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Dilemma and Breakthrough on Large-scale Commercial Exploitation of Hot Dry Rock: A Novel Enhanced Geothermal System

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ABSTRACT

Hot Dry Rock is widely regarded as one of the most promising renewable clean energy sources, which is also expected to be the ultimate option of energy structure transformation. However, HDR exploitation is facing great difficulties, resulting in a low utilization rate with total installed capacity of 17.85 MWe at 52 projects in the world. The Enhanced Geothermal System (EGS) for HDR exploitation relies too much on the in-situ stress field and natural fracture characteristics of the thermal reservoir, leading to most reservoir quality failing their expectation. Most of the EGS projects in the world have some common shortcomings such as insufficient thermal reservoir volume, unstable fracture network, low flow rate with low temperature, significant water loss, and considerable risk induced seismic events, which fundamentally limit the large-scale commercialization of EGS. The proposal of the enhanced geothermal system based on excavation technology (EGS-E) inspires us to overcome the technical shortages and scale limitations of EGS. In this paper, EGS-E is illustrated more systematically and comprehensively in the aspects of the system composition, working principle and technical advantages. Based on mature mining technology, EGS-E replaces the conventional drilling and hydraulic fracturing technologies by the excavating, blasting and caving technologies, forming a unique reservoir reconstructing and two-stage heat exchange system. This novel system can overcome the restriction of geological conditions, providing customizable thermal reservoir volume, stable fracture network, sufficient flow rate with high temperature, little water loss as well as minimal risk of induced earthquakes. E-EGS may break through the existing dilemma, contributing a brand-new idea and scheme for the commercial exploitation of HDR utilization.

1. INTRODUCTION

With the continuous growth of the global economy, the population and energy consumption per capita are increasing, leading to increasingly prominent problems of energy reserves and environmental pollution(Li and Wang,2015; Zhu et al.,2015). More and more countries have begun to reduce the use of traditional fossil energy gradually, and are committed to the development the renewable energy. As a result, the installed capacity of renewable energy makes fantastic progress, which increased by 107.50% from 2009 to 2018.(IRENA,2019).

Due to limitations in time and space, however, most of the renewable energy, including solar energy, wind energy, hydro energy and so on, cannot necessarily meet the power requirements of the basic load. Compared with other renewable energies, geothermal energy is a clean, sustainable, and reliable natural resource with widely distributed and vast reserves(Hendron,1987). It is considered to be a kind of energy with broad development prospects and potential, which may fulfill the shortage of fossil fuels without greenhouse gas emissions(Brown et al.,2012; Kruger and Otte,1973; Li and Wang,2015; Rybach,2010).

Geothermal energy, mainly derived from the heat generated by the natural decay of radioactive substances below the surface, is a kind of the natural energy existing in the earth's crust(Olasolo et al.,2016), which can be roughly divided into hydrothermal energy and Hot Dry Rock (HDR) energy(Li and Wang,2015). Hydrothermal resources, as known as traditional geothermal resources, mainly existing in natural groundwater and its steam, is the earliest and most widely used geothermal resources by human beings, which has been directly utilized in 82 countries and generated electricity in 26 countries all over the world(Lund and Boyd,2016; Lund et al.,2011). During the five years from 2010 to 2015, the utilization of geothermal resources has increased rapidly, showing that the direct-use capacity increased from 49.40GW_t to 69.13GW_t(Lund and Boyd,2016), and the power generation capacity grew from 10.7GW_t to 13.5GW_t(Olasolo et al.,2016).

Although hydrothermal resources have made significant achievements, some major analysts believe that the total hydrothermal reserves are not infinite as well as their renewable rate is extremely slow(Olasolo et al.,2016). Therefore, it is necessary to find new geothermal resources to maintain a promising future of geothermal resources, among which HDR is considered to be the ideal alternative under the existing technological conditions.

HDR is the most abundant geothermal resources(Breede et al.,2013), the exploitation potential of which is 100 to 1000 times that of hydrothermal resources(Kruger and Otte,1973). Generally speaking, the lithology of HDR used for utilization is granite with low permeability; temperatures should more than 150℃ at depths of more than 3 km. Different from the hydrothermal resource, there is no natural seepage channel in HDR, which determines the need to use artificial stimulation methods to enhance the permeability to form a fracture network. This enhanced technology for HDR is called Enhanced Geothermal System(EGS), This enhanced exploitation technology is called Enhanced Geothermal System(EGS), and the concept of which was proposed by Los Alamos Scientific Laboratory in 1970(Hendron,1987). The first EGS project was established at Fenton Hill, New Mexico, in 1972(Breede et al.,2013; Hendron,1987). which successfully verified the feasibility of EGS and achieved the thermal capacity of 10MW_{th} finally(Olasolo et al.,2016). The success of this project demonstrates the considerable potential of EGS, prompting more and more

countries to join the EGS research and development queue(Bachmann et al.,2011; Breede et al.,2013; Cuenot et al.,2006; Grigoli et al.,2018; Kwiatek et al.,2010; Matsunaga et al.,2005; Parker,1999).Up to now, a total of 12 countries and regions have conducted field test studies on EGS, which accumulated a lot of experience and lessons for subsequent EGS research(Kwon et al.,2019; Massachusetts Institute of Technology,2006; Stafford,2010).

2. EGS DEVELOPMENT OVERVIEWS

The success of the Fenton Hill project triggered a boom on EGS research in advanced countries, resulting in Germany(Tenzer,2001), Britain, France, Japan, and other 12 countries started different numbers of EGS projects since 1976. Up to now, there are 52 recorded ongoing or terminated EGS projects in the world(Kwon et al.,2019; Massachusetts Institute of Technology,2006; Stafford,2010).

Fig.1 shows the total number of EGS projects launched since 1970. During 1971-2000, there were fewer EGS projects launched every five years, resulting in a total of 10 projects were launched in 30 years. After 2000, the EGS project achieved fantastic growth with 10 projects launched in 2001-2005, which is almost the same as the total number of 1971-2000. What's more remarkable is that the number of EGS projects by 2006-2010 increased dramatically to 29, nearly three times that of 2001-2005. This significant growth trend, however, was suddenly interrupted in 2011, leading to only two projects launched since 2011.

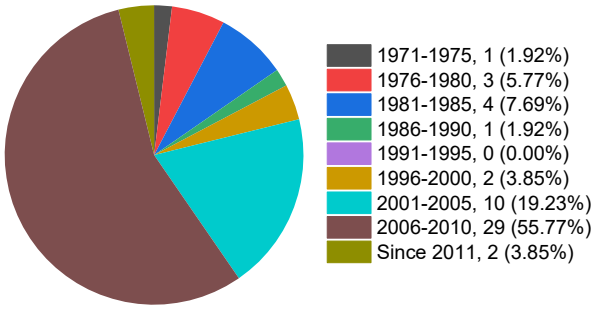


Figure 1: Pie chart of the start time of the projects in the world

Fig.2 depicts the distribution of EGS projects in different countries. There are three countries with a total number of EGS projects more than 10, namely the United States, Australia, and Germany. The United States and Australia both are the countries with the largest number with 12 field projects. Closely followed by Germany, carried out 11 projects in total. Subsequently, France, the United Kingdom, Japan, and Switzerland launched four, three, three, and two projects, respectively. The remaining five countries launched only one EGS project in each country.

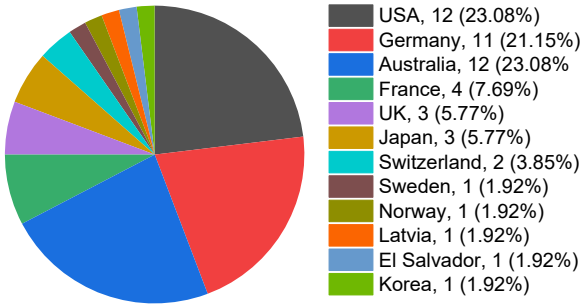


Figure 2: Pie chart of the regional distribution of EGS projects in the world

According to the time and region distribution characteristics shown in Fig.6, the development of EGS should be divided into two stages, namely the research and development stage from 1970 to 2000 and the demonstration and commercialization stage since 2001.

Before 2000, it was the experimental stage of EGS, the projects in that phase aimed at research and development of EGS technology, most of which have been shut down already, except the Soultz project in France. It is noted that most of the countries (the United States, Germany, Britain, France, Japan) that initiated the EGS project participated in the Fenton Hill project by the form of funding and personnel, mastering the most advanced technology and first-hand on-site data. These valuable data provided a guarantee for them to start the EGS field test in their respective countries after the completion of that project. It is worth mentioning that Japan, the country with the most EGS in that stage, started three pilot projects in Ogachi, Higashi, and Hijiori respectively from 1982 to 1986.

After 2000, it is the demonstration and commercialization stage of EGS. In that stage, EGS achieved a booming development. Countries with successful experience in the experimental stage increased more investment to launch a large number of new EGS projects, such as the United States with 11 new EGS projects. On the contrary, countries that did not succeed in the pilot phase temporarily suspended EGS investment, such as Japan, which had three projects before 2000 and no new one after 2000. Also, some countries with abundant HDR resources started EGS projects successively, such as Sweden, Korea, and so on. It is mentioned that Australia, the country with the fastest-growing of EGS at that stage, built 12 projects in only 10 years, making it one of the countries with the largest number of EGS projects in the world.

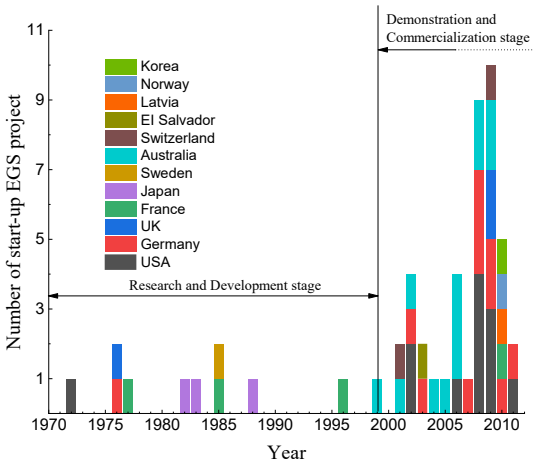


Figure 3: Comprehensive map of the time and area distribution of EGS projects in the world.

3. CURRENT STATUS OF COMMERCIALIZATION

3.1 Summary of EGS construction Process

As shown in Fig.2, the Enhanced Geothermal Systems for HDR exploitation is generally composed of injection wells, production wells, artificial geothermal reservoir formed by stimulation methods, and surface power generation devices (Massachusetts Institute of Technology,2006).

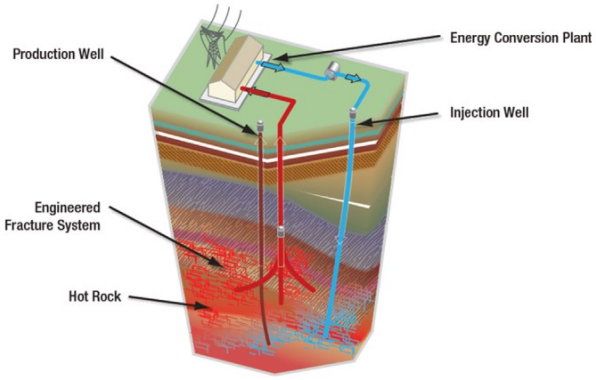


Figure 4: A conceptual two-well EGS in hot rock(Olasolo et al.,2016)

Its necessary technological process of EGS is as follows(Baria et al.,1999; Olasolo et al.,2016): The first step is to select an ideal site, which needs to drill an exploratory to confirm the properties. The next step is to drill an injection well to the target horizon. Then, artificial stimulation techniques including hydraulic fracturing or shearing, thermal stimulation, chemical stimulation and so on, is used to induce the connection of natural cracks or generate new ones in the reservoir to form the fracture network(Tezuka and Niitsuma,2000). At the same time, micro-seismic monitoring or other means are adopted in the process of reconstruction to observe the feature and scope of fractures, which can be used as a reference for the location of the production well. After the production well is completed in the ideal position, the injection well and the production well are connected to form a fluid channel. Subsequently, the cryogenic fluid is injected into the thermal reservoir fracture network through the injection well. When the working fluid flows through the fracture surface, it exchanges heat with the high-temperature rock and turns into a high-temperature liquid. Finally, the high-temperature working fluid is elevated to the surface for power generation or direct utilization through the production well(Hendron,1987).

3.2 EGS current status of commercialization

Different from hydrothermal resources, HDR exploitation needs to be reformed by artificial stimulations, which is the key to the success of EGS. Breede et al. (Breede et al.,2013) indicated that the capacity of EGS is closely related to the quality of a thermal reservoir, which plays a significant effect on the reservoir volume, active heat exchange area, fluid resistance, rate and temperature of the working fluid, and other factors. Rybach (Rybach,2010) concluded that commercial capacity of EGS is related to factors such as flow rate, outlet temperature, effective heat-transfer area, thermal reserior volume and so on, which need to meet the limit values together, as shown in Table 1. Jung(Jung,2013) also considered that the thermal reservoir capacity of a commercial EGS project should guarantee that the system operates at flow rates between 50 and 100 l/s and produces electricity of 3 to 10 MW_e over a life of at least 25 years. After 40 years of development and improvement, however, the theoretical system and construction technology have been greatly improved, but most of the projects cannot guarantee the quality of thermal reservoir to meet this expectation, resulting in that the utilization of HDR is extremely low with a global cumulative installed capacity of 17.85MW_e(Breede et al.,2013).

Table 1: The limited Value Table of Related Factors for EGS Satisfying Power Generation Capacity

Relevant parameters	Limited value
Flow rate	50~100l/s
Outlet Fluid temperature	150~200°C
Effective heat exchange area	$>2\times10^6 m^2$
Reservoir volume	$>2\times10^8 m^3$
Water losses	<10%

3.3 Common shortages of EGS

Through statistical analysis of current and past EGS projects in the world, we found some common characteristics, which may be helpful to the development of EGS. Based on artificial stimulation methods, EGS projects are generally characterized by insufficient thermal reservoir volume, unstable fracture network, low flow rate with a low temperature, significant water loss, and considerable risk to induce seismic events, which fundamentally limits the large-scale commercialization of EGS(Hendron,1987; Matsunaga et al.,2005; Pierce and Livesay,1993).

3.3.1 Insufficient thermal reservoir volume.

The volume of the thermal reservoir of EGS is determined by the two-well distance and artificial stimulation method, which is challenging to meet the scale of commercialization under the current technology (Hendron,1987). For example, although Fenton Hill II project in the United States achieved a good result in fracturing, its estimated reservoir volume was only $0.035 km^3$, far from the minimum capacity required for commercial exploitation.

3.3.2 Unstable fracture network.

The fracture network of EGS mainly depends on the characteristics of natural fractures in the rock mass, which has strong randomness and instability(Breede et al.,2013).

3.3.3 Low flow rate with low temperature.

The working fluid of EGS consumes a lot of power in the heat transfer process, including the frictional power consumed to overcome the resistance of the fracture network and the lifting power consumed by the working flow from the bottom of the production well to the ground. This high resistance results in a short circuit of the fluid, and the flow rate is not up to standard. As shown in Figure 5, of the 21 recorded EGS projects, only 23.81% had a flow rate over 50L/s, but 57.14% below 20L/s(Breede et al.,2013). Meanwhile, the terminal temperature of the working fluid mainly depends on the heat energy absorbed in the heat transfer process. Because most of EGS projects cannot guarantee enough heat transfer areas, the outlet fluid temperature is generally lower than the economic value.

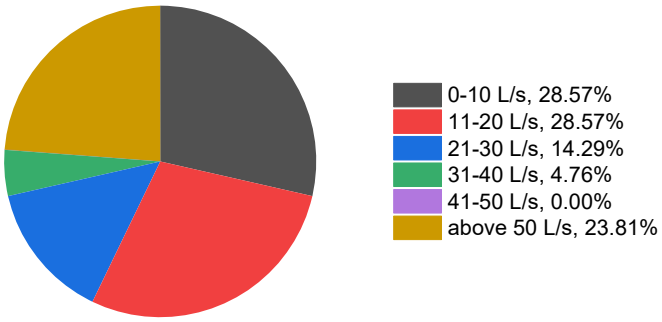


Figure 5: Flow rate distribution of EGS projects

3.3.4 Significant water loss.

EGS requires high-pressure water to break rocks into a fracture network, and to conduct heat transfer through the fracture network. Both processes need to consume a large amount of water resources. Besides, the unstable fracture network may cause short circuit to make water loss further, leading to some EGS even lose water more than 20%. The St Gallen project in Switzerland was enclosed in 2014 because of the insufficient flow due to excessive water loss.

3.3.5 Great risk to induce seismic events.

According to statistics, almost all of the world's EGS produced the seismic event in the process of drilling, fracturing, or even production, most of which are too small to be felt. However, there were still a few seismic events caused irreparable damage, resulting in the suspension or abandonment of the EGS project. such as Basel in Switzerland and Pohang in Korea(Breede et al.,2013; Kim et al.,2018). Among 16 EGS projects with seismic records , four of them have triggered seismic events with the Richter magnitude greater than 3(Breede et al.,2013; Kim et al.,2018). The most notable one was the earthquake with a 5.5 Richter magnitude, occurring during the fracturing of the Pohang EGS project in South Korea in 2017. That earthquake resulted in the suspension of this EGS project that has invested enormous funds and personnel for nearly eight years (Kim et al.,2018; Kwon et al.,2019).

The main reasons for this situation are as follows: The first one is the insufficient attention and investment. Note that most countries began to advocate the development and utilization of clean energy, which is merely suggestions, leading to the lack of government funding; At the same time, the pre-investment of EGS project is too large as well as a low recovery ratio of capital, which leads to the lack of investment from private capital(Sanyal et al.,2007). The second aspect is the lack of successful projects and experience. Despite four decades of development, there are too few successful EGS projects, resulting in relatively limited experience available for the current EGS sits. Moreover, most of success projects are still in R&D status with many concealed vital technologies, which leads to leads to the need for independent innovation in new projects under a slow speed of technology iteration. The third and most important reason is that the reconstruction technologies of the existing thermal reservoir rely too much on the in situ stress field of the reservoir (Breede et al.,2013) and characteristic of natural fracture in the rock mass (Schill et al.,2017; Willisrichards et al.,1995), which cannot be predicted and controlled in advance, resulting in the uncertainty of the fracture distribution in the reservoir (Pierce and Livesay,1993). It is this uncertainty that leads to various problems in EGS.

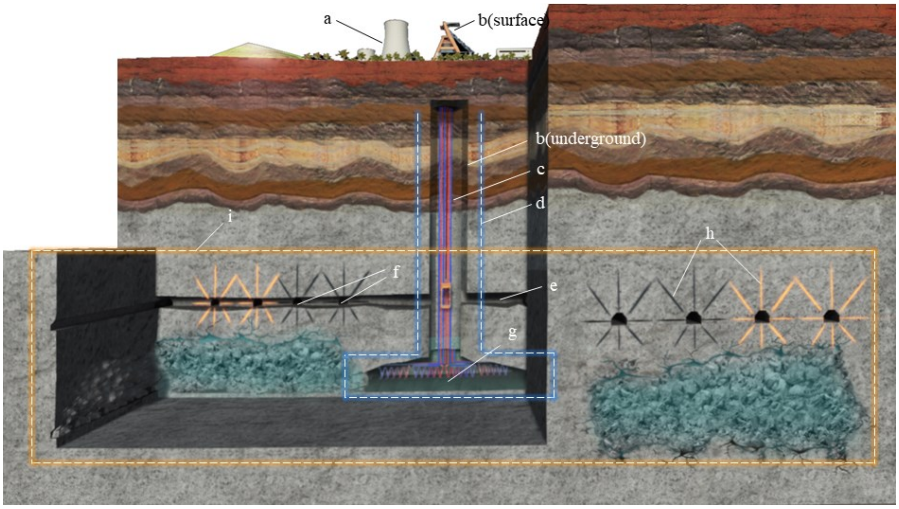
Therefore, the large-scale commercialization of EGS must break through the bottleneck that the current reservoir modification technology relies excessively on in-situ stress and natural fractures. Based on this, Chinese scholar Tang Chun'an et al.(Tang et al.,2019; Tang et al.,2018) proposed a novel type of enhanced geothermal system based on excavation technology (Abbreviated as EGS-E to distinguish the traditional EGS), which replaced conventional drilling and hydraulic fracturing technologies by excavating, blasting and caving technologies. This system may change the dependence of traditional EGS on reservoir conditions, providing a new possible solution for HDR exploitation.

In this paper, EGS-E was systematically illustrated in the aspects of the general situation, engineering principles, and technical advantages, which can be used as follow-up EGS-E provides a reference for research and engineering application.

4. ENHANCED GEOTHERMAL SYSTEM BASED ON EXCAVATION

4.1 Model overview

On the whole, EGS-E is generally composed the surface power plant (Fig.6.a), shaft (Fig.6.b) and thermal reservoir (Fig.6.i), as shown in Fig.6. The shaft is the key to the construction of the whole EGE-E project, providing ventilation, lifting, maintenance, and other functions. Inside of the shaft is the heat exchange pipeline (Fig.6.c), and bottom of which is the heating pool (Fig.6.g). Heat exchange pipes, extracting energy from the heating pool, replace injection wells and production wells to realize working fluid circulation and change its circulation mode from open to closed. Artificial thermal reservoir of EGS-E, formed by the combining method of excavating, blasting and caving technologies, including main roadways, blasting roadways, blasting boreholes and so on. The main roadway (Fig.6.e), extending to the edge of the thermal reservoir, connects the shaft, the heated pool, and all blasting roadways, whose length is related to the volume of thermal storage. The blasting roadway (Fig.6.f) can not only provide compensation space for caving, but also loose the overlying rock with blasting boreholes to obtain an excellent caving effect.



a. Power plant； b. Shaft; c. Heat exchanging pipes (blue is the injection pipe; red is the production pipe）； d. Heat exchange zone in pipes; e. Main roadway； f. Blasting roadway; g. Heating pool; h. Blasting boreholes； i. Heat exchange zone in thermal reserve.

Figure 6: Schematic diagram of EGS-E engineering model

The process of EGS-E can be summarized as follows: (1) Exploration is necessary to select an ideal site with a tremendous geothermal gradient. (2) Construction of a shaft with a diameter of 8-10m at the selected location. (3) Once the shaft is completed, the heating pool and main roadways should be built at its bottom. (4) Prolonging the main roadway to the edge of the expected reservoir, and locating the blasting roadway and borehole according to the design. (5) Installing heat exchange pipes in the shaft and heating pool. (6) At the same time, the artificial reservoir with a fracture network is formed by detonating boreholes and block caving. (7) Blocking up the shaft and injecting water into the thermal reservoir through injection pipelines. (8) Injecting the working fluid into the enclosed heat exchange pipelines that connected with the power plant to generate electricity.

4.2 Contrast of key processes between EGS and EGS-E

The principle of EGS-E is basically like the same as that of EGS, which is using artificial stimulation methods to make HRD cracked to form a fracture network, and extracting heat energy by driving water (other working substances) to flow through these cracks.

The difference is that the cracking and heat transferring methods used in EGS-E are different from those used in EGS. Most of the stimulation technologies adopted by EGS are the hydraulic fracturing or shearing, while mining technologies such as excavating, blasting, and caving are used in EGS-E. Meanwhile, EGS carries out a kind of direct heat exchange between the working water and the rock surface, while EGS-E uses a sort of two-stage heat exchange, including one exchange between the working water and the rock surface and another exchange between the working liquid in the pipes and the working water in the heating pool.

In this section, the cracking method and heat-exchange method of EGS-E will be described in detail.

4.2.1 The cracking method of the EGS-E thermal reservoir

To overcome the limitation of blasting and caving technology on the vertical direction, EGS-E adopts multi-level mining technology thrived from mining engineering, dividing the thermal reservoir into several mining levels along this direction, as shown in Fig. 7. A single-layer fracture network is formed by blasting and caving in a single level, and then, the multi-layer fracture network of EGS-E consists by many single-layer networks. It is worth noting that the vertical height of the cracking level is determined by the blasting capacity, while the amount of mining level is according to the scale of required capacity. Thus, various production demands can be met by different heights and amounts of the cracking level in actual production.

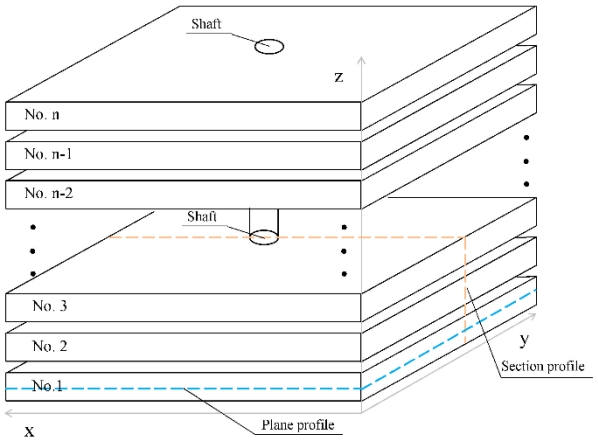


Figure 7: Schematic diagram of EGS-E multi-level thermal reservoir

Fig.8 and Fig.9 are the enlarged profiles on section and plane of thermal reservoir in EGS-E, respectively. As shown Fig.8, the horizontal fracturing system in a signal level is composed of main roadways, blasting roadways, blasting boreholes, and supporting projects. The main roadway is the connecting roadway with the length extends to the horizontal boundary, whose responsibility is to connect all blasting roadways in this level. The blasting roadway is arranged in the main roadway and intersect vertically with them, covering the entire horizontal plane. The blasting borehole is built in the blasting roadway in a radial manner, which covers the whole of vertical range, as shown Fig.9. The quality of heat storage is determined by its volume and effective heat transfer area, which are affected by the parameters of the borehole, the geological condition of the thermal reservoir and the physical properties of HDR. Therefore, the reservoir quantity at all levels can be guaranteed to meet the anticipated requirements by adjusting these factors.

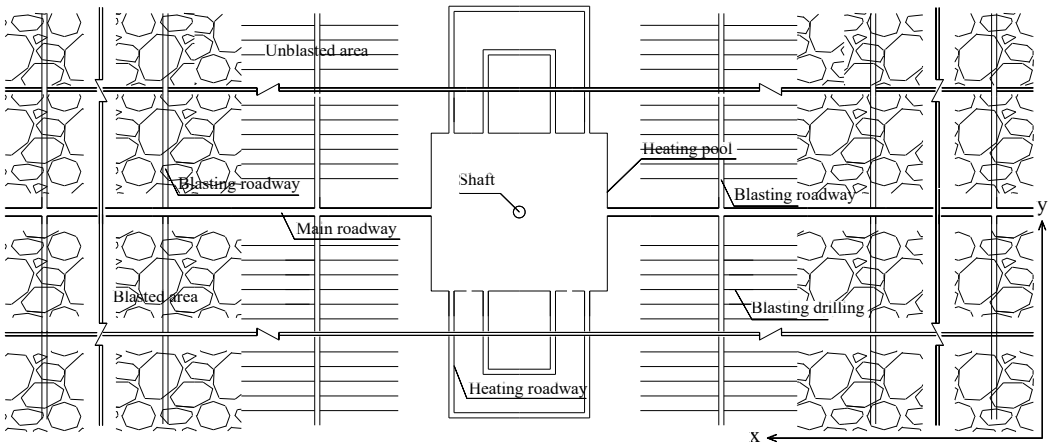


Figure 8: EGS-E enlarged plane profile of the No.1 mining level

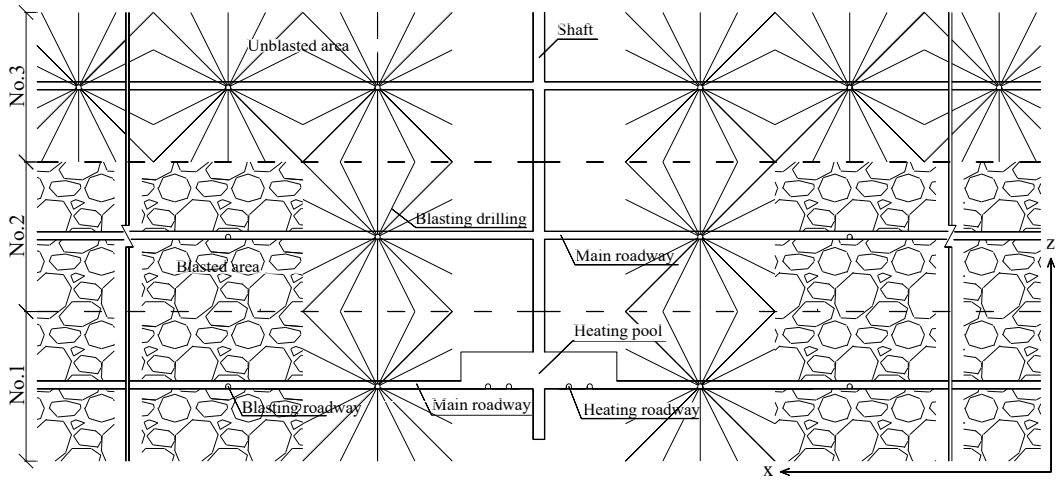


Figure 9: EGS-E enlarged section profile of the mining level from No.1 to No.3

4.2.2 The heat-exchange method of the EGS-E

EGS-E heat exchange system is composed of the fracture circulating heat transfer system and the pipeline circulating heat exchange system, which provides a two-stage heat exchange method to complete the thermal energy extraction of HDR. One stage is the fracture circulating heat transfer system for "rock-water heat transfer," and the other is a pipeline heat transfer system for "water-water heat transfer." The heat transfer between these two systems is completed in the heating pool.

The fracture circulating heat transfer system, locating in the facture heat transfer zone (Fig.6.d), is composed of the heating pool, heat exchange pipes, the heat storage and working fluid fulfilled in its cracks, whose function is to complete the "rock to water heat transfer" in the fracture network. During this process, the working fluid with low temperature flows through the fracture network and goes back to the heating pool after being heated to a high temperature. The pipeline circulating heat exchange system is in the pipe heat exchange zone (Fig.6.i), which consists of several enclosed pipes arranged in the shaft and heating pool, and their internal working fluid. Its function is to complete the "water to water heat transfer" of the cold and hot working fluid in the pipeline to extract the heat energy from the working fluid in the heating pool. The working fluid injected into pipes from the entrance flows through the spiral pipeline in the heating pool for conducting heat exchange. Subsequently, the heated working fluid flows out through the exit, and reinjected into the pipes after being used in the power plant.

Fig.10 shows that the whole process of extracting thermal energy in EGS-E. The energy from HDR is first transferred to the working fluid in fractures and then transmitted to the heating pool through the fracture circulating heat transfer system. In the heating pool, the energy is transferred to the working fluid in pipes through heat conduction with the surface of pipes and finally lifted to the ground generating plant through the pipeline circulating heat exchange system.

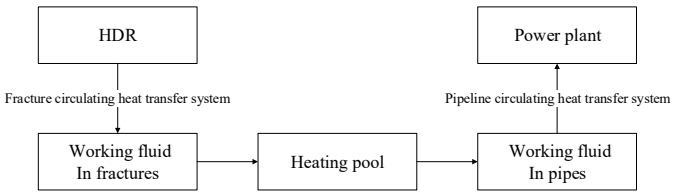


Figure 10: Flow chart of thermal energy extraction in EGS

4.3 Advantages of EGS-E

From the above section, EGS-E adopts the unique reservoir fracturing method and thermal exchange system, which can overcome the restriction on geological conditions of the thermal reservoir, providing customizable thermal reservoir volume, stable fracture network, sufficient flow rate with high temperature, little water loss, and minimal risk of induced earthquakes for the commercial utilization of HDR.

4.3.1 Customizable thermal reservoir volume

By using the excavation to construct the thermal reservoir, EGS-E gains an advantage that it can make different scale reservoirs by adjusting the length of main roadways and the amount of mining level without the restriction of geological restrictions to realizing customization to meet the needs of various production scales.

4.3.2 Adjustable heat transfer area

The stimulation of thermal reservoir is the blasting and caving, the crushing and cracking zone produced by which are strictly related to the parameters of drilling and blasting and the mechanical properties of the blasted rock mass. Therefore, by this method, we can control the volume and crack density of the caved rock mass by adjusting blasting parameters, achieving accurate cracking of thermal storage, forming a predetermined scale of the crack network, and ensuring sufficient and stable heat transfer area.

4.3.3 Stable and sufficient flow rate with a high temperature

The fracture network of EGS-E by the caving technology can significantly increase the width of single fracture, increasing fracture stability to reduce the resistance between the working fluid and the rock surface in the fracture circulating heat transfer system. Meanwhile, the enclosed U-tube in the pipeline circulating heat exchange system can effectively reduce the lifting drop of the working fluid. Thus, stable and sufficient flow rate with a low power consumption can be guaranteed by EGS-E. Besides, EGS-E can create a sufficient heat reservoir volume and a stable fracture network, which can ensure the high-temperature environment in the heating pool. At the same time, the long-distance pipeline in the heating pool can guarantee the sufficient heat transfer between the U-tube pipe and the working fluid, resulting in that the temperature of the terminal fluid maintains in an appropriate range.

4.3.4 Reducing the water loss

The cracking process adopted by EGS-E hardly needs to consume water resources at the stimulation and production stage, while the two-stage heat exchange system can also maintain extremely low water loss during production.

4.3.5 Avoiding the risk of induced earthquakes

It has been confirmed that the maximum magnitude of the earthquake induced by EGS is 5.5, which was caused by a large-scale fault slip caused by hydraulic fracturing(Grigoli et al.,2018). On the contrary, the mining only caused seismic events with magnitude less than 3.0, but did not cause greater magnitude hazards. Moreover, the world mining depth has exceeded 4750m, but no earthquakes caused by mining have been reported.

5. DISCUSSION OF FEASIBILITY OF EGS-E

Although HDR geothermal resources are generally believed to be the ultimate direction of the transformation of human energy structure(Massachusetts Institute of Technology,2006), so far, its utilization is tiny with a global accumulative installed capacity of 17.85MWe. EGS is still on a learning curve, remaining a long way to go before being utilized feasibly under existing technical conditions(Breede et al.,2013). The key to the economic exploitation of EGS is to obtain the availability of cost-effective multi-reservoir construction technique to guarantee that there is sufficient thermal reservoir for the long-term commercial operation(Massachusetts Institute of Technology,2006). For this requirement, EGS-E may provide a viable solution.

From the view of the technical feasibility, the implementation of EGS-E faces two significant problems under the existing technical conditions: the ultra-deep shaft construction and ultra-high temperature environment operation. With the increasing shortage of shallow mineral resources in the world, the mining depth of mineral resources has gradually shifted to the deep and ultra-deep stage, the mature mining technology may provide necessary technical to support for solving these problems. On the one hand, Hecla's Lucky Friday Mine, South Africa, successfully completed the construction of a shaft with a depth of 2923m(Durrheim et al.,2017). With the continuous improvement of mining equipment capacity and the continuous enrichment of construction experience, the realization of 4000m shaft should not be impossible. On the other hand, the working face temperature of South Africa gold mine is above 80 ℃, while that of China tunnel is above 89℃. With the development of cooling technology, it is possible to construct deep underground with a temperature exceeding 200 ℃. Of course, besides these two critical problems, EGS-E also faces other technical difficulties, such as supporting under high stress, blasting under high temperature, etc. In order to solve these critical problems, it is necessary to carry out a large number of multidisciplinary and multidisciplinary scientific research, which are necessary for deep mining in the future, even without EGS-E.

From the view of the economic feasibility, it’s not very economical to mine the mineral resources with buried depth below 3000m under the current mining technology and cost. However, the comprehensive utilization of deep space may open up an effective way to significantly reduce this cost. For the comprehensive use of resources, EGS-E can open up an effective way to realize the co-exploitation of mineral and geothermal resources. By this way, EGS-E can be divided into three mining stages according to the burial depth, namely shallow, middle and deep, respectively. Only mineral resources are mined in the shallow stage; mineral resources are exploited after completing the geothermal extraction in the middle stage, and only geothermal resources are utilized in the deep part. For the in-depth environmental studies, scientific research facilities, such as underground laboratory(Xie et al.,2018) and deep-space capsule(Xie et al.,2017), can be built under suitable geological environment for in-situ research during geothermal mining process by EGS-E. These above approaches may significantly reduce engineering cost to solve the economic problems of EGS-E effectively.

6. CONCLUSION

(1) From the comprehensive analysis of the time and regional distribution of EGS projects all over the world, EGS can be divided into the research and development stage from 1970 to 2000, and the demonstration and commercialization stage from 2001 to now. In these two stages, the most active countries are the United States, Australia, Germany, France, Japan, the United Kingdom and so on, which invested a lot of personnel and funds that made significant contributions to the development of EGS.

(2) Although there are some successful cases, most of EGS still face some unavoidable problems, such as insufficient thermal reservoir volume, unstable fracture network, low flow rate with high temperature, significant water loss, and possible risk induced earthquake. The dependence of artificial stimulation technology adopted by EGS on reservoir geological conditions and natural cracks in rocks may be the fundamental reason that restricts its commercialization, resulting in the fact that EGS still has only 17.85MWe installed capacity in the world.

(3) EGS-E, based on mature mining technology, uses excavation instead of drilling technology, which adopts blasting and caving technology instead of the traditional stimulation methods such as hydraulic fracturing or shearing. This method may break through the existing dilemma, which may provide customizable thermal reservoir volume, stable fracture network, sufficient flow rate with high temperature, neglectable water loss, minimal risk induced earthquake, contributing a novel method for large-scale commercial development of HDR.

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