets and other objects and the breakdown voltage estimated with Paschen law, for a drill bit of the Zaptec/Glasgow type.

Table 9: Surface properties of objects in the Solar System

Objects	Surface material	Atmosphere (Gas/dielectric)	Surface Pressure (atm)	Surface Temperature (K)	Atmospheric breakdown voltage (kV)
Venus	Desert Rock	Carbon dioxide	90.80	737	2800
Earth	Silicate Rock	Air	1.0	288	36
Mars	Ice	Carbon dioxide	0.0063	210	0.74
Moon	Lunar Soil (Regolith)	Weak Vacuum	$9.87e^{-13}$	220	Vacuum
Europa	Ice	Oxygen	$9.87e^{-12}$	102	Vacuum
Titan	Ice	Nitrogen	1.45	93.7	40
Asteroids/ Comets	Ice	Vacuum	—	—	Vacuum

5.1 Venus

Venus is the second planet from the Sun with no natural satellite and the second-brightest natural object in the sky at night after the Moon. It is bright enough to cast shadows (Lawrence, 2005). Venus is a terrestrial planet and is sometimes called Earth's "sister planet" due to their similarities in size, mass, proximity to the Sun, and bulk composition. It is however extremely different from Earth in other respects. Water oceans that may have existed in the past, are no more available, due to a runaway greenhouse effect (Shiga, 2007). Observation of Venus' surface is nearly impossible in visible light due to the thick clouds; hence the first detailed maps could only be produced after the arrival of the Magellan orbiter in 1991. It was the first planet beyond Earth visited by a spacecraft (Mariner 2) in 1962, and the first to be successfully landed on (by Venera 7) in 1970.

5.1.1 Atmosphere

It has the densest atmosphere of the four terrestrial planets, consisting of 96.5% carbon dioxide, 3.5% nitrogen, and traces of sulphur dioxide gas (Taylor, 2014). The mass of its atmosphere is 93 times that of Earth's, whereas the pressure at its surface is 9.2 MPa which is about 92 times that at Earth's surface. The density at the surface of the planet is 65kg/m^3, 6.5% that of water.

Venus generates the strongest greenhouse effect in the Solar System, making it the hottest planet in the Solar System, with a mean surface temperature of 735 K (Wikipedia, 2012). This temperature is higher than that used for sterilization on Earth. An ozone layer in the atmosphere was reported by the "Venus express" in 2011 (ESA, 2011). The possibility that life exists in the upper cloud layers of Venus, 50 km up from the surface, where the temperature ranges between 303 and 353 K (30 and 80 °C) is also speculated (Landis, 2003).

The atmosphere of Venus has the highest estimated breakdown voltage according to the calculations in chapter 4. The idea of plasma drilling here seems highly possible. Conditions such as the extremely high temperature of will however be a source of worry.

5.2 Mars

Mars is the fourth planet from the Sun and it is often referred to as the "*Red Planet*" for it reddish appearance the prevailing iron oxide gives to its surface (NASA, 2001). Mars has two small and irregularly shaped moons: Phobos and Deimos. It's rotational period and seasonal cycles are like those of Earth, as is the tilt that produces the seasons (Yeager, 2008).

The volume of water ice in the south polar ice cap, if melted, would be sufficient to cover the entire planetary surface to a depth of 11 meters (Franklin, 1996). On November 22, 2016, NASA reported finding a large amount of underground ice in the Utopia Planitia region of Mars. The volume of water detected has been estimated to be equivalent to the volume of water in Lake Superior (Davies, et al., 1994).

Mars can easily be seen from Earth with the naked eye, as can its reddish colouring. Its apparent magnitude is surpassed only by Jupiter, Venus, the Moon, and the Sun. Mars is approximately half the diameter of Earth with a surface area only slightly less than the total area of Earth's dry land (Konopliv, et al., 1999).

5.2.1 Atmosphere

Mars is a terrestrial planet with a thin atmosphere, composed of about 95.32% carbon dioxide with about 2.7% nitrogen and 1.6% argon (Hoftun, et al., 2014). The average *atmospheric pressure* on the surface today is 600 Pa, which is about 0.6% that of the Earth (101300 Pa) (Bolonkin, 2009). The dusty atmosphere of Mars has it highest atmospheric density equal to that found 35 km above Earth's surface and it *scale height* is about 10.7 km in height, (Carr, 2006) higher than Earth's, 8.2 km. This is so, because the surface gravity of Mars is only about 38% of Earth's, an effect neutralized by both the lower temperature and molecular weight of the atmosphere. The average surface temperature on Mars is approximately 213K(-60^{o}C).

The current conditions on Mars does not allow liquid water to exist on the surface due to the low temperature and atmospheric pressure. However, in very few locations at low elevation during summer, water may exist for short periods (Hoftun, et al., 2014).

Very unfortunately the Paschen law estimation suggest that Mars is the worst planet to drill with plasma, the atmosphere of the planet has the least breakdown voltage according to the estimated results. Sparking in this atmosphere is very severe than on Earth and will have serious consequence on electronic equipment sent there. The current estimate of 740V/cm is close to the 540V/cm indicated by Stumbo, (2013) currently used as limit to avoid unwanted sparking on the electrical systems necessary for the Mars spacecrafts.

Plasma drilling on Mars may be made feasible with some other tricks, maybe playing with the rise time of the pulse, or utilizing a liquid drilling fluid.

The scale height, H of a planet is given by (NASA, 2017)

$$H = \frac{kT}{mg} \qquad 5.1$$

Where T is temperature in Kelvin, m: average mass of atoms in kilograms, g: acceleration of gravity in meters/sec and k: Boltzmann's Constant.

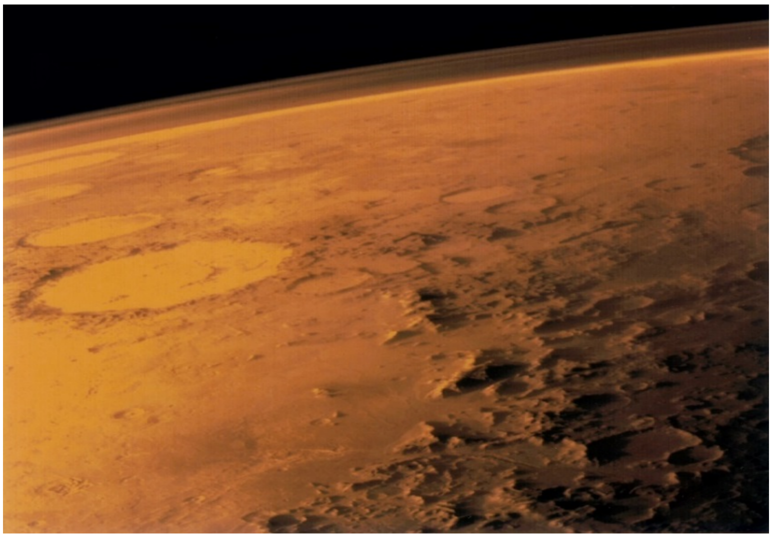


Figure 5.1: The rarefied atmosphere of Mars. Credit:(NASA)

5.3 Moon

The Moon is the fifth-largest natural satellite in the Solar System and the only permanent natural satellite that orbits planet Earth. The moon with a mean density of about 3.344 g/cm3 (Williams, 2006) happens to be the second densest satellite after Jupiter's satellite Io. The average distance of the Moon from the Earth is 384,400 km (Scott, 2016).

The ocean tides and the slight lengthening of the day is caused by the moon’s gravitational influence. The NASA Apollo crewed lunar missions of 1969 and 1972 returned over 380kg of lunar rocks, for further understanding of the Moon (Wikipedia, 2017).

5.3.1 Atmosphere

The tenuous s atmosphere of the moon is nearly vacuum, with a total mass of less than 10 x 10^3 kg (Globus, 1977). The surface pressure is around 3×10^{-15} atm and the average surface temperatures are reported to be between 150 to 220 K. Elements such as sodium, potassium, helium, neon, argon, and polonium-210 have been detected in the atmosphere of the Moon (Steigerwald, 2015). The absence of such neutral species (atoms or molecules) as oxygen, nitrogen, carbon, hydrogen and magnesium, which are present in its regolith, is a mystery (Stern, 1999). The first Indian mission to the moon in October 2008 (Chandrayaan-1) detected water vapour in the atmosphere, which vary with latitude, with a maximum at approximately 60–70 degrees; it is possibly generated from the sublimation of water ice in the regolith (Sridharan, et al., 2010).

The moon with it “vacuum atmosphere” present a good environment for plasma drilling. The moon has been drilled before, and drilling again might not be a top priority.

5.4 Titan

Titan (planet-like moon) is the largest and sixth ellipsoidal moon of Saturn, and the only moon known to have a dense atmosphere. Unmistakable evidence of surface water has been found of Titan. Earth is the only object apart from Titan with stable bodies of water. Titan is 50% larger than Earth's Moon, and 80% more massive. It is the second-largest moon in the Solar System, after Ganymede, and is larger than Mercury. Discovered in 1655 by the Dutch astronomer Christiaan Huygens, Titan is primarily composed of water ice and rocky material. The Cassini–Huygens mission in 2004, discovered liquid hydrocarbon lakes in Titan's polar regions. The seas of Titan is composed of liquid methane (Greicius, 2016).

5.4.1 Atmosphere

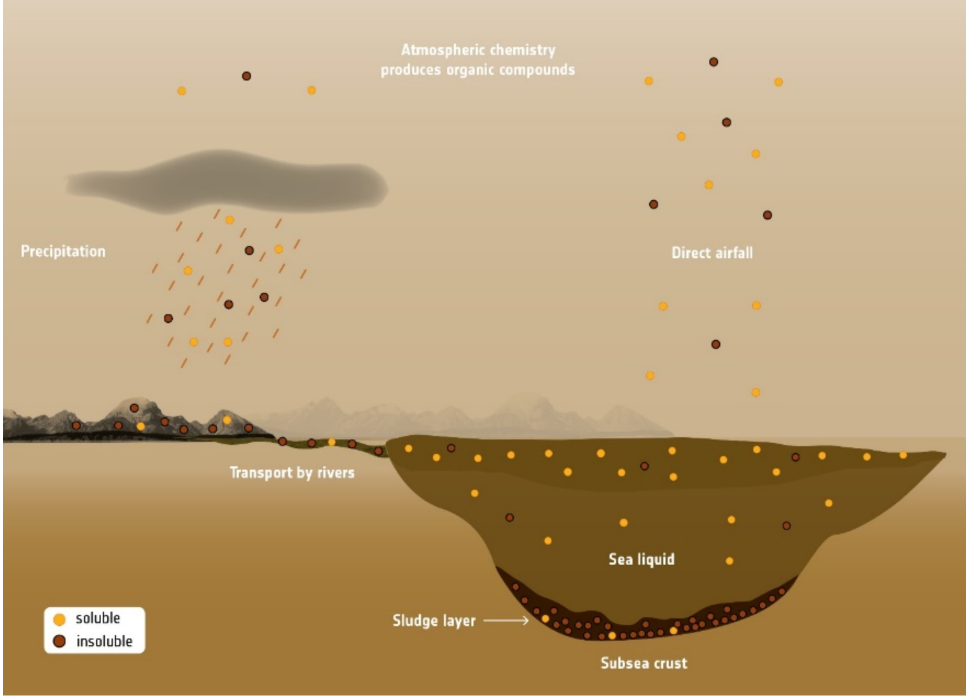


Figure 5.2: Organic compounds make their way to the seas and lakes on Titan (Greicius, 2016).

The atmosphere of Titan is largely nitrogen (N_2) with minor components leading to the formation of methane and ethane clouds, and nitrogen-rich organic smog. The climate including wind and rain creates surface features like those of Earth, such as dunes, rivers, lakes, seas (probably of liquid methane and ethane) (figure 5.2), and is dominated by seasonal weather patterns as on Earth. With its liquids (both surface and subsurface) and robust nitrogen atmosphere, Titan's methane cycle is analogous to Earth's water cycle, at a much lower temperature of about 94 K. Earlier observations from the Voyager space probes have shown that Titan's atmosphere is denser and massive than Earth's, with a surface pressure of about 1.45 atm. Titan's lower gravity means that its atmosphere is far more extended than Earth's (Turtle, 2007).

The atmosphere of Titan is opaque at many wavelengths and as a result, a complete reflectance spectrum of the surface is impossible to acquire from orbit. Titan's atmospheric composition in the stratosphere is 98.4% nitrogen with the remaining 1.6% composed mostly of methane (1.4%) and hydrogen (0.1–0.2%) (Niemann, et al., 2005).

In recent years, the detection of polycyclic aromatic hydrocarbons and propene in the atmosphere of Titan has been reported by researchers at the IAA-CSIC on June 6, 2013 and on September 30, 2013 by NASA’s Cassini spacecraft respectively.

Furthermore, the experiment already done on earth in our atmosphere can be representative of how drilling will be on Titan, so we can test it easily.

In Titan, there is liquid methane that can be used as drilling fluid, solving many of the problems encountered with using gas. The breakdown strength of methane is expected to be high like the Breakdown strength of pure liquids.

5.5 Europa

Europa is the sixth – closest moon of Jupiter and the smallest of its four Galilean satellites. It is also the sixth largest moon in the solar system and was discovered by Galileo Galilei on January 8, 1610 (Blue, 2017).

Europa is covered in smooth ice with salty water lying beneath it surface and it is believed to be the smoothest solid surface known in the solar system (Eur17). A water ocean which could habit extra-terrestrial life is believed to exist beneath the surface of Europa. NASA also reported in 2014 evidence of plate tectonics in Europa’s thick ice shell which happens to be the first of such geological activity on a world other than earth.

5.5.1 Atmosphere

Figure 5.3: Animated image of possible water plumes 'erupting' on Europa. Credit: (NASA)

Europa has a thin atmosphere mostly of molecular oxygen. The oxygen is not from biological source but from the splitting of water into oxygen and hydrogen constituents by solar ultraviolet radiations and charged particles from the Jovian magnetospheric environment which collide with Europa's icy surface. The surface pressure of Europa's atmosphere is 0.1μPa or 10^{-12} times that of the Earth. The presence of a tenuous ionosphere was confirmed by Galileo spacecraft in 1997 providing evidence of an atmosphere.

Europa's mean surface temperature is about 102K (-171°C), which makes the crust as hard as possible (McFadden, 2006).The radiation levels at the surface of Europa (moon) is equivalent to a dose of about 5400mSv per day, enough to cause severe illness or death to humans in just a day (Williams, 2015).

Plasma channel drilling will work great on Europa since it is vacuum and will be very interesting to drill deep here to access the water oceans beneath it. However, the breakdown strength of ice is high at 300-700 KV/cm and spark channels are self-healing (Kosaki, et al., 1978). If possible melted ice (water) can be used as drilling fluid.

5.6 Asteroids and Comets

Asteroids and comets are rock remnants or debris believed to be left over from the early formation of our solar system some 4.6 billion years ago (Dunford, 2017). They have no atmosphere, but rich in water (NASA, 2017). These small bodies are time capsules that may contain interesting clues about our solar system.

Asteroids, sometimes called minor planets, are mostly found orbiting between the planets Mars and Jupiter (main asteroid belt), but many swing nearer to Earth and even cross our orbit. The first and the biggest asteroid, Ceres, was discovered in 1801 by Giuseppe Piazzi (Dunford, 2017). Asteroids are smaller in size and irregular in shape compared to the planets and moons of the solar system. The total mass of all the asteroids combined is less than the mass of Earth's moon.

Asteroids are classified into three categories based on their composition. The *C-type or chondrite asteroids* are the most common of the group and consist mainly of clay and silicate rocks and are dark in appearance. The S-type or stony asteroids are mostly made up of silicate materials and nickel iron. The M-type or metallic asteroids are mostly nickel iron (2017).

Comets are found in the outer reaches of our solar system, either in the Kuiper Belt just beyond the orbit of Pluto, or in the vast, mysterious Oort cloud that may extend halfway to the nearest star. Over billions of years, countless comets and asteroids have collided with Earth, enriching our planet with water. Chemical markers in the water of our oceans suggest that most of the water came from asteroids. Recent observations hint that ice, and possibly even liquid water, exists in the interiors of asteroids and comets (NASA, 2017).

Asteroids and comets presents the best working environment for PCD. Problem here, will be how to remove the drill cuttings because of the complete lack of gravity and specially absolutely no gas to be used as fluid.

Maybe an electrostatic- electromagnetic- plasma system can be developed to carry away the cuttings in absence of gravity.

5.7 Rocks

The nature of the rock-type present on a planet or object may play a key role as to which type of drilling technology is needed. Different rock-types may exist on different objects in the solar system. This section outlines the type of rocks found on other Solar System objects.

Venus, the nearest planet to ours is reported to be covered with fine-grain dust, smaller than 0.02 mm and with other sizable rocks as well (Basilevsky, et al., 2003). The planet is home to porous and easily crushed, weakly lithified sediment rocks or volcanic tuff. This was brought to light after the Venera and Vega missions (Bougher, et al., 1997).

The Martian regolith is very porous, and is likely to have low bulk densities (W.Squyres, et al., 1992). The rocks found on the plains of Mars in the Gusev crater is olivine-rich basalts. The presence of basaltic sandstone fused with magnesium sulphates and calcium sulphates may perhaps point to a localized episode of water (Jean-Pierre, et al., 2006).

Figure 5.4: Martian soil and boulders (rock fragments) as viewed by Curiosity (NASA, 2014)

The entire surface of the moon is nearly covered with lunar regolith, with a few bedrocks seen on very steep-sided crater walls (Williams, 2015). The regolith was formed because of impacts from of large and small meteorites. The density of regolith at the Apollo 15 landing site was found to be between 1.35g/cm^3 and 1.85g/cm^3 (Alshibli, 2013).

The surface of Titan was first described by Huygens as clay-like. Images taken shows a flat plain covered with pebbles (water-ice mixed with hydrocarbon ice) (Amos, 2005). This assertion was however changed to “sand” made of ice grains, after subsequent and better analysis. The outermost 500 kilometres of Titan’s crust is devoid of any rock, while a mixture of ice, rock, and metal elements such as silicates and iron are found at greater depth (Facula, 2010).

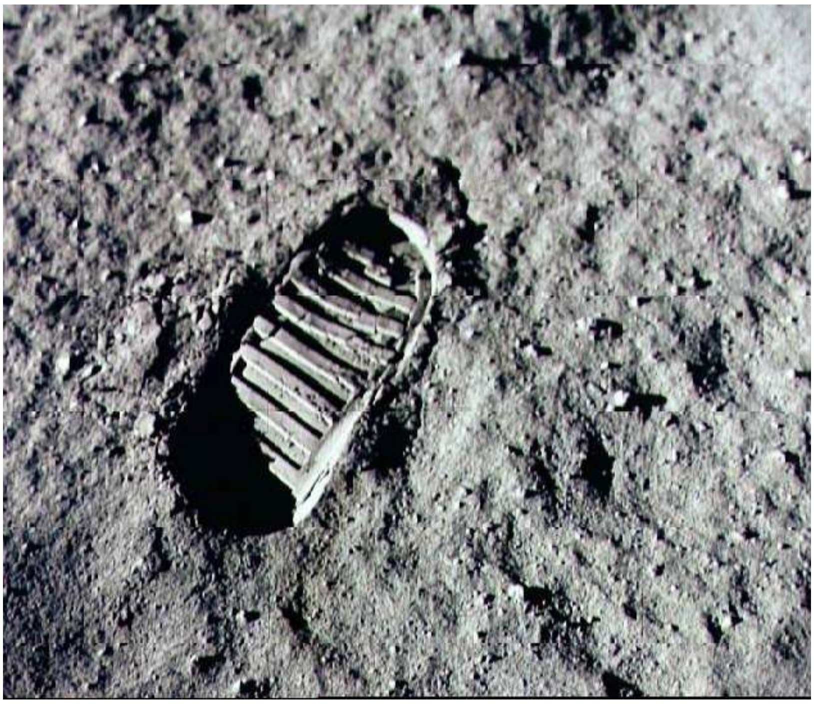


Figure 6.5: Apollo 11 boot print on the lunar surface, which left a deep indentation in the regolith. (NASA 2017)

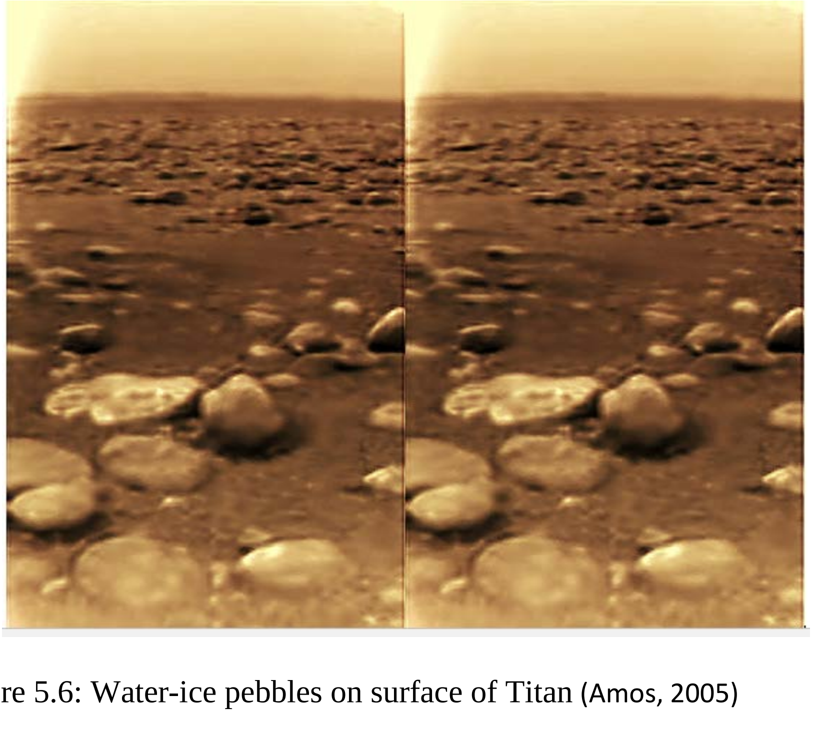


Figure 5.6: Water-ice pebbles on surface of Titan (Amos, 2005)

Jupiter's moon, Europa, is basically made of silicate rock with a water-ice crust and probably an iron-nickel core (Kargel, et al., 2000; Chang, 2015). NASA have analysed new data from NASA's Galileo mission and revealed clay-type minerals at the surface of the icy moon that appear to have been delivered by a collision with an asteroid or comet (Greicius, 2013).

Figure 5.7 describe the breakdown strength of sandstone, limestone granite and water with pressure.

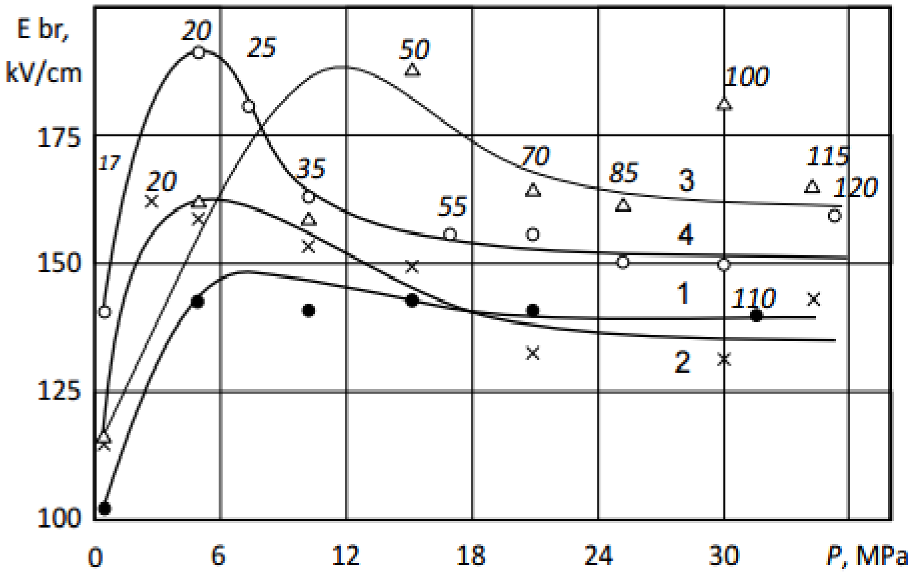


Figure 5.7: The function of rock breakdown strength with pressure and temperature: 1 – sandstone, 2 –limestone, 3 – granite, 4 – water (figures next to dots are temperature values) (Vazhov, et al., 2014)

5.8 Drilling Systems for Pasts and Future Missions on Other Solar System Objects

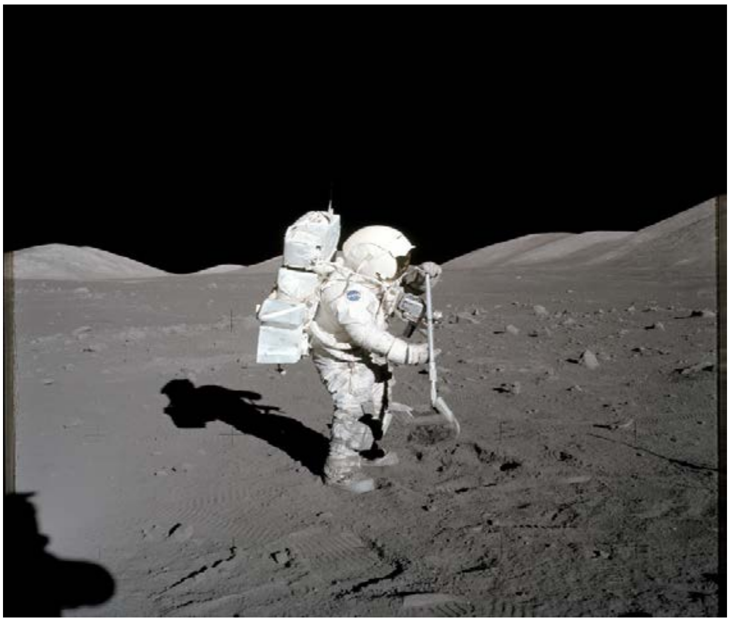


Figure 5.8: The lunar rake, an Apollo lunar geology hand tool. Credit: NASA

Future space drilling missions will require smaller and low mass but very efficient drilling system for subsurface access and in situ analysis. The drill of the Apollo 15 and 17 missions in 1971 and 1972, drilled up to 1.4 meters and 2.0 meters respectively into the lunar regolith (Lowman, et al., 2009).

New and improved systems are being developed for efficient and effective drilling on Mars and other objects. The Moon/Mars Underground Mole (MMUM) is built with a similar design to the Pluto mole, which was deployed on the unsuccessful “Beagle 2” lander of ESA’s 2003 Mars Express mission (Richter, et al., 2001). The mole can produce a downward impart force of over 63N at 12 impacts per minute (Stoker, et al., 2010). The maximum penetration depth of the MMUM is 2 metres and collects sample of volume 5cm3 (Zacny, et al., 2009).

Another drill system under development is the Ultrasonic and percussive actuated drills which uses high frequency oscillations, superimposed on the cutting motion of a conventional twist drill. It can be used on rocks and other brittle materials with several advantages over conventional drilling (Hoftun, et al., 2014).

Mars Integrated Drilling and Sampling (MIDAS) System is a lightweight system developed by Alliance space system. It combines two system (1) a five degree of freedom robotic arm of the Mars Exploration Rover (MER). (2) an Ultrasonic/Sonic Driller/Corer (USDC) which enables the automatic retrieval of multiple samples from regolith (Bar-Cohen, et., 2001). The first prototype drilled to a depth of 0.5 metres after testing (Zacny, et al., 2009).

For extremely elevated temperatures such as that on Venus, an extreme temperature drill system for Venus exploration is under development by Honeybee robotics and NASA. A prototype of this system, operated with low thrust reaction in low gravity environment and was still operational after 20hours at 460oC. It achieved a drilling depth of 6 inches deep in chalk (Zacny, et al., 2009).

The Ground Mole Demonstrator (GMD), is the first prototype of the Subsurface Explorer (SUBEX). The drill system is 87 mm wide and more than 2 metres in length. It can drill to a depth of 100 metres with just 100 watts of power. The system uses both rotary and percussive boring and is suitable for almost all soil type. (Hoftun, et al., 2014)

5.8.1 Zaptec Plasma Channel Drill

One of the prospective planetary systems is PCD. The concept was presented by Zaptec AS. (Johansen, et al.). A powerful, lightweight, and energy efficient micro transformer has been developed by Zaptec. The transformer allows high voltages and high currents to be transformed in very compact and small devices for space applications (Johansen, et al.).

High energy plasma discharges are delivered through low mass, low volume power transformers in the drill head. A depth of 2 km is anticipated to be reached with less than 1 metric ton of surface payload encased in a SpaceX Dragon-sized capsule with maximum power requirements of less than 2 kW (Hoftun, et al., 2014).

The projected weight and volume of the complete Zaptec drill is less than 20 kg and 0.04 m^3 respectively. The Plasma Drill for Mars Exploration (PLASMARS), which is designed to reach a depth of 10 metres, will have a peak power consumption of less than 100 W with a spark frequency of approximately 0.1 – 1 sparks per second during drilling (Hoftun, et al., 2016).

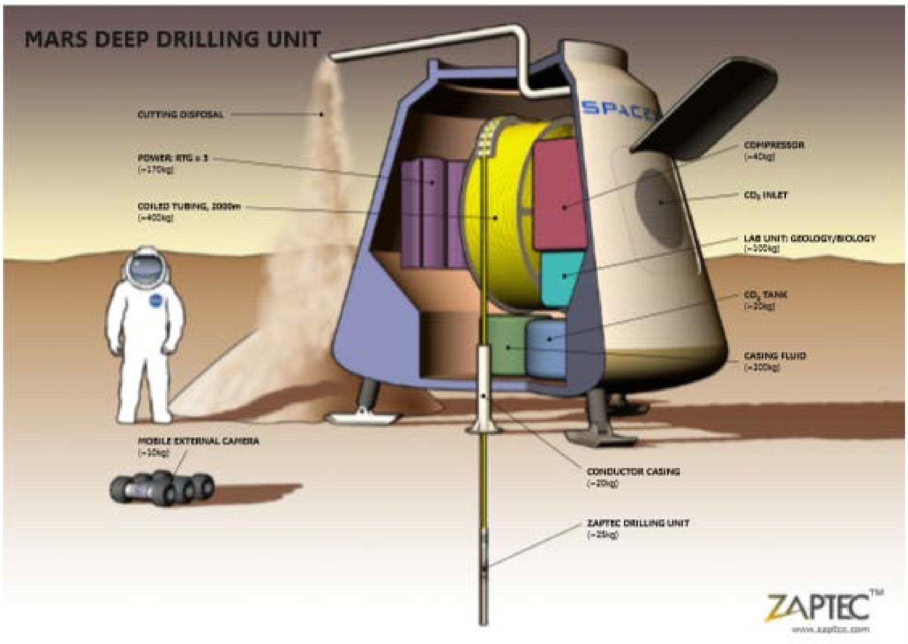


Figure 5.9: Zaptec deep drilling system deployed from a SpaceX Dragon-class landed capsule (Johansen, et al.)

To achieve such depth of 2 km with the Zaptec drill, several systems that include: “1) An autonomous unit at ground level that can assemble, control and operate the drilling process; 2) A tethered plasma drilling system that can achieve 1-2 km down/up/diagonally to explore the sub surface geology and 3) Topside or in situ sensors that can identify and analyse bio signatures of life” is needed (Hoftun, et al., 2014).

Drill cuttings may be removed from the borehole by circulating CO_2 and/or mechanically by a mole tethered at the surface. The concept presented by Zaptec is practical, affordable and reliable (Johansen, et al.).

The geometry tested by Zaptec is close to that of Glasgow in figure 3.4. Zaptec tried to drill with air at Earth atmosphere, and maybe also tried low pressure but was not successful. This issue has been the inspiration of this thesis.

The technology has been focused for the recent Mars application but can be adapted to other planets; in vacuum for example should work well. Having a small amount of fluid available on the spacecraft will help the drilling.

The Plasma drilling in planets is in competition with other more traditional or newly invented drilling systems. It has unique advantages but also challenges.

Chapter 6 CONCLUSIONS

The feasibility of the PCD technology working on other extra-terrestrial objects have been investigated and the following outcome have been drawn

PCD with water as drilling fluid has been proven effective by Zaptec. The use of gas as a drilling fluid has been applied since ancient times and may work in space with the right technologies in place. The breakdown field strength of gases is usually far less than rocks which causes gas to fail electrically before the rocks, when it is used as drilling fluid. Venus is the only place where PCD seem feasible but the planet has other problems like high temperature. Titan having high breakdown voltage of 39.7 kV is similar to Earth and its atmosphere may support PCD.

The situation on Mars is not as good as the first two objects, having an estimated breakdown voltage of only 0.74 kV for the Zaptec drill bit. The problem with sparking in the gap in this condition is much severe than on Earth. A strong plasma channel in the rock might be difficult to achieve, looking at how quickly sparks will extinguish after igniting thanks to the poor insulating properties of Mars atmosphere. The electronic parts of the drilling system may be damaged due to short circuiting; hence all high voltage circuitry must be insulated.

PCD can be possible with gas as drilling fluid, but the use of low conductivity liquid works much better such as water, transformer oil and some hydrocarbons and their great insulators with superior breakdown strength than both rocks and gases. Liquid is a superior fluid to gas and has a well understood rock-piston-explosion mechanism.

Unfortunately, the use of liquid in space is difficult and with a prohibitive cost. The transport of small amount of disposable liquids or better still, the use of locally (space) resourced liquids can solve the issue of low breakdown strength in drilling fluid (gas) which will make the Zaptec/Glasgow/Slovakia drill bit concept more feasible in solar space.

The vacuum environments of Europa, the Moon, asteroids and comets presents seems to be the ideal conditions for plasma drilling thanks to the superior insulating properties of vacuum. It might however be difficult to remove the drill cuttings in vacuum and may need a new technology.

The simulations of the electric field suggest that the use of insulators such as (BaSmTi) in the inter-electrode gap, around the centre electrode could increase the electric field into the rock slightly but unfortunately, the field in the gap or test area is also enhanced using these insulators.

The downward field is stronger when a little complexity is added to the drill bit, by attaching insulated metal rings to either the centre electrode or the outer electrode. The issue of increasing both the field in the rock and in the gap, is also seen here.

More improved configurations and regimes should be explored to enhance the field in the rock, without necessarily increasing the field in the gap and to make PCD with gas feasible.

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