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Drilling Technical Difficulties and Solutions in Development of Hot Dry Rock Geothermal Energy

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Abstract
The exploration and development of hot dry rock resources, first of all, needs to address the drilling issues in deep, hot, hard and unstable formations. By studying geological features and storage conditions of hot dry rocks, the key technical difficulties of hot dry rock drilling are presented. The high-temperature resistance performance index of oil and gas drilling technologies at home and abroad are investigated. The applicability of high effective rock breaking tools, MWD instruments, drilling fluid systems, well cementing and completion technologies are analyzed, and feasibility analyses have been conducted on gas drilling, dry wellbore cementing and foam pressurized drilling techniques. On the basis of the above analyses, the developing directions and issues urgently to be addressed about domestic hot dry rock drilling technology are discussed so as to provide references for drilling program optimization and drilling technology research in the development of hot dry rock geothermal energy.

Key words: Hot Dry Rock (HDR); Drilling; High-temperature resistance; High effective rock breaking

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INTRODUCTION

Dry hot rocks are a kind of dense and impermeable hot rock mass with no or only a small amount of fluid in it buried in the depth of 3,000-10,000 m. The rocks with a general temperature of 150-650℃, in a dry and hot state, belong to clean and renewable green resources. The dry and hot rock resources are widely distributed all over the world, storing extremely high thermal energy. The study of Massachusetts Institute of Technology shows that developing only 2% of dry and hot rock resources in the crust of the earth can produce energy of 2×10^{20}(EJ). By scientific estimation, the stored energy in dry and hot rocks in China is about 2.09×10^{1} (EJ), equal to 7.15×10^{14} tons of standard coal. If the utilization rate is 2%, it is equivalent to 4,400 times of the domestic average annual energy consumption. Dry hot rocks can be used for power generation and heating. They are generally explored with well pattern fracturing, and U-shape wells etc.. High-pressure water is injected into the dry hot rocks through the water injection wells to fully absorb the formation heat, and then the high temperature water and steam are produced from the production wells. After heat exchange and ground circulation treatment, the cooled water is injected back into the formations. The dry hard rock heat can be developed by such a cyclic process, which is safe and environmentally friendly without emissions of carbon dioxide, dust particles, waste water or other wastes, therefore, the dry hot rock geothermal resources have broad prospects for development and utilization [1].

At present, drilling is the only way to dry hot rock exploration and development. In the drilling process, downhole instruments and drilling fluid systems are facing a severe test under the extreme harsh environment of high temperature and pressure. In this paper, the geological and engineering difficulties of dry hot rock drilling are analyzed, the high temperature resistance performance of oil and gas drilling technology is investigated, and the optimization of dry hot rock drilling programs and technologies is effectively explored.

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1. GEOLOGICAL FEATURES OF DRY HOT ROCKS

The heat sources of dry hot rocks include the heat generated by deep rock radioactive isotope metamorphism, the residual heat generated by fracture-dislocation in deep rock tectonic movement, and the conductive heat within the interior of the earth including the parts beneath the radioactive prolific zone and the earth's core. Therefore, the dry hot rocks can be easily found in thin crustal areas. The average crustal thickness of Hainan Province is 20,000 m thinner than other areas in China， and the hot dry rock resources are abundant with relative less development difficulty. The hot dry rocks are mainly of various metamorphic rocks and crystalline rocks, generally including biotitegneiss, granite, granodiorite, etc..[2] Compared with conventional formations, the differences of geological characteristics of hot dry rocks are mainly reflected in the three aspects [3] as follows.

(a) High rock hardness and compressive strength. The extreme crushing strength and firmness coefficient of gneiss fall into the ranges of 1,400-1,800 MPa and 14-18f respectively, the extreme crushing strength and firmness coefficient of diorite fall into the ranges of 1,800-2,500 MPa and 18-25f respectively, and the rock uniaxial compressive strength is generally above 200 MPa.

(b) The temperature of hot dry rock formations is high, generally falling into the range of 150-650℃, and its geothermal gradient is greater than 4℃/100 m. The geothermal gradient in the north-central part of Qinghai Gonghe Basin is 6.8℃/100m, being 2 times of the normal geothermal gradient, and the temperature can reach 168℃ at 2,735 m. Under the thermal shock produced by high-temperature environments, the rocks are inflicted with thermal cracking inside, which is a kind of cracking related to mechanical property, causing the deformation behavior to change and making the elasticity modulus, compressive strength, tensile strength, peak stress and strain to decrease significantly.

(c) The rocks are dense with small porosity, extremely low permeability and basically no fluids contained, but relatively well-developed fissures and the faults. While being developed with well patterns, natural fractures or artificial fracturing are needed to facilitate the opening of flow channels. Bachler and Kohl (2005) found through the study that in the process of water-flooding development, along with the dissolution, precipitation, migration and deposition of mineral substances, the porosity and permeability of hot dry rocks are changing constantly. At the initial stage of development, the porosity and permeability around the water injection wells will increase constantly, while the porosity and permeability around the producing wells will decrease constantly, both of which will achieve a balance after a period of development

2. TECHNICAL DIFFICULTIES IN HOT DRY ROCK DRILLING

(a) The drilling environment temperature is very high, thus imposing great limitations on the performance and service life of downhole drilling tools and drilling fluid systems. It is generally believed at abroad that only the hot dry rock reservoirs with temperature over 350℃ are relatively fit for development economically. In the high temperature environment, the drilling fluids and treating agents are easy to degrade and become useless, having difficulty in playing the normal role of circulation, wall retaining, rock debris carrying, etc.. The measurement accuracy and reliability of the measurement-while-drilling instruments can be easily affected by high temperature. The rubber parts of directional screw rods have difficulty in sealing, which can directly affect the well trajectory control in directional sections and horizontal sections. The high-temperature and corrosion resistance of well completion casing and the stability of cement slurry are influenced, and the well cementation quality is difficult to meet the requirements for hydraulic fracturing development at the later stage[5].

(b) The drilling depth and poor drillability of hot dry rocks render higher requirements on the drilling equipment, drill bits and auxiliary rock-breaking tools. The well depth of hot dry rocks generally falls into the range of 3,000-6,000 m, some even close to 10,000 m; and for the deep wells and extra-deep wells, it is required to drill through many sets of geological formations and pressure systems. The high difficulty in wellbore configuration design, the frequent occurrence of downhole complex conditions, the low transmission efficiency of mechanical energy together with the high hardness and poor drillability of hot dry rocks, and the slow drilling speed due to restrictions on the auxiliary rock-breaking tools under high temperature and high pressure all present great challenges to hot dry rock drilling.

(c) There are fissures and faults developed in the formations, rendering serious lost circulation problems. As the deep wells and super-deep wells are drilled through many sets of pressure systems, their drilling fluid density is difficult to select and control, and they have conspicuous lost circulation problems in themselves. Besides, many fissures, fractures and faults are developed in the hot dry rock formations, which further increases the risk of lost circulation and raises the difficulty of leak protection and sealing under high-temperature and high-pressure conditions. For example, in the drilling process of Tibet Yangbajain ZK201 well, the leak occurs from the position of dozens-of-meters almost through to the well bottom.

(d) The well wall surrounding rocks are lack of stability. In the process of drilling, the well wall surrounding rocks suffer from the multi-field coupling

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effects of temperature field- seepage field- stress field, and obvious thermal rupture phenomenon will occur to the well wall, resulting in a large number of fissures, significantly decreased rock strength, and rock slabbing, drill bit sticking and bit bouncing, as shown in Figure 1. Xi Baoping et al. found through study that for granite with the same burial depth of 5,000 m, the creep rate of granite under 500℃ is 1.87 times of that under 400℃, and the creep rate will increase as the temperature and burial depth (i.e., loading stress) increase, and the probability and extent of wellbore occurring with "necking-down" will increase, resulting in jammed drill bits and collapsed casing etc..

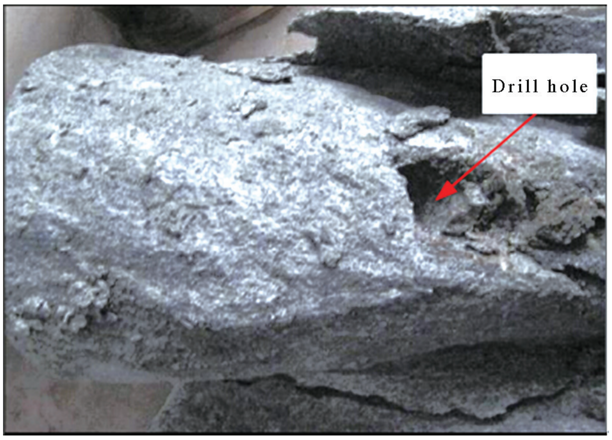

Figure 1
Thermal Fracturing of Surrounding Rocks Contacting Water in Hot Dry Rock Drilling

3. THE APPLICABILITY ANALYSES OF DRILLING TECHNOLOGY

The key to technical difficulties of hot dry rock drilling is to improve the high temperature resistance performance of drilling fluids and downhole instruments with the purpose of achieving efficient rock breaking and smooth carrying under the environment of high temperature and pressure. The high temperature-resistance and no-failure operating limits of high temperature-resistant drilling fluid technology, high temperature-resistant MWD technology, high temperature-resistant well cementing and completion technology, high temperature-resistant drill bits and highly-efficient rock breaking auxiliary tools are investigated, and the technical feasibility of gas drilling, dry wellbore cementing, and drilling with pressurized foam technologies are analyzed.

3.1 High Temperature-Resistant Drilling Fluid Technology

The most typical high temperature-resistant drilling fluid systems include sulfonated drilling fluids and polysulfonate drilling fluids. The sulfonated drilling fluids are prepared on the basis of one or more treating agents of SMC, SMP-1, SMT and SMK, and it is mainly featured by good thermal stability, good rheological property and less filtration loss under high temperature and high pressure, strong salt resistance, good compactness and compressibility of mud cake, and good anti-collapse and anti-jamming performance. The polysulfonate drilling fluids are a kind of high temperature-resistant drilling fluid system that is formed by polymer drilling fluids combined with sulfonated drilling fluids, which retains the advantages of polymer drilling fluids in increasing drilling speed, suppressing stratigraphic mud making and improving the well wall stability and also perfects the mud cake quality and rheological property under high temperature and high pressure[6].

At present, the foreign water-based drilling fluids and oil-based drilling fluids can respectively resist high temperatures of up to 260℃ and 290℃, and can resist the maximum temperature of 37℃ in the application of geothermal wells . The domestic drilling fluids can resist about 240℃ high temperature, therefore, it is possible to adopt the domestic self-owned drilling fluid technology to develop the hot dry rocks at 150-240℃. The application conditions of high temperature-resistant drilling fluids in the drilling of some domestic and foreign super-deep wells are shown in Table 1.

Table 1
Applications of Drilling Fluids at Home and Abroad in Some Super Deep Wells

№	Well number	Well depth (m)	Temperature ℃	Remarks
1		6981	232	Lake Pontchartrain region of the USA
2			371	California (with SSMA and lignosulfonate)
3	Rosa-1	7265	290	Texas (oil-based drilling fluid)
4	Mo Shen-1	7380	200	Xinjiang Oil Field
5	Sheng Ke-1	7026	235	Shengli Oil Field
6	Mi Shen-1	6005	236	Henan Oil Field
7	Xu Shen-22	5300	213	Liaohe Oil Field

High temperature foam drilling fluid system is another drilling fluid system used at home and abroad for resolving the difficulties related to high-temperature resistance of super-deep wells. In the process of preparation and maintenance, high temperature-resistant foaming agent and high temperature-resistant protective

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agent are used to improve the stability of foam under high temperature conditions, and the conventional foam drilling technology is used to realize highly-efficient drilling. At present, the foam drilling fluid technology for 300℃ high temperature has basically been matured, and CNPC Great Wall Drilling Company has used the high-temperature foam drilling fluid technology to drill out a geothermal well in OLKARIA block of Kenya where the formation temperature reaches up to 350℃[7].

3.2 High Temperature-Resistant MWD Technology

In the drilling of directional wells, horizontal wells and U-shape wells, the instruments for measurement-while-drilling (MWD) and the hole trajectory control technology are equivalent to the “navigation system” of drilling. At present, the foreign high temperature-resistant wireless MWD instruments can resist high temperature up to 200℃. The foreign companies’ MWD instruments’ performances for high temperature and high pressure resistance are shown in Table 2; the domestic matured wireless MWD technology can resist high temperature up to 175℃ and the mechanical wireless survey steering tool can resist high temperature up to 260℃. Therefore, while drilling 150-200℃ hot dry rocks, the parameters such as well deviation, azimuth, etc. can be measured; while drilling 200-260℃ hot dry rocks, well deviation can be measured using the mechanical wireless survey steering tool (vertical shafts); but there is not a long-time continuous measurement technology available for the drilling of hot dry rocks above 260℃ at present.

Table 2
High Temperature & High Pressure Resistance of Foreign Companies’ MWD Instruments

Foreign companies	Schlumberger survivor HDS-1R	Halliburton extremeHT-200™	Baker hughes NAVI185SM	Weatherford HELTM
Max. operating temperature ℃	175	200	185	180
Max. operating pressure MPa	172	172	172	207

The wellbore trajectory control can be realized with the help of directional tools on the basis of precise guiding of MWD instruments. The common directional tools include positive displacement motor (PDM) drill, rotary steering tool and turbo drill, wherein, the PDM drill can resist about 150℃ high temperature, the rotary steering tool (Weatherford RSS) can resist the maximum temperature of 175℃, and the turbodrill can generally resist the maximum temperature of 250℃[8]. In combination with the high temperature resistance of MWD instruments, the MWD technology solutions can be selected as follows. Carry out the measurement while drilling (MWD) and hole trajectory control in the whole process of drilling directional wells, horizontal wells and U-shape wells in 150-200℃ hot dry rocks; and conduct MWD and orientation in the low-temperature area and single point measurement in the high-temperature area after cooling through circulation and turbo drill (below 250℃) or bottom hole assembly for hole trajectory control for directional wells in the hot dry rocks with temperature over 200℃.

3.3 High Temperature Wellbore Cementing and Completion

In high temperature environment, the cementing quality can be affected by cementing ability, casing corrosion, casing strength and formation creep on casing squeeze. The strength and life of high-temperature resistance casing materials such as V140, V160, being influenced by long-term high temperature, extrusion and corrosion, are limited. Halliburton’s high-temperature retarder and boric acid (salt) compound has the applicable circulating temperature of 316℃. Schlumberger’s UNIFSET retarder is applicable for temperature less than 232℃. Schlumberger’s D700, Uniflace and other high temperature fluid loss agents can be applicable for temperature of 260℃. At present, the domestic cement slurry system and additives are still mainly working in the circulating temperature below 200℃, and the performance parameters and stability can hardly meet the requirements of dry hot rock formation cementing with temperature of above 200℃[9-10] . High temperature resistant oil well cement additives, developed by Changchun Institute of Applied Chemistry Chinese Academy of Sciences, can be used within temperature up to 230℃, with high pressure water loss being controlled within 50 mL.

Deep well and super-deep well cementing is also facing the problems of cement slurry loss, borehole necking, difficult casing running etc. Among the high temperature resistance lost circulation additives for common use, the temperature resistance capacity of Neotoy lost circulation additive NTS-M can reach up to 275℃, with pressure bearing capacity of 14 MPa. Borehole reaming tools are applicable for addressing the issues of borehole necking, and the borehole can be expanded by 20% with a new type of reaming tool-RHINO, developed by Smith Company. This kind of tool has high reliability, durability and high borehole concentricity, and the temperature resistance capacity may reach up to 230℃. In comparison, the temperature resistance capacity of domestic reaming tools may reach up to 170℃. As shown in Figure 2, the shell of a new type of casing running tool, Turbocaser Express developed by Deep Casing Company, is made of high-grade steel with the molding technology, high temperature and high pressure resistance, corrosion

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resistance and can be used for casing running in horizontal intervals[11].

Figure 2
Turbocaser Express System

3.4 Highly Effective Rock Breaking Technology

In process of drilling with bits in high temperature, high hardness formations, not only the rock breaking efficiency is low, but the bits service life is short. The temperature resistance of pioneer high-temperature rolling cutter bit, developed by Schlumberger, may reach up to 288℃,and its cutter wear resistance can meet the requirements of dry hot rock formation drilling. The PDC bit has ultra-hard and thermally stable PDC cutting teeth, while the ReedHycalog ultra-hard and thermally stable PDC Bit can drill out the hard formations with the compressive strength of 280 Mpa, relying on its high wear resistance and impact resistance, as show in Figure 3. At present, under the cooling effect of the drilling fluid systems, the drill bit can meet the requirements of drilling dry hot rock formations of 350℃, but it is not allowed to stay at the bottom hole without circulation for a long period and in special circumstances, it should be pulled up to the low temperature intervals when no circulation is required for a long time[12].

Figure 3
ReedHycalog Ultra-Hard and Thermally Stable PDC Bit

In highly efficient rock-breaking auxiliary tools, the rotary percussion drilling tool is a kind of oil-sealed mechanical device with no rubber sealing parts and high temperature resistance up to 350℃ or above, and it can increase the rate of penetration by 50% when drilling in hard formations. The twisting percussion auxiliary rock breaking tool, developed by SINOPEC Shengli Petroleum Engineering Co., Ltd, has no rubber parts and is high temperature resistant, therefore it can protect the PDC bit. PDC bit optimization can greatly prolong the service life of the drilling bits and increase the rate of penetration for hard formation drilling[13].

3.5 Gas Drilling and Dry Wellbore Cementing

Gas drilling technology is achieved by using air, nitrogen, etc. as the circulating medium so as to overcome the problems of insufficient high-temperature-resistance of liquid drilling fluids. Application of gas drilling technology in dry hot rock drilling has advantages as follows: (a) The well head can be more safely protected. The safety control of wellhead equipment is easily achieved due to large displacement of gas drilling and the not-too-high temperature of gas returned to the wellhead. (b) Borehole wall collapse can be avoided. The thermal rupture caused by heat exchange between borehole wall surrounding rocks and circulating medium can be avoided due to the low gas thermal conductivity and low rate heat exchange between gas and borehole wall. (c) The formation leakage is addressed. There are more developed fractures in dry hot rock formations, and liquid drilling fluids are prone to leakage, which can be effectively avoided by gas drilling. (d) The penetration rate can be increased. Gas drilling is suitable for highly effective rock breaking and carrying in hard formations and can greatly increase the penetration rate of drilling in dry hot rock formations. The deepest record of gas drilling in China is 6,200 m created by nitrogen medium in Mandong No 2 well in Tarim Basin, with the bottom hole temperature of 145℃, and formation pressure of 100.06 MPa[14].

Dry wellbore cementing refers to the well completion method by direct casing running and cementing operations without drilling fluid conversion after gas drilling. Application of dry wellbore cementing for dry hot rock formations has the advantages as follows: (a) Borehole wall collapse and other complex circumstances caused by borehole thermal rupture can be avoided. (b) Wellbore cementing quality can be improved apparently because there is no impact of drilling fluids and filter cakes, and the cementing slurry directly contacts the casing and borehole wall. (c) The wellbore cementing efficiency is improved, eliminating the need for drilling fluid conversion, etc., shortening the drilling time and saving the drilling costs [15-16]. At present, the domestic deepest record of dry wellbore cementing is 3179.68 m.

3.6 Foam Pressurized Drilling Technology

Foam pressurized drilling technology refers to using of high-pressure air compressors for foam perfusion and pressurizing and is a kind of drilling method with the pressurized foam as the circulating medium. The core of the technology is the foam pressurizing equipment with large powerfull and highly effective performance. Foam drilling can be used in areas with complex terrain and geological conditions, areas where drought is serious and mountain areas where water supply is inconvenient, low-

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pressure formations prone to leakage, water-sensitive formations, permafrost strata and formations with high temperature. This technology is successfully applied in geothermal well construction in Beijing area. If it is used to drill deep dry hot rock formations with high temperature, there is still room for breakthroughs in technology and process [17].

The advantages of foam pressurized drilling technology lie in: (a) High Drilling efficiency. Low foam density, low hydrostatic column pressure of circulation medium in wellbore, small amount of cuttings deposited at the bottom hole and high rock carrying efficiency of foam fluids can greatly increase the drilling rate. (b) Wide temperature ranges. At present, high-performance foaming agent and foam stabilizer have been developed to ensure the normal application of foams in high or low temperature environment. (c) Few downhole complex circumstances. In foam drilling, the medium flowback rate is relatively small and the erosion to the wall is insignificant, which can ensure the stability of the borehole wall. In addition, the foam contains little liquid phase, reducing the borehole wall instability caused by permeation of liquid phase. (d) Low drilling costs. The overall cost of foam drilling is only about 70% of the conventional drilling fluid drilling cost.

4. PROSPECT OF DOMESTIC HOT DRY ROCK DRILLING TECHNOLOGY

The hot dry rock geothermal resources in China are developed relatively late, and the drilling technology is still being researched and practiced. In 2012, the “Research on key technologies in the development and comprehensive utilization of hot dry rock geothermal energy”, a project of National High-tech R&D Program (863 Program) was approved and initiated. In 2014, the first hot dry rock well in China-DR3 well was drilled out in Gonghe Basin of Qinghai Province, finding hot dry rocks with 168℃ high temperature at 2,735 m where the geothermal gradient reaches up to 6.8℃/100m, and the rocks have relatively shallow burial depth and high temperature, indicating the good prospect of hot dry rock resources in China. Through the above analysis of difficulties and solutions on the drilling technology of hot dry rocks, the development direction and strategies of hot dry rock drilling technology in China have been preliminarily discussed.

(a) Carry out the research on the whole technical solutions for hot dry rock well drilling and completion equipment and tools based on the actual conditions in China

Carry out investigation on the drilling technology, equipment, drilling fluids and rock breaking tools used in the hot dry rock demonstration projects in foreign countries, and analyze the distribution conditions, geologic characteristics, temperature range and ground-surface environment of hot dry rock resources in China; carry out the research on the high-quality and high-speed drilling technology of hot dry rocks, including the drilling rigs and ground equipment solutions, high temperature-resistant high-efficient rock breaking drill bits, high temperature-resistant rock breaking auxiliary tools, trajectory measurement and control instruments, etc., so as to form the highly-efficient drilling technology solutions for deep, high-temperature and hard formations; increase the research efforts on tackling the problems of hot dry rock drilling fluid systems and circulation cooling devices for satisfying the maintenance and operation requirements of circulating media in the drilling process of hot dry rocks and guaranteeing the inlet temperature of drilling fluids so as to effectively protect the downhole tools; carry out the research on well head safety technology in the drilling process of hot dry rocks, including the high temperature-resistant rubber materials, high temperature well control devices, etc., so as to meet the requirements on high temperature and high pressure; carry out the research on the optimal selection technology of high temperature-resistant, anti-corrosion and high-strength well casings, and study the thermal stress properties of casings of different brands, including the free elongation, high temperature and corrosion resistance, thermal stress intensity and the influences of the casing materials on the strength of casings themselves, and the requirements on well cementation technology and well head equipment under different working conditions.

(b) Select optimal geological target regions and speed up the construction of hot dry rock drilling development demonstration projects

In 2013, China Geological Survey initiated the investigation and evaluation work on hot dry rock resources, and has completed the analysis of geologic settings of areas with hot dry rock geothermal resources in China by now, preliminarily establishing the geothermics indicators with which to select strategically the hot dry rock resources, and blocking out some preferential target regions for the development and utilization of hot dry rock resources. On the basis, it is necessary to speed up the construction of hot dry rock drilling development demonstration projects, utilize the relatively mature hot dry rock drilling technology to make a 3000-3500m hot dry rock demonstration well. During the construction process, optimize and upgrade the drilling programs, further clarify and specify the tackling directions of key technologies in hot dry rock drilling, and gradually form sound technical solutions for hot dry rock drilling so as to guide the drilling and exploration of hot dry rocks in China.

CONCLUSION AND UNDERSTANDINGS

(a) The hot dry rocks are mainly of various metamorphic rocks and crystalline rocks, being featured

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by compact rock mass, high hardness and compressive strength, high formation temperature, low porosity, and extremely low permeability and almost no fluids. The difficulties of hot dry rock drilling technology mainly lie in: High drilling environment temperature, imposing great restrictions on the performance and service life of downhole drilling tools and drilling fluid systems; large drilling depth of hot dry rocks and poor drillability of rocks, rendering higher requirements on the drilling equipment, drill bits and auxiliary rock breaking tools; fissures and faults developed in the formations, introducing serious lost circulation problems; the well wall surrounding rocks suffering multi-field coupling effects of temperature field- seepage field- stress field, showing very poor stability.

(b) The key technology of hot dry rock drilling is to improve the high temperature resistance performance of drilling fluids and downhole instruments with the purpose of achieving efficient rock breaking and smooth carrying under the environment of high temperature and pressure. The high temperature-resistant drilling fluid technology, high temperature-resistant MWD technology, high temperature-resistant well cementing and completion technology, high temperature-resistant drill bits and highly-efficient rock breaking auxiliary tools in China can basically satisfy the needs on drilling of medium and low temperature hot dry rock formations. There are advantages for hot dry rock drilling by using gas drilling, dry well cementing, and drilling with pressurized foam, but the shortage in the high temperature resistance performance of the technical equipment is still to be overcome.

(c) The drilling technology of hot dry rocks is still at the stage of research and practice in China in comparison with the foreign countries, and it is necessary to carry out the research on the whole technical solutions for hot dry rock well drilling and completion equipment and tools based on the actual conditions in China, select optimal geological target regions, speed up the construction of hot dry rock drilling development demonstration projects, and form the drilling technical solutions that are suitable for the development of hot dry rocks in China as soon as possible.

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