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Research progress on electric heating technology for oil shale in situ mining

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Abstract. *Oil shale, the most important unconventional oil and gas reservoir resource, is characterized by large geological reserves, difficult development technology, and great development potential. Although it cannot be exploited in a large area due to cost issues, with the development and utilization of conventional oil and gas reservoir resources, it is the main direction of future oil exploitation. Based on the classification of in situ conversion technologies of oil shale electric heating into in situ conversion process technology, Electrofrac™ technology, geothermal fuel cell heating technology, high-voltage power frequency electric heating technology, and other electric heating technology, this paper summarizes the research progress on existing electric heating technologies to provide a reference for the engineering research and development of oil shale electric heating in situ mining technology.*

Keywords: *oil shale, electric heating, in situ conversion, geothermal fuel cell, high-voltage power frequency electric heating.*

1. Introduction

The industrial utilization of oil shale began in France in 1838, having thus a nearly 200-year history [1]. In situ oil shale extraction was first proposed in Sweden in 1940 with the invention of the electrothermal or Ljungström method of in situ extraction [2–4]. As research progressed, various technologies emerged, including the in situ conversion process (ICP) technology of Shell Global, the Electrofrac™ technology of ExxonMobil Corporation, the CRUSH technology of Chevron Corporation and Los Alamos National Laboratory, and the radio frequency/critical flow technology of RTX Corporation. Among the existing in situ mining technologies, electric heating technology offers flexible

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heating methods, but it has a slow heating rate and it takes a long time to exploit. Radiation heating technology can uniformly heat the selected area as needed, but the current microwave generation method is costly [5]. Thermal fluid heating technology provides a fast heating rate and has a relatively short development time, but separation is needed when collecting the produced gas, which presents a production challenge [6]. Combustion heating technology has the advantages of fast heating speed and high energy utilization rate, but maintaining mining stability requires further studies [7].

These methods have not been fully popularized because of cost issues. At present, numerical simulations of oil shale in situ mining are focused on electric heating technology [8]. This paper aims to summarize and analyze the more mature research on in situ mining technologies of electric conduction heating, providing valuable insights for the further research and development of these technologies, more specifically ICP, Electrofrac™, geothermal fuel cell (GFC) heating, and high-voltage power frequency (HVF) electric heating (Table 1).

2. Electric heating technology and the original properties of oil shale

Electric heating in situ mining is a technology that directly distills oil shale underground by using electric heating elements to input heat. To improve efficiency and maximize yield and quality, it is necessary to effectively control temperature and pressure, two important parameters affecting oil shale pyrolysis [15]. The general process of oil shale pyrolysis is shown in Figure 1. During pyrolysis, the residual moisture in oil shale is released first, and then kerogen is converted into bitumen. After the thermal degradation of asphalt, shale oil, gas, carbonaceous residues, and pyrolysis water are generated [16]. The vaporized shale oil, gas, and pyrolysis water are driven by downhole pressure, released from the shale pores, and recovered through production wells.

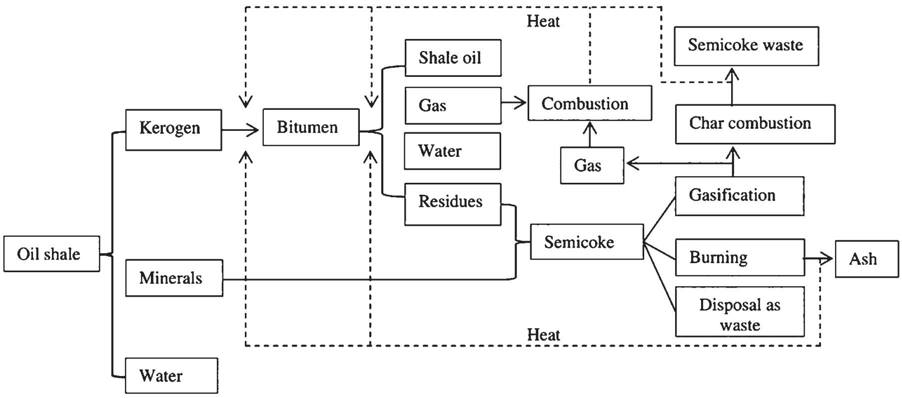

Fig. 1. General flow chart of oil shale pyrolysis process [16].

Table 1. Classification, application status, advantages, and disadvantages of selected in situ conversion technologies of oil shale electric heating

Electric heating technology	Research and development unit	Progress	Advantages	Disadvantages	Reference
ICP	Shell Global	Demonstration project	1. Uniform heating, low heating temperature 2. Establishes a frozen wall to protect groundwater resources 3. Deep oil shale with low oil content can be developed	1. Complex and faulty electric heating process, difficult to exclude 2. High power consumption, small spread area, high cost 3. Temperature field is cylindrical distribution, large loss 4. Small oil and gas migration power, low recovery	[7, 9–12]
Electrofrac™	ExxonMobil Corporation	Plan tests	1. Uses fracturing technology to improve porosity 2. Fast heating rate	1. High energy consumption 2. Easily causes groundwater pollution	[7, 9, 10, 12]
GFC	Independent Energy Partners (IEP)	Laboratory	1. Uniform heating 2. Energy self-sufficiency	1. Complex process, difficult to control 2. High cost, low economic efficiency	[7, 9, 10, 12]
HVF	Jilin University	Laboratory	1. Oil shale pyrolysis can be completed under aerobic and anaerobic heating conditions 2. Strong adaptability, simple process 3. Low pollution, small ecological footprint	1. Shale oil post-processing is difficult, excessive oxidation of organic matter, excessive decomposition of carbonates	[7, 9, 10, 13, 14]

Oil shale is a fine-grained sedimentary rock containing an inorganic mineral skeleton and extremely rich organic matter [17]. The organic matrix is widely and closely distributed within the structure of the inorganic materials. Several factors affect the enrichment of oil shale, including climate, global anoxic events, sedimentation rate, geological structure, water stratification, and the origin of organic matter [18]. The elastic modulus and hardness of oil shale vary widely, with its mechanical properties being affected by the composition of the kerogen layer [19]. There are very few naturally developed pores and cracks inside oil shale [20]. Additionally, oil shale is generally softer in the parallel direction compared to the vertical direction. These characteristics are related to the influence of the sedimentary environment and the composition of kerogen.

2.1. Influence of depositional environment on oil shale

Different sedimentary environments affect the composition of oil shale. In areas with high deposition rates, even with rich terrestrial input, the organic matter is easily diluted, making it difficult for oil shale to form. In deep lake areas with moderate deposition rates, both lacustrine and terrestrial organic matter are deposited together, which is conducive to the preservation of organic matter and easy formation of high-yield, thick oil shale. In deep lake areas with low deposition rates, organic matter is degraded and there is no supply of sediment, which hinders the input and enrichment of soil organic matter, resulting in the formation of only thin oil shale with low oil content [21]. When using in situ heating technology to conductively heat oil shale, an increase in the thickness of the oil shale reservoir allows the heating well to supply more energy to the oil shale compared to the bedrock, which increases the oil shale's heating rate and improves heating efficiency [22].

Due to variations in the composition of oil shale across different regions, differences in porosity, water content, and organic matter sedimentation are observed. During the sedimentation process, the presence of microfractures and the arrangement of minerals result in anisotropic thermal conductivity [23]. For instance, flat minerals, such as clay, tend to align parallel to the bedding direction. This alignment forms a natural barrier to fluid flow perpendicular to the bedding direction, leading to low thermal conductivity in the perpendicular direction (Kper). The anisotropy of oil shale impacts the thermal conductivity of oil shale reservoirs and subsequently influences temperature conduction range and thermal efficiency [24].

2.2. Thermal decomposition of kerogen and its products

Kerogen, the primary constituent of organic matter in oil shale, constitutes the principal precursor for thermal cracking to yield oil. The thermal decomposition of kerogen essentially represents the process where oil shale undergoes thermal breakdown to produce shale oil and thermal cracking gas. A schematic diagram illustrating kerogen's thermal decomposition is depicted in Figure 2.

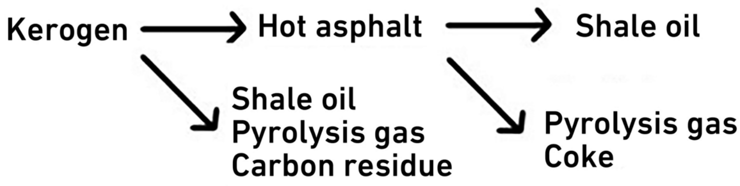

Fig. 2. Thermal decomposition of kerogen.

Due to variations in depositional environments, kerogen is categorized into three types: type I (muddy type), type II, and type III (humic type) [25]. Types I and II are predominantly associated with oil production, while type III primarily yields gas. Chang conducted thermal decomposition experiments on oil shale from Huadian (containing type I kerogen) and Tailao (containing type II kerogen), observing that decomposition commenced at 390 °C, with peak yields of thermal bitumen occurring at 450 °C. Notably, type II kerogen demonstrates a higher hydrocarbon-producing capacity compared to type I [26]. However, Xiong et al.'s findings indicate that on average, type I exhibits superior potential for hydrocarbon generation, though actual hydrocarbon generation ability is constrained by other parameters [27].

3. Research on electric heating in situ mining

Electric heating involves converting electrical energy into thermal energy through molecular excitation. This process creates a current by establishing a potential gradient between low-conductive elements, but the current passes through these elements because of high resistance and the current cannot flow smoothly, leading to the conversion of some electrical energy into thermal energy [28]. While electrical engineers developed the technology for this conversion, the real connection of electric heaters to the in situ extraction of unconventional oil and gas reservoir resources, such as oil shale and heavy oil, was achieved by petroleum engineers through the flexible design and modification of electric heaters.

3.1. Underground electric heating mechanism

Electric heaters are typically employed using the heat transfer equation ($Q = UA\Delta T$) and Joule's law of electric energy generation ($Q = I^2 Rt$) [29]. In situ oil shale mining utilizes resistance heating technology in electric heating, harnessing the Joule effect to convert electrical energy into heat energy for object heating. This technology is commonly categorized as direct resistance heating and indirect resistance heating. Direct resistance heating is utilized in

ICP, Electrofrac™, GFC, and HVF. In this method, power voltage is directly applied to the heated object, causing it to heat up when current flows through it. Indirect resistance heating involves using special alloys or non-metallic materials fashioned into heating elements that generate heat energy, which is transmitted to the heated object through radiation, convection, and conduction – commonly referred to as fluid and radiation heating.

Underground electric heating is used to raise the temperature of oil shale (to approximately 500 °C) via current flow for the thermal decomposition of asphaltene [30, 31]. Failure to reach this temperature results in insufficient thermal decomposition of asphaltene necessary for oil shale deposit formation [32, 33]. Currently, two primary modes exist for underground in situ oil shale mining using electric heaters: induction heaters, generating heat based on Maxwell's law, and resistance heaters, producing heat through the Joule effect.

3.2. Electric heating technology classification

When using electric heating technology for in situ mining of underground oil shale, simply cracking oil shale at high temperatures is insufficient. It is impossible to ensure that the electric heater achieves maximum efficiency for the thermal cracking of oil shale, and the cost of the extracted shale oil would be too high. Therefore, many companies and research institutions worldwide have studied various electric heating technologies. Among many technologies, four have emerged as particularly mature: Shell's ICP for underground electric heating, ExxonMobil's Electrofrac™ involving fracturing and conductive proppant, IEP's GFC, and HVF developed by the Jilin University in China.

3.2.1. ICP technology

ICP technology was first proposed by Shell in the 1970s [34, 35]. This technology involves drilling directly from the ground to the deposit and heating the oil shale through an electric heater placed in the borehole. When the oil shale near the heating area is heated to 600–700 °C, the kerogen is completely pyrolyzed to generate vaporized shale oil, combustible gas, and char. As kerogen cracking proceeds, the porosity around the heating area increases, allowing the vaporized shale oil and combustible gas to escape from the pores and flow to the production well. During this process, the high-temperature vaporized shale oil and gas achieve convective heat transfer, thereby rapidly heating the ore body, as shown in Figure 3.

To enhance the efficiency of in situ oil shale electric heating, numerous researchers have conducted experiments and simulations. Brandt from Shell proposed the frozen wall technology to mitigate heat loss caused by groundwater circulation [37]. Pei et al. discovered that additional nitrogen injection can accelerate the heating rate, oil yield, and energy efficiency of the oil shale layer during conventional ICP technology extraction [38]. Meng et al. also considered incorporating catalysts to improve efficiency, utilizing porous silicon aluminophosphate to reduce the activation energy for organic

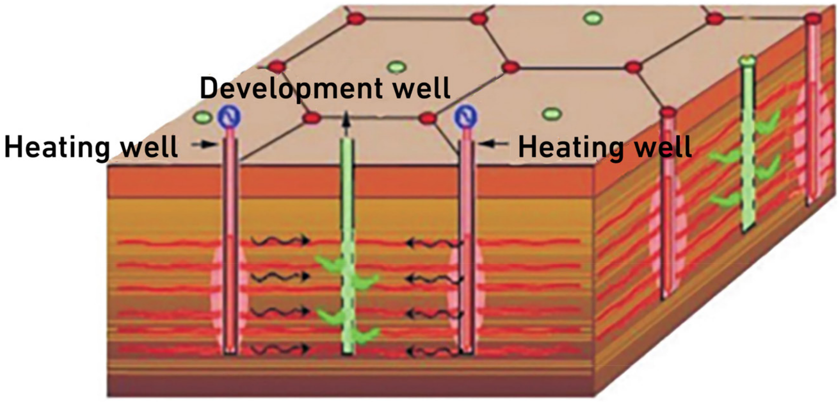

Fig. 3. Technical principle diagram of Shell's ICP technology [36].

matter conversion from 113.80 to 37.28 kJ/mol. However, there is limited dedicated research on ICP oil shale pyrolysis experiments [39].

Shen et al. utilized CMG numerical simulation software to model the electric heating of oil shale and inferred that oil shale oil production can be forecasted by comparing predicted production data for the next year with actual data based on thermal decomposition information [40]. Li et al. developed a non-stationary mathematical model to investigate the temperature field distribution in electrically heated oil shale, concluding that oil can be produced from shale two years after electric heating, consistent with experimental data from the MDP-MTE area of Coronado, USA [41]. He et al. constructed an electric heating model using finite element software and determined that in situ mining at 600 °C yields an effective mining radius of 2 m [42]. Han et al. established a transient thin oil shale electric heating model using ANSYS software and observed that the initial three-year heating efficiency is significantly higher than in the subsequent three years when employing a horizontal well as the heating well [43]. Hou et al., through semi-open thermal decomposition experiments utilizing the total organic carbon (TOC) method, discovered a positive correlation between TOC values and the potential for oil production, subsequently establishing a quantitative prediction model for TOC [44].

3.2.2. Electrofrac™ technology

Electrofrac™ technology is an oil shale electric heating in situ mining technology proposed by ExxonMobil [9, 10]. Firstly, the oil shale is subjected to in situ hydraulic cracking, and the conductive material is filled into the fractures to form a resistive heating element. After conduction, heat is released according to Joule's law, which radiates from the fractures into the surrounding strata, gradually converting the kerogen into liquid shale oil and natural gas [37]. Finally, liquid shale oil and natural gas are discharged to the ground through vertical production wells between horizontal wells, as shown in Figure 4.

This technology offers higher heating efficiency than the linear heat source used in ICP technology by increasing the heat transfer area of the reservoir by plane heating. However, it requires numerous preliminary operations, such as drilling horizontal wells and performing hydraulic fracturing [45]. As a heating element in cracks, the continuity of electrical conductivity must not be affected by kerogen conversion. ExxonMobil uses calcined petroleum coke, which is heated to 1200–1400 °C in a rotary kiln, as the conductive agent [46, 47]. The physical properties of this agent make it well-suited for pumping into cracks.

In 2007, the technology was tested in the Colorado oil shale field, where its feasibility was preliminarily verified, although no oil shale oil was produced [48]. While this technology has not yet been employed for practical extraction, several researchers have conducted experiments and simulations. In a simulation by Lee et al., it was observed that increasing the spacing between hydraulic fractures could lead to higher oil and gas production, albeit at the cost of a longer heating time [49]. Hazra's simulations of various in situ oil shale extraction technologies revealed that Electrofrac™ technology exhibits optimal efficiency at 600 °F and can achieve enhanced performance when heating deeper layers [50].

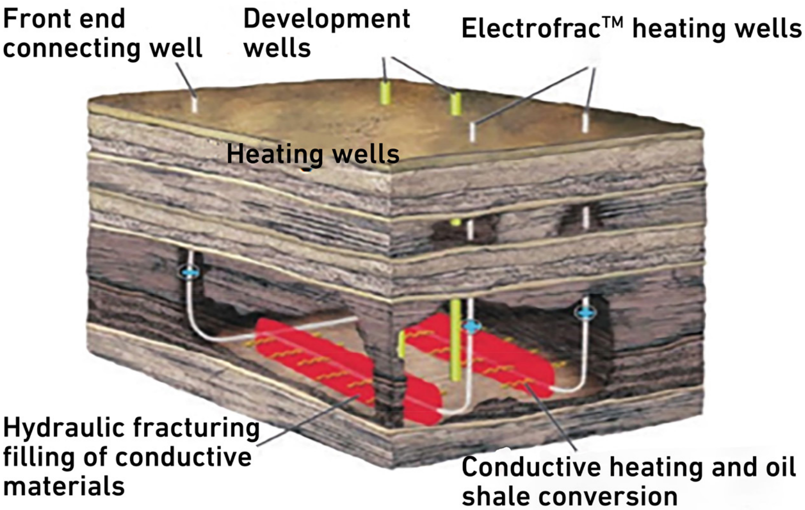

Fig. 4. Principal diagram of ExxonMobil's Electrofrac™ technology [37].

3.2.3. Geothermal fuel cell heating technology

IEP has also proposed a geothermal fuel cell heating technology, which uses the heat produced by solid oxide fuel cell power generated to heat oil shale. In this method, the fuel cell is placed in the wellbore of the oil shale reservoir. The fuel cell power generation releases heat through very little energy, heating the surrounding oil shale to 400 °C. At this time, a large amount of kerogen is pyrolyzed to generate shale oil, hydrocarbon gases, and char, as shown in Figure 5.

This technology is cleaner and more sustainable than other in situ mining technologies [51]. GFC heating technology uses inefficient coal power to supply energy for mining. According to IEP's estimation, this technology can obtain a 24 kWh/t oil-to-electricity conversion rate, and the output of toxic waste can be ignored. Anyenya et al. developed a thermoelectric chemical model for a geothermal fuel cell and utilized the Aspen Plus optimization tool to concurrently adjust the current, fuel utilization rate, and air pressure. The temperature of the pilot stack was constrained to remain below 800 °C to prevent overheating. Additionally, the geothermal heat flux was maintained at levels exceeding the required average of 1.5 kW m^{-1}. The maximum heating efficiency reached 43%, resulting in an overall combined heat and power efficiency of up to 79.3% [51].

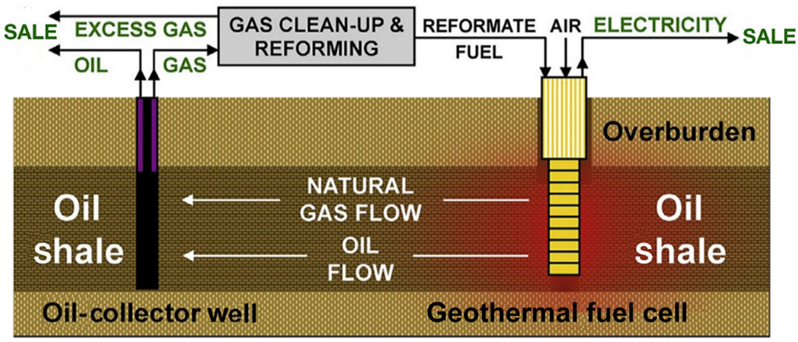

Fig. 5. Schematic diagram of the GFC heating technology [52].

3.2.4. High-voltage power frequency electric heating in situ pyrolysis technology

HVF technology was developed by Jilin University in China and is divided into three parts, as shown in Figure 6. Firstly, the electrode is set in the oil shale ore layer and high-voltage electricity is introduced. According to the theory, under certain conditions, the material breaks down, transitioning from an insulator to a conductor. After the high-voltage electricity breaks through the

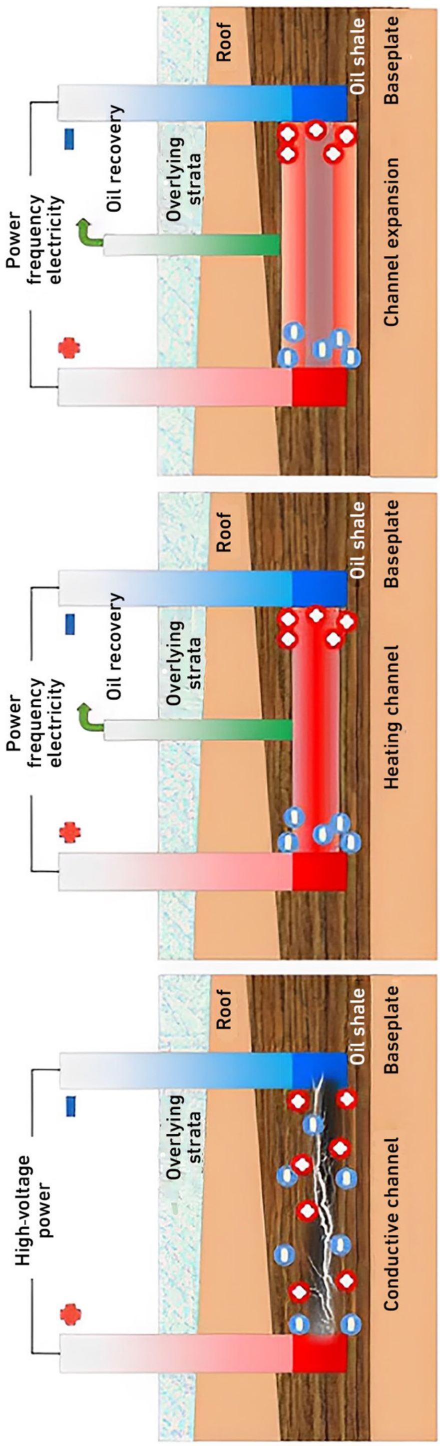

Fig. 6. Principle diagram of Jilin University's HVF technology [13].

oil shale, the irreversibility of solid breakdown causes the conductive channel and plasma of melting or burning appear inside the oil shale [53], resulting in insulation failure [54, 55]. Sun found that when the electric field strength ranges from 100 to 180 V/cm, higher electric field strength facilitates thermal breakdown and reduces energy consumption. When the motor is far away, hydraulic fracturing technology can also be used, which not only induces cracking in the oil shale but also greatly reduces the breakdown voltage after the water infiltration crack is dampened [13].

Next, power frequency electricity is switched on, and the nearby oil shale is heated by the plasma generated by the breakdown and the inner surface of the carbonized conductive channel. The heat is transmitted through the plasma within some oil shale in the conductive channel. After a certain period, some oil shale reaches the pyrolysis temperature, producing shale oil and combustible gas. Li et al. found through thermogravimetric experiments that oil shale pyrolysis can be completed in both anaerobic and aerobic environments, with the pyrolysis process remaining the same [56].

As the pyrolysis reaction progresses, a significant amount of kerogen undergoes pyrolysis, leading to increased porosity. The vaporized shale oil and combustible gas generated during this process contribute to the convective heating of the oil shale, facilitating the flow of heat conduction fluids and the expansion of the heat conduction channel. Eventually these products are discharged from the production well. Liu established a mathematical model of breakdown by HVF electric heating, obtained the water and oil contents, and verified the model's reliability by comparing the temperature distribution of oil shale at different time points during the breakdown process, as well as the temperature variation patterns at measurement points, and energy consumption [57].

This new in situ mining method is more environmentally friendly than the ICP and Electrofrac™ technologies because no substances that could affect the environment and groundwater are injected during the mining process. Additionally, the underground equipment is very simple, and the requirements for oil shale layers are not high.

4. Conclusions

With the development and exploitation of conventional oil and gas reserves, oil shale mining represents the primary focus for future oil extraction. Among the various in situ mining methods for oil shale, electric heating technology stands out as the most promising for achieving commercial-scale mining due to its technical feasibility.

1. In situ conversion process technology, which pioneered field trials of electric heating technologies, offers simplicity in operation but suffers from high energy consumption and poor economic efficiency. Electrofrac™

technology necessitates hydraulic fracturing of the mining strata, which carries the risk of groundwater pollution that cannot be overlooked. Geothermal fuel cell heating technology, which is a novel approach, inflicts less environmental damage but its complexity requires careful consideration of economic efficiency. High-voltage frequency electric heating technology is straightforward and environmentally friendly; nevertheless, the challenge of excessive oxidation leading to increased carbonate formation remains unresolved and is still under laboratory research.

2. To achieve the objective of economically viable, high-yield, and environmentally friendly commercial exploitation of oil shale, future research should focus on heating technologies, thermal materials, hydraulic fracturing techniques, subsurface reservoir sealing and engineering adjustments, and the integration of novel energy sources in pursuit of a holistic solution.

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