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RESEARCH ARTICLE

REVIEW OF DEEP DRILLING TECHNIQUES FOR HIGH ENTHALPY GEOTHERMAL RESERVOIRS.

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Abstract

Most of the supercritical geothermal systems exist at depths near or below the transition zone, where the reservoir fluid remains in the supercritical conditions i.e., at temperature above 374^{o}C and pressure around 221 bar. Few of them have been drilled in world, which exist in Iceland, Japan, US and Mexico. Supercritical systems have gained attention in recent years by their possible direct as well as indirect utilizations. These systems are more productive then the shallow depth reservoirs because of their high enthalpy and temperature range. IDDP-1, 2 wells at Iceland are the examples of such reservoirs. Present paper does not only discuss about such type of reservoirs in the world but it also gives a brief description of technologies utilized for deep supercritical drilling of geothermal wells. It talks about the techniques like Laser drilling, Electropulse boring, Hydrothermal spallation, Millimeter wave technology etc. along with their features and restrictions. The paper also discuss about the types of equipments used for supercritical drilling in terms of bits, casing, string, drilling fluid etc.

Introduction:-

In year 1988 at Nasjavellir geothermal field which is situated on the NE flank of the Hengill volcano a 2265m deep well was drilled which has manifestated with very high pressure and flowrate of the water having temperature around > 380°C (Steingrimsson *et al.*, 1990; Fournier, 1991). Due to the greater hydrostatic pressure to prevent the well from blowout the lower portion of the well was plugged with a gravel plug. This well escorted the concept of deliberately seeking out supercritical temperatures as a part of Deep Vision initiative in Iceland in 2000, which was further transformed to Iceland Deep Drilling Project (Fridleifsson and Elders, 2005; Fridleifsson *et al.*, 2007).

The primary objective of the Iceland Deep Drilling Project was to drill a deep supercritical geothermal well at different sites of Iceland which are having very high thermal gradients ranging from 450- 600°C encountered at 3.5-5 km. This high gradient thermal energy can be commercially used for Power generation, Space heating, Greenhouse effect etc. (Fridleifsson and Elders, 2005; Fridleifsson *et al.*, 2007; Elders and Fridleifsson, 2010). The initial attempt was made in Reykjanes peninsula (RN-7) where the first exploratory well of about 3.1 km depth was drilled after going through the sufferings of wellbore collapse during flow testing; therefore this well was not deepened. After the failure of this well the IDDP-1 well was spudded in year 2008 at Krafla geothermal field. The plan was to drill a well of depth 4.5 km, however at the depth of 2104 m a rhyholitic magma was encountered and the well was completed at 2072 m depth (Elders and Fridleifsson, 2010; Elders *et al.*, 2014a, c). Subsequent flow testing resulted in production of superheated steam with flow rates of 10-12 kg/s, wellhead temperatures reaching up

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to 450°C, fluid enthalpies of 3200 kJ/kg, and wellhead pressures of up to 140 bar (Fridleifsson *et al.,* 2014). The well and its associated surface equipment experienced corrosion resulting from acid gases (HCl, HF, and H_2S) along with silica scaling and erosion; well head valve failure ultimately led to this well being shut in (Einarsson *et al.*, 2015). Similarly at Kakkonda Geothermal field in Japan a scientific exploratory well was drilled in 1994-1995 which was the part of Deep Geothermal Resources Survey, led by NEDO (Muraoka *et al.*, 1998). This well WD-1a has penetrated through the upper hydrothermal system into a high temperature granitic pluton with a conductive gradient temperature of 500°C at a depth of 3729 m. An inflection of brittle- ductile boundary system was found in the temperature profiles of the well at temperature 380°C. No permeable fluid entries were observed below this transition, and a lower fracture density was observed in the conductive portion of the well (Kato *et al.*, 1998). While there was no production of supercritical fluid from this well, it has demonstrated the feasibility of the drilling at elevated temperatures by the means of borehole cooling techniques, and proved the pluton underlying the Kakkonada geothermal field was the major heat source for the hydrothermal system and had even higher temperatures.

Review of Types of Deep Drilling:-

PLASMABIT Drilling Technology:-

PLASMABIT drilling technique can be summarized on the basis of 6 features:

- **5-times cheaper** than any other of today’s drilling methods.
- **4-times faster** in comparison with the other drilling procedures.
- **3-times larger** diameter at the bottom.
- **2-times deeper** than common drilled well.
- **1 process** for casing and drilling.
- **0 tripping** and drilling bit replacement.

PLASMABIT is a revolutionary innovative cost-effective system for drilling and casing-while-drilling system (ContiCase system add-on). This comprehensive system consisting of several complementary subsystems each solves a specific task during drilling process:

- **PLASMABIT Rock disintegration system -** Non-contact drilling process based on innovative approach modified for extreme thermal, physical and pressure conditions.
- **PLASMABIT Interface with surface subsystem -** Advanced cabling solution for energy and material supply for PLASMABIT rock disintegration system enabling real-time Measuring-While-Drilling with online connection to downhole drilling activities.
- **PLASMABIT Movement and anchoring subsystem -** Autonomous movement and anchoring subsystem works in underground extreme conditions of high temperatures and high pressure securing synchronization of the drilling process with surface material supply channels.

The detail of all the three PLASMABIT drilling technology is described in Figure 5.3 which gives better understanding of the technique along with their individual characteristics.

The features of this technology are as follows:

The electrical arc with temperatures up to ten thousand of degrees Kelvin heats directly the surface of the disintegrated material, especially the radiation component; with minimized heating of intermediate gas (intermediate gas flow in conventional plasmatorchs reduces the efficiency of the heat transfer into the material).

- The heat flow is area-wide, relatively homogenous by applying long arc on the whole surface for high-intensity disintegration process.
- Rotating spiral arc, in addition to the thermal influence, has “built-in” centrifugal pump function for disintegrated material removal.
- Direct electric arc plasma technology allows the use of electrohydraulic phenomena, generating shockwaves and pressure waves. It utilizes generated mechanical power for the destruction and transport of disintegrated material out of the BHA (Bottom Hole Area) area.
- The pressure waves are generated using high intensity short current pulses. These pulses are accumulated with a time transformation of charging/discharging from 4 to 7 orders of magnitude (s/µs), thus allowing an increase in instantaneous pulse disintegration effect with power pulses in scale of MW.

Hydrothermal Spallation Drilling:

Thermal spallation involves the application of thermal stress to fracture the rock surface. The method is mainly dependent on flaws (micro-cracks) inherent in the rock formation. On application of heat, thermal stresses are generated due to the steep temperature gradient between the rock surface and the underlying layers, causing the extension of microcracks. When the thermal stresses exceed the compressive stress of the rock, a chip violently buckles off the surface. Thermal energy can be supplied using a flame, super-heated water jet, microwave or laser beam. Thermal spallation has found wide application in drilling of boreholes, opening small orifices for installation of explosive charges and other mining applications (Figure 1).

To be considered, however, is the fact that spallation drilling hinges on the capability of rocks to spall. Experiments by Williams and Potter (Williams, 1996) indicated that certain soft and ductile rocks (limestone, soft sandstone, shale) did not spall under application of continuous heat.

Spallation is largely dependent on the energy applied to the rock. The spalling zone of rock occurs just below the melting temperature of the rock. Initial application of heat creates thermal stresses in the material due to the low diffusion rate into the rock. The delicate balance between supply of heat flux and surface temperature of the rock should be maintained within the brittle-plastic transition region.

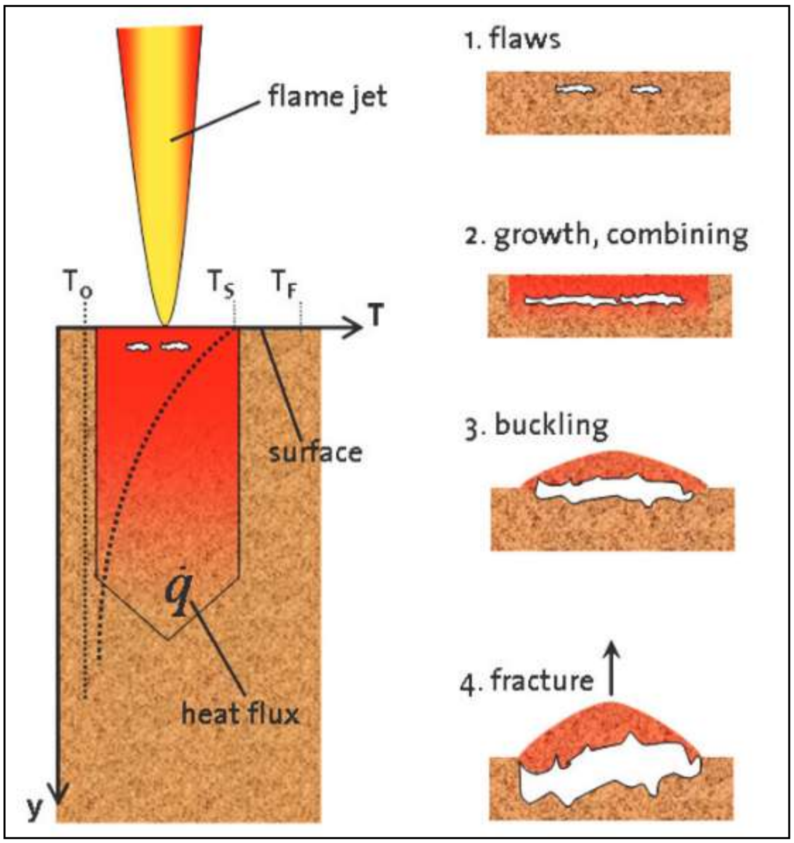

Figure 1:- Principle of Hydrothermal Spallation Drilling

Flame Jet Drilling:-

Flame Jet Drilling is one of the most popular techniques of thermal Spallation. The technique have high rate of penetration that are achievable in hard rock types (Augustine, 2009; Tester *et al.*, 1995). For the removal of spalls from the drill site, gas flow from the burner has been utilized in flame jet drilling.

The commercial test for this technology was performed in 1940 in mining of taconite (Calaman and Rolseth, 1961). The technology was dormant till the mid-70s in case of taconite industry while the technology was used for geothermal well drilling during this period. While drilling through granite using flame jet drilling technology, Browning Engineering Company in mid-70s indicated the average rate of penetration of about 52ft/hr which is favorable for deep geothermal drilling point of view (Browning, 1981). In comparison to conventional methods which have an average rate of penetration 16.2ft/hr the jet drilling technologies show massive improvement in this region. It can also drill well bores of very narrow holes as well the holes having 20 times more than the flame jet nozzle (Silva *et al.,* 2006). Due to several reasons like air filled environment for maintenance purpose of the well as well as spall removal from drill site. Due to the high pressures in deep drilling, the air-filled hole is largely unstable, aggravated by the water intrusion which may hamper the gas-enabled spall removal (Potter *et al.,* 2010). A further limitation in drilling large hole diameters is the reduction in lift velocity of the exhaust gas. Efficiency of spall removal is, therefore, impeded (William, 1985). Second, deep drilling requires a high density drilling fluid, commonly known as drilling mud, which apart from carrying away particles, serves to balance the pressure in the well. This would mean ignition and maintenance of the flame in a liquid filled environment.

Millimeter Wave Technology:-

Radio waves or electro-magnetic (non-ionizing) radiation in the extremely high frequency (EHF) range (between microwave/MHz and infrared/ THz classifications), between 30 to 300 GigaHertz (GHz) frequencies or 1-mm to 10-mm wavelengths (X), are called millimeter waves (MMW). They are useful in near line-of-sight applications and can have efficient guided transmission. MMWs are generated using commercially available gyrotrons at efficiencies greater than 50% and at megawatt average power levels. Current applications of MMWs are- heating, communications (PAN), airport security, non-lethal weapons, radar, medicine, and astronomy.

The scientific basis, technical feasibility, and economic potential of directed energy millimeter wave (MMW) rock drilling at frequencies of 30 to 300 GHz (or 1000 times longer wavelengths than infrared lasers) are strong. It avoids Rayleigh scattering and can couple/transfer energy to a rock surface 10^{12}x more efficiently than laser sources in the presence of a small particle extraction plume. Continuous megawatt power millimeter-waves can also be efficiently (>90%) guided to great distances (>10 km) using a variety of modes and waveguide (pipes) systems, including the potential of using smooth bore coiled and jointed/ joined tubing (Woskov et al., 2014).

The potential benefits of using MMW for drilling and lining wellbores include:

1. Commercially available efficient, megawatt gyrotron sources;
2. Simple, direct and efficient conversion of MMW energy into heat to melt and vaporize targeted rocks;
3. Simple system w/no rotation or mechanical components to wear out; Drill rate with depth is expected to be constant; Figure 2 represents the Drill Rate of Penetration Vs Borehole Diameter for different MMW power levels along with the components of MMW.
4. Drill cost with depth expected to increase linearly and not exponentially;
5. Rock hardness and temperature not limiting parameters;
6. Potential for vitrified liner with drilling, all in one process;
7. Flexible system with various MMW modes of delivery to the target;
8. Compatible with dirty environment and small particle plumes, due to Rayleigh scattering (note that 1 mm (MMW) has 10^{12}x less scattering loss.
9. Absorption of the beam by rock melt is more efficient in the MMW frequencies over IR;
10. Remote real-time diagnostic (radiometry, radar, spectroscopy) and monitoring technology available with MMW;

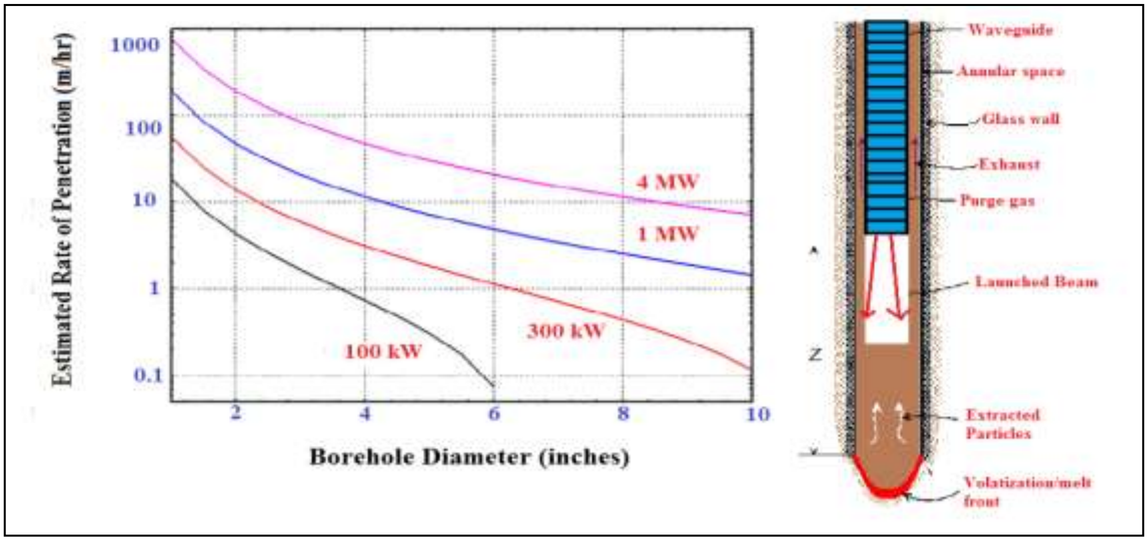

Figure 2:- Drill Rate of Penetration Vs Borehole Diameter for different MMW power levels along with the components of MMW (modified after, Woskov et al., 2014)

Electropulse Boring (EPB):-

The technology came in existence during 70s, along with the notion of pulsing electrical voltage for the generation of shock wave (Allgood, 1974). The mechanism behind this technology is that the electrode pair is hitting the rock surface with around 1-5, 00,000 Volt electric pulse and breaks the front of the rock (Rodland, 2004). Subsequent application of pulse causes further cracking of underlying rock. The technology is having high Rate of Penetration (ROP) with the large cuttings of rock. For drilling of geothermal wells through electropulse an innovative research have been carried out during 2009 in Bergen-Norway (Schiegg *et al.*, 2015). The major advantage of this technology is that it can drill large diameter, super-deep holes in hard formations with low coasts.

Laser Drilling:-

The technique was initially used for the analysis of drilling well. The physical properties like oil film thickness measurement (Qieni *et al.*, 2006), permeability damage (Abdulrazag *et al.*, 2007) and detection of the crude properties are measured through this technique. In late 60s and 70s the research has been carried out for the use of laser drilling, but due to the inefficiency of lasers the method got rejected. But with time and by the development of laser beam delivery technique (Graves and Brien, 1999) and fiber laser beam (Faircloth *et al.*, 2013) delivery has ensured the delivery of the beam to the downhole environment in addition to its ability to drill.

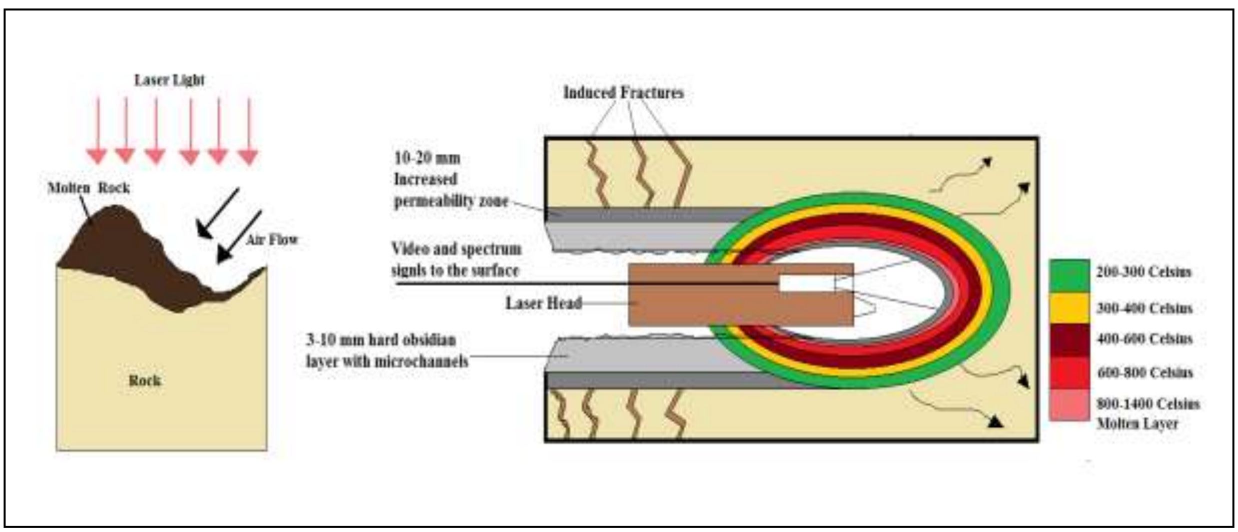

Figure 3:- Laser drilling technique (modified after Bajcsi et al., 2015)

Figure 3 represents the mechanism of Laser drilling. The major advantage of this technique is lack of contact between the tool and the rock face which reduces the tripping time due to the reduced wear. The laser drilled wells take 90% less time than the conventional wells because of its high rate of penetration (Adeniji, 2014), which also leads to reduction in damage to the ecosystem. It is also found that the laser drilling technique has low environmental impact than the conventional drilling.

Types of Laser:-
In 1960, Maiman demonstrated the first laser action on Ruby crystal. After that large number of substances in different phases has been found to give laser actions with the wavelength ranges within visible, ultraviolet and infrared regions. Substances used for laser action includes solids, liquids, plastics, glasses, semiconductors and dyes etc. numerous types of lasers are steadily increasing and can be broadly classified according to their production techniques. Some of the major categories are described in Table 1 with respect to their power generation.

Category	**Sub- Category**	**Power**
Optically pumped Solid State lasers	Ruby laser	500MW
	Rare Earth Ion laser	>1000W
	Nd: YAG (neodymium-doped yttrium aluminium garnet, Nd: $Y_3Al_5O_{12}$)	15kW
	Fiber Diode	>5kW
	Tunable solid state lasers	17W
Chemical lasers	Chemical Oxygen Chemical Laser (COIL)	>7kW
	Mid-InfraRed Advanced Chemical Laser (MIRACL)	>1000kW
Gas lasers	CO_2	>200kW
	CO	>200kW
Other type of lasers	Excimer Laser	10-20MW
	Semiconductor Lasers	-
	X-ray Laser	-
	Free- Electron Laser	-

Table 1:- Types of laser used for laser drilling of geothermal well

Equipments of Geothermal Drilling:-
BITS:-
Drag bits:-
It is one of the oldest rotary drilling bits (Figure 4A). The cutting blades are integrally made of bit body. The whole unit is attached and rotates with the drilling string. This type of bits is majorly used in soft and gummy types of formations. As drag bits are not having moving parts it gets advantages in case of geothermal environments. This restricts the problems with the high temperature bearings, lubricants and seals.

Polycrystalline diamond compacts (PDC) bits:-
In this type of bits diamonds are embedded on the bit body (Figure 4B). In PDC drilling bit technique the diamond embedding is done into the formation and then it is dragged across the face of the rock in ploughing condition. The diamond drill bits follow the mechanism of shear failure. PDC bits are of higher cost but their long life makes them economically viable. Around 5% of the PDC bits are mainly used in oil industries, however this drill bits are hardly used in geothermal drilling (Moore, 1986). The sales of PDC bit in 2007 were estimated around $1.9billion, in comparison to roller cone bit which was around $1.2 billion (Market Survey, Spears and Associates, Tulsa, Oklahoma). Although it has been found that the PDC bits are rarely used in geothermal projects with large sedimentary reservoirs (e.g., Cerro Prieto, Mexico). For the acceptance of PDC in geothermal industry, their performance in harder rocks requires broad improvement.

Roller cutting bit:-
The roller cone bits are being used since 1970s. The rock surface is crushed and gouged by the conical rollers present on the bottom of these bit, the bit rotates and the cone rolls across the bottom of the hole. There are mainly two types of teeth used on the cones: (1) Milled put steel cones (usually used for softer formations) and (2) Tungsten Carbide Inserts (usually used for harder rock and longer bit life). More than 95% of the oilfield footage is drilled today with tri-cone roller bits (Figure 4C).

Hybrid or Combinational Bit (Figure 5.10 D):-

This type of bits uses the combined mechanisms of PDC to shear the rock formations and roller cones to crush it (Pessier and Damschen, 2010). This kind of hybrid bit is having high rate of penetration which can drill through shale and other plastically behaving formations with two to four times more faster than the roller cone and PDC bits.

Figure 4:- Three major types of bits used for geothermal drilling, (A) Drag Bit, (B) PDC bits and (C) Tri-cone roller bits and (D)A hybrid bit that combines the mechanism of roller cone bit and PDC bit (Pessier and Damschen, 2010).

Drill String:-

The major components required for a bit to perform is rotary motion, water for cleaning the bit along with hole bottom and a force (weight) to crash the rock. The drill string (Figure 5) serves to provide essential requirement for the bit to perform. The drill string is therefore an essential part of the rotary process. It is the connection between the rig and the bit.

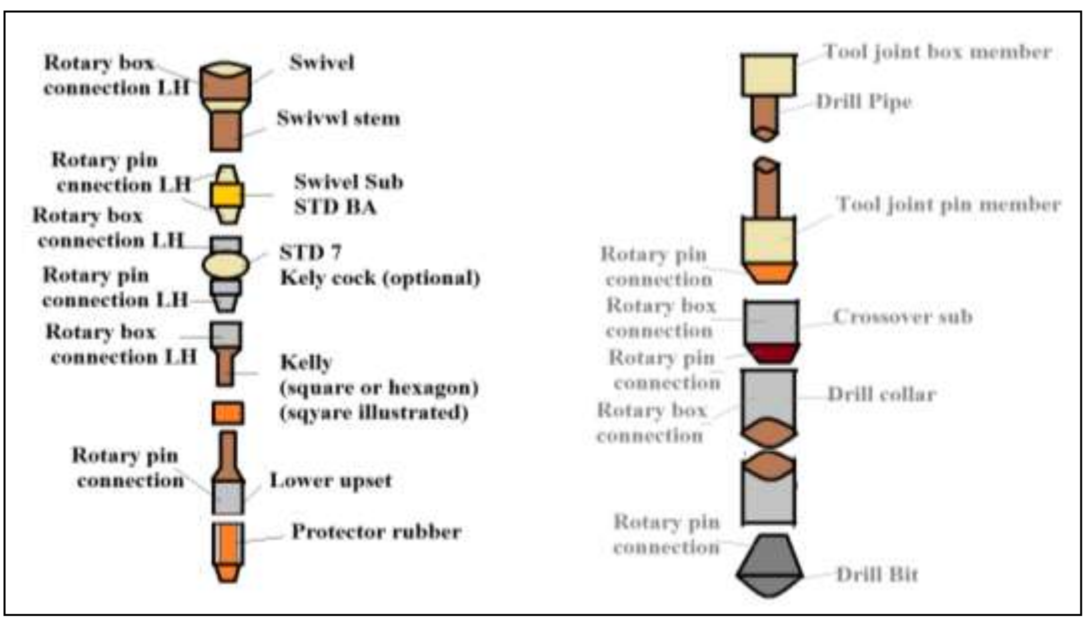

Figure 5:- Components of drill string (modified after Ngugi, 2008).

Purpose:-

There are several general purposes of using drill string which are as follows:

- It provides fluid conduits to drilling bits.
- It imparts rotary motion to the drilling bits.
- It provides to allow weight/force to be set on drill bits.
- It lower and raise the motion of the bits.

Casing:-

In geothermal industries the production of geothermal resources are done through casing rather than the tubing of the well. The diameter of casing is also a debatable topic. The casing diameter will be either 8½” or 12¼”. This open hole have largest diameter through which the slotted or perforated liners are running. Clearly from a diameter point of view there is an advantage of utilizing this extreme line casing connections, however this is often offset by reduced connection strength of this type of casing connection.

The internal diameter of casing should not be less than 50mm larger than the outside diameters of connection accessories and collars for allowing satisfactory cementing.

Different casing diameters for a standard well design include (Table 2):

Type of Casing	**Diameter of Casing (inches)**	**Depth of Casing (m)**
Conductor	30” driven or drilled and set with a piling augur	24m
Surface Casing	20” casing in 26” diameter hole	80m
Anchor Casing	13 3/8”casing set in a 17½” diameter hole drilled	270m
Production Casing	9 5/8” casing set in a 12¼” diameter hole drilled	800m
Open Hole	7” perforated liner set in 8½” diameter hole drilled	2400m

Table 2:- Different casing diameters at different depths (Hole, 2008)

Drilling Fluids:-

In geothermal industries there are mainly four types of drilling fluids in use, which are (1) water based mud (bentonite and polymer), (2) water, (3) aerated mud or water, and (4) air and foam. Oil and gas industry has evolved the geothermal drilling industry therefore most of the drilling equipments and materials are sourced from the oil and gas industry. The chemical additives used in geothermal industries are comparatively very less in respect to oil and gas. As there is no problems like overpressure due to the hard rock formation the simple fluids like mud and water can also be used. Some of this major type of drilling fluids is mentioned below which is as follows:

Water Based Mud:-

In case of geothermal drilling mud, water is used as a base fluid. Sometimes the geothermal brines produced from other wells are also used as base fluid. To increase the viscosity of fluid so that it can carry the cutting to the surface easily the active and inert solids are added to the mud. To produce a colloidal suspension the amalgamation of active solids, clay (bentonite) and polymers are added to water. These are known as viscosifiers because they are used to determine the viscosity of the mud. The carrying capacity of cuttings to the surface depends on the size and density of cuttings along with viscosity and density of the mud. The range of up hole velocities varies from 0.2 to 0.7 m/s (U.S. Army Corps of Engineers, 2001). There are three basic additives which are usually used in geothermal industries which are as follows:

a. Bentonite mud
b. Polymer mud
c. Mixture of bentonite and polymer mud

Water:-

It is the cheapest drilling fluid which has been used in geothermal industries now days. In case of open hole section the water or aerated water is the most preferred drilling fluid which has been used. In case of using water as a drilling fluid the range of rising fluid in annulus should be 0.5-1 m/s; to ensure the transportation of cuttings from borehole to surface (Thorhallsson, 2011).

Air and Foam Drilling:-

Air and foam drilling is extremely effective drilling fluid in arid climates in dry formations, in consolidated rock formations or in a frozen grounds. The detergents or drilling soaps are added to remove the cuttings from borehole to the surface. The range of the foam utilized in case of foam drilling for geothermal wells ranges from mist to a stiff foam. As increasing with depth and diameter when the cuttings become larger the technique of stiffer foam is used for such kind of removals.

Well completion strategies:-

The purpose of well completion is to seal the wellbore from the surrounding formation by lining the well with steel casing which is cemented in place. The casing protects the wellbore by several phenomena like protecting from groundwater aquifers, by isolating the formations which are unstable in nature and it also protects surface operations from an uncontrolled ‘kick’. Depending upon the factors like rock properties, formation fluids and well control considerations etc. the length of the casing strings determined. In case of geothermal well completion the casing needs to be cemented from surface to the production zone, rather than only cemented at the bottom as in case of oil and gas industries. Figure 6 represents the process flow chart for stages of well completion.

Placement of Casing:-

The first casing joint into the well has a guide shoe at the bottom and float collar at the top. The function of guide shoe is to protect the casing in the well. While in case of float collar it contains a valve which helps the casing to float into the well to lessen the hoisting system load. The float collar also acts as check valve that keeps drilling fluids from entering through bottom of the casing (Finger and Blankenship, 2010). The centralizers and scratchers are placed on the exterior part of the casing. The function of centralizer is to ensure about good cement job by casing off the borehole wall. While in case of scratchers it ensures about a good cement bond by removal of wall cake in borehole (Aboholi, 2013).

Cementing:-

During cementing the first step is to drop the bottom wiper plug into the casing. The cement is pumped by high pressure pumping unit pumps through the cementing head slurry inlet and into the casing. The bottom plug is pushed down by cement pump pressure inside the casing. The plug forces the mud off inside the casing and pushes the drilling fluid out of the casing. When it reaches to the bottom of the casing the cement pressure breaks the diaphragm in the plug by opening a passage for the cement to exit the casing and enter in annulus.

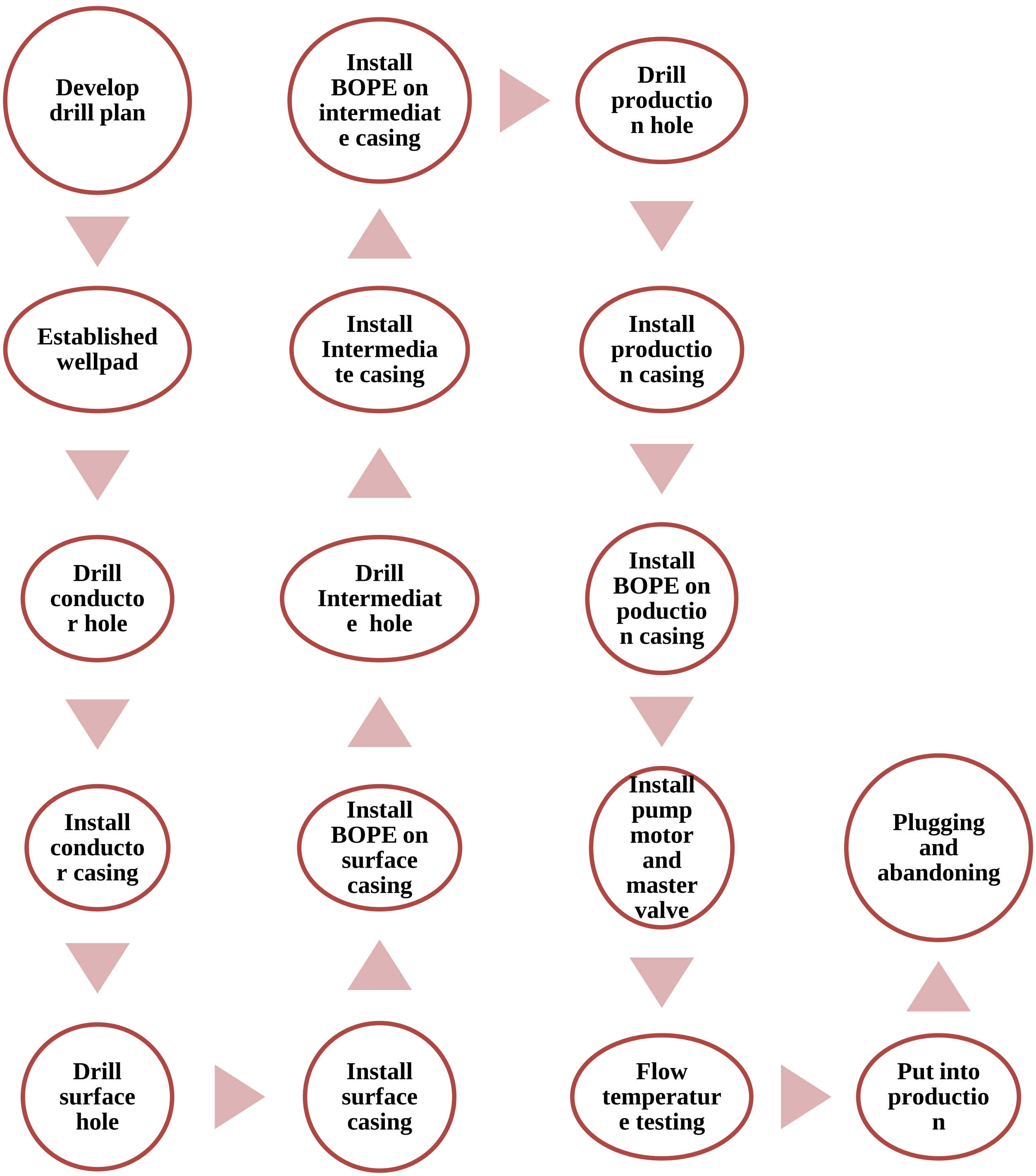

Figure 6:- Flow chart for stages of well completion

The pumping of cement will continue until the calculated cement volume is displaced. During these phenomena the top wiper plug is dropped from the cementing head into the casing on top of the cement. This is further followed by displacement fluid, which is pumped through the fluid inlet. The displacement fluid pushes the wiper plug down the casing. The cement off inside the casing is wiped by plug which pushes the cement slurry into the annulus. The plug wipes the cement inside of the casing and pushes the cement slurry into the annulus. When the top wiper plug reaches the bottom of the casing, it will seat on the bottom wiper plug. This plug is solid, so when there is a sharp rise in displacement fluid pressure the pumps are stopped. When the cementing process is complete, a waiting period (typically 12-24 hours) is necessary to allow the cement to set (Finger and Blankenship, 2010; Aboholi, 2013). If additional drilling is necessary, such as for the next lower hole, the drill bit is capable of drilling through the wiper plugs and any cement at the bottom of the casing. Figure 7 shows different process steps involved in cementing.

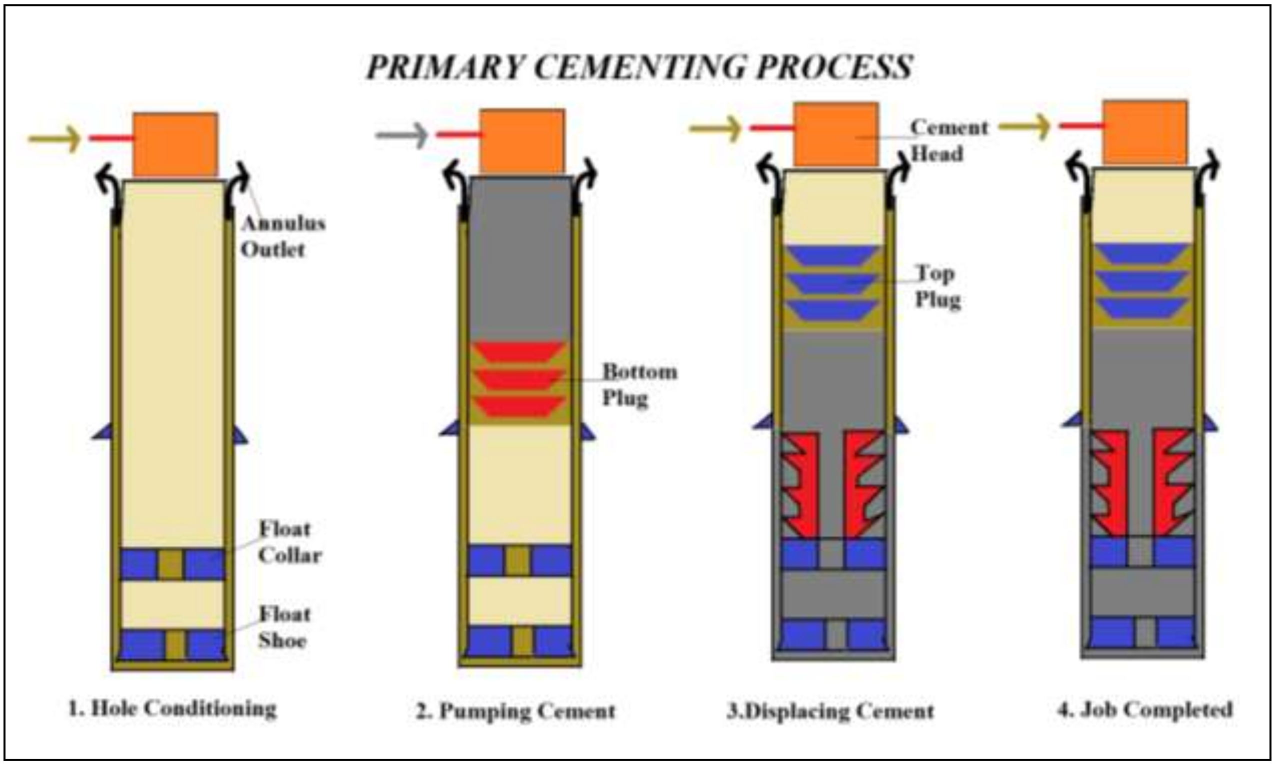

Figure 7:- Process steps for Cementing (modified after Finger and Blankenship, 2010)

Installation of BOPE:-

After the cement is set the well is sealed properly. The BOPE assembly is bolted to the flange which is welded on the top of the casing that has just been cemented. Prior to installing the BOPE, there should be two valve lines known as choke and kill lines installed below the BOPE on the casing as an outlet for fluids within the well or as an inlet for pumping fluids into the wellbore. Once the BOPE is installed, the drill string for the next phase of drilling is lowered through the BOPE.

Conclusion:-

The paper reviews the various drilling techniques used or proposed for high enthalpy geothermal reservoirs. These reservoirs exist at a depth greater than 2000m and exhibits challenges in terms of high temperature and pressure. Equipments and techniques used for such drilling differ from conventional oil and gas drilling. Completion strategies for such wells differ also from traditional ones. The paper provides a roadmap for overcoming such challenges and drill successful high pressure and high temperature wells.

References:-

1. Abdulrazag, Z. Y., Shedid, A. S., and Alkashef, H., (2007): A New Technique for treatment of permeability damage due to asphaltene deposition using laser technology. Journal of Petroleum Science and Engineering, 59 (3): 300–308.
2. Aboholi, M., (2013): Overview of Oil & Gas Well Casing & Cement. https://www.youtube.com/watch?v=D6tGTGHbYqE. Accessed April 26, 2013.
3. Bajcsi P., Bozso T., Bozso R., Czinkota I., Kovacs B., Tivada M., Schubert F and Szanyi J., (2015): Geothermal well completion technology using high power laser device. In: Proceedings to World Geothermal Congress, Melbourne, Australia, 19-25 April, 2015.
4. Calaman, J. J., and Rolseth, H. C., (1961): Technical advances expand use of jet-piercing process in taconite industry. International symposium on mining research, US Bureau of Mines: 473–498.
5. Einarsson, K., Sveinsson, K.E., Ingason, K., Kristjansson, V., and Holmgeirsson, S., (2015): Discharge testing of magma well IDDP-1. In: Proceedings, World Geothermal Congress 2015, Melbourne, Australia, (2015): 13.
6. Elders, W.A., and Friðleifsson, G.O., The science program of the Iceland Deep Drilling Project (IDDP): A study of supercritical geothermal resources. In: Proceedings to World Geothermal Congress 2010, Bali, Indonesia, (2010): 9.
7. Elders, W.A., Friðleifsson, G.O., and Albertsson, A., (2014a): Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide. Geothermics, 49: 111-118.
8. Elders, W.A., Nielson, D., Schiffman, P., and Schriener, A. Jr., (2014c): Investigating ultra high-enthalpy geothermal systems: a collaborative initiative to promote scientific opportunities. Scientific Drilling, 18: 35-42.
9. Faircloth, B. O., Zediker, M. S., Rinzler, C. C., Koblick, Y., and Moxley, J. F., (2013): Methods and apparatus for delivering high power laser energy to a surface. April 23 2013. US Patent 8,424,617.
10. Finger, J., Blankenship, D., (2010): Handbook of best practices for geothermal drilling. Sandia National Laboratories: Albuquerque, New Mexico. USA. p. 84.
11. Fournier, R.O., (1991): The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active continental hydrothermal systems in crystalline rock. Geophysical Research Letters, 18 (5): 955-958.
12. Fridleifsson, G.O., Albertsson, A., Stefansson, B., Gunnlaugsson, E., and Adalsteinsson, H., (2007): Deep unconventional geothermal resources: a major opportunity to harness new sources of sustainable energy.In: Proceedings to 20th World Energy Conference, Rome, World Energy Council: 21.
13. Fridleifsson, G.O., and Elders, W.A., (2005): The Iceland Deep Drilling Project: a search for deep unconventional geothermal resources. Geothermics, 34: 269-285.
14. Friðleifsson, G.O., Pálsson, B., Stefánsson, B., Albertsson, A., Gunnlaugsson, E., Ketilsson, J., Lamarche, R., and Andersen, P.E., (2010b): Iceland Deep Drilling Project, The first IDDP drill hole drilled and completed in 2009. In: Proceeding to World Geothermal Congress, Bali, Indonesia, April 25-29 (2010b) paper 3902.
15. Ngugi, P.K., (2008): Geothermal Well Drilling. In: Proceedings to Short Course III on Exploration for Geothermal Resources, organized by UNU-GTP and KenGen, at Lake Naivasha, Kenya, October 24 - November 17, 2008.
16. Pessier, R., Damschen, M., (2010): Hybrid Bits Offer Distinct Advantages in Selected Roller-Cone and PDC Bit Applications. IADC/SPE Drilling Conference and Exhibition, 2-4 February 2010, New Orleans, Louisiana, USA.
17. Potter, R. M., Potter, J. M., and Wideman, T. W., (2010): Laboratory Study and Field Demonstration of Hydrothermal Spallation Drilling. GRC Transactions, 34: 249–252.
18. Qieni, L. U., Baozhen, G., Wenda, Y., and Yimo, Z., (2006): A Method for Measuring the Thickness of Transparent Oil film on Water Surface using Laser Trigonometry. Applied Optics, 45: 4916–4926.
19. Rodland, A., (2004): International Patent Application No.PCT/NO2004/000369
20. Schiegg, H. O., Rodland, A., Zhu, G., and Yuen, D. A., (2015): Electropulse- boring (EPB): Novel super-deep drilling technology for low cost electricity. Journal of Earth Science, 26(1): 37–46.
21. Silva, F. J. R., Netto, D. B., da Silva, L. F. F., and Placido, J. C. R., (2006): Analysis of the Performance of a Thermal Spallation Device for Rock Drilling. In: Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering – ENCIT, (Curitiba, Brazil), Brazil Society of Mechanical Sciences and Engineering – ABCM.
22. Steingrimsson, B., Gudmundsson, A., Franzson, H., and Gunnlaugsson, E., (1990): Evidence of a supercritical fluid at depth in the Nesjavellir field. In: Proceedings to 15th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 81-88.
23. Thorhallsson, S., 2011: Geothermal drilling technology. UNU-GTP, Iceland, unpublished lecture notes.
24. William, R. E., (1985): Thermal Spallation Drilling," in Geothermal Resources Council Symposium, (Kailua-Kona, Hawaii), Los Alamos National Laboratory.
25. Williams, R. E., Potter, R. M., and Miska, S., (1996): Experiments in Thermal Spallation of Various Rocks. Journal of Energy Resources Technology, 118 (1): 2–8.
26. Woskov, P.P., Einstein H.H. and Oglesby K.D., (2014): Penetrating Rock with Intense Millimeter- Waves. 39th International Conference on Infrared, Millimeter, and Terahertz Waves, Tucson, Arizona, MIT Report PSFC/JA-14-17, 2014.