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Invited review

Advances of Geological Storage Engineering and Technology

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Abstract:
Geological storage refers to the storage of energy, scarce and important strategic materials, as well as carbon dioxide sequestration in geological bodies or underground spaces. Geological storage is an important form of underground space utilization and a crucial measure for achieving energy transition and human green and sustainable development. With the continuous expansion of application fields,geological storage has developed into a new interdisciplinary field, involving geotechnical engineering, underground fluid resource development, fluid mechanics, rock mechanics, engineering thermophysics, geochemistry, energy conversion and utilization, and many other disciplines. Based on extensive research, this paper comparatively describes the main application scenarios, engineering progress, and major scientific and technological challenges of geological storage, and proposes key scientific issues that need to be addressed in future geological storage engineering, providing reference for the implementation of geological storage projects and scientific research.

1 Introduction

Geological storage refers to the storage of energy, scarce and important strategic materials, and carbon dioxide sequestration in geological bodies or underground spaces. The geological bodies primarily consist of underground porous reservoirs, including depleted oil and gas reservoirs, aquifers, unmineable coal seams, and basalt formations. Underground spaces include artificially excavated rock caverns, mined-out areas and abandoned roadways caused by mining activities, and naturally formed underground caves. Geological bodies and underground spaces are often collectively referred to as generalized underground spaces.

Currently, the main application scenarios of geological storage primarily include: underground energy storage, carbon dioxide geological sequestration, underground storage of important materials, and underground disposal of waste and nuclear waste. Underground energy storage mainly includes underground oil storage facilities, underground natural gas storage facilities, underground hydrogen storage facilities, underground thermal energy storage facilities, as well as underground compressed air energy storage and underground pumped storage for energy conversion. Underground storage of important materials primarily involves storing essential living materials such as grain, food, and water, as well as strategic materials like helium and precious metals in underground chambers for use in wartime or other special situations. Large-scale gases such as helium can also be stored in depleted oil and gas reservoirs. Carbon dioxide sequestration sites are diverse, mainly including depleted oil and gas reservoirs, unminable coal seams, saline aquifers, salt caverns, and abandoned underground spaces from mines. Fig.1 Shows the main scenarios of geological storage.

With the development of the times, the scenarios and applications of underground space utilization are becoming increasingly extensive. Underground space offers advantages such as minimal land occupation, large capacity, temperature stability, isolation, protection, and good seismic performance. Utilizing

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underground space and porous reservoirs for material storage is a crucial approach to underground space development, which is of great significance for conserving land resources, ensuring energy security, promoting energy structure transformation and upgrading, enhancing emergency response capabilities, and achieving green and low-carbon development of human society.

In order to summarize the development of geological storage science and technology as well as engineering implementation, based on comprehensive research, this paper summarizes the main application scenarios of geological storage, aiming to provide reference for relevant research and engineering projects.

2 Oil and gas geological storage

Underground oil and gas storage facilities are crucial infrastructure for ensuring the secure supply of energy. Due to the mismatch between oil and gas production areas and consumption regions, as well as significant seasonal variations in energy consumption, coupled with emergency energy supply needs under special conditions such as extreme weather and war, numerous oil and gas storage facilities have been constructed worldwide. However, surface storage facilities have limited capacity and low safety levels. Building large-scale underground oil and gas storage facilities has become an important choice for energy security in various countries.

2.1 Underground oil storage

Large underground oil storage facilities are typically divided into two types: one is the underground water-sealed oil storage, and the other is the salt cavern oil storage.

2.1.1 Underground water-sealed oil storage

Groundwater-sealed oil storage caverns are constructed by excavating chambers in hard rock formations. The location of underground water-sealed oil storage caverns must be below the stable groundwater level. After excavation, groundwater seeps into the fractures to form a continuous hydraulic barrier. When the water pressure in the fractures exceeds the oil pressure, the oil cannot leak out, achieving a natural sealing effect. The schematic diagram of its working principle is shown in Fig.2 (Yang et al., 2023).

The principle of sealing storage is achieved by utilizing the groundwater pressure in rock fissures, which exceeds the pressure of oil products. In 1939, Swedish scholars H. Jansson and T. Hagerman first proposed the concept of unlined oil storage below the groundwater level, and in 1948, they built an experimental storage facility to verify its technical feasibility (Morfeldt, 1983). After the 1950s, it was gradually applied to crude oil reserves in Western Europe, the United States, Norway, Japan, Singapore, South Korea, etc. Singapore completed a group of granite caverns 100 meters below the seabed in 2011, equipped with a seawater circulation cooling system (Yang et al., 2023).

China built its first 150,000 m^3 underground water-sealed oil storage facility in Huangdao in 1973, using a three-level simultaneous excavation process (Ma et al., 2015). After 2000, it entered a rapid development phase, with 200,000 to 500,000 m^3 cavern storage facilities successively built in Ningbo, Shantou, and other places. Since 2000, with the successive construction of petroleum reserve projects, large-scale underground water-sealed oil caverns exceeding 3×10^5 m^3 have entered a development period, with projects constructed in Liaoning, Shandong, Guangdong, and other regions. Some enterprises in Jiangsu, Zhejiang, and Shandong have also begun planning and constructing underground water-sealed oil caverns. As of 2023, the scale of completed and under-construction underground water-sealed oil caverns in China has exceeded 2×10^6 m^3 (Xia et al., 2023).

Compared with ground storage facilities, underground water-sealed oil depots have advantages such as 40% cost savings, a construction period shortened by two-fifths, strong security and concealment, and low oil and gas loss. Underground water-sealed oil depots save 80% of steel compared to traditional storage tanks and reduce the construction period by 40%. The construction cost of similar projects in Germany is only one-third to one-fourth of that of ground oil depots. American cases show a 50% reduction in operation and maintenance costs. Data from 2016 indicates that insurance costs for underground water-sealed oil depots in China are only 33% of those for above-ground facilities.

2.1.2 Salt cavern oil storage

Salt caverns are underground cavities left after salt mining. The salt mining method uses water dissolution, where water is injected into underground rock formations through boreholes, and the brine formed from dissolved salt rock is extracted through these boreholes. After repeated water dissolution mining, underground caves are formed in thick salt layers or salt domes. During oil storage in salt caverns, brine is discharged through brine discharge pipes, while oil is injected through oil injection pipes, thus achieving oil storage, as shown in Fig.3 (Li et al., 2024).

Unlike many underground caves, salt caverns can self-heal fractures under high temperature and pressure conditions. This unique characteristic allows the surrounding rock damage caused by high pressure from large-scale oil injection to be self-repaired. Therefore, salt caverns are considered an ideal location for storing oil, natural gas, and related products, and are currently the most cost-effective and safest oil storage method for large-scale oil reserves. Salt cavern oil storage facilities offer the following advantages: (1) Located hundreds to thousands of meters underground, the storage caverns are connected to the surface through small wellbores, making them less vulnerable to ground explosions or external attacks; (2) Benefiting from natural geothermal gradients, the temperature and pressure conditions in deep salt caverns facilitate petroleum flow within the storage facility, helping to prevent oil degradation; (3) The surrounding rock and wellhead of underground salt caverns provide excellent sealing properties, preventing oil and gas volatilization and leakage. There is virtually no loss during storage. Moreover, being located in deep rock formations; (4) Salt cavern oil storage facilities can be constructed rapidly,especially when utilizing existing mined-out areas of salt mines, which significantly reduces both economic and time costs associated with construction (Shi et al., 2023).

Since the 1960s, the Soviet Union began to focus on the construction of underground salt cavern oil storage facilities. After

Fig. 1 Main scenarios of geological storage

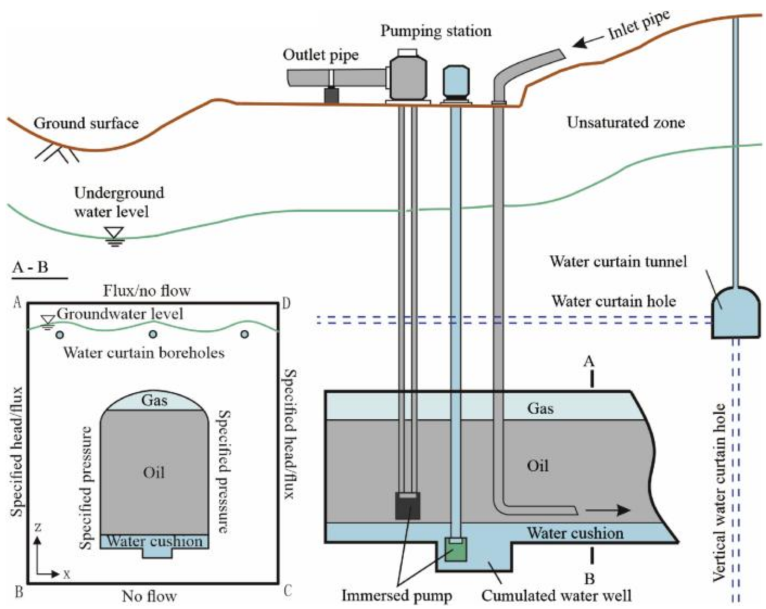

Fig. 2 Conceptual model of underground water-sealed oil Storage in rock caverns (Yang et al., 2023)

the oil crisis in the 1970s, the United States started utilizing numerous abandoned salt caverns in the Gulf of Mexico region to store petroleum. Five strategic oil storage facilities were successively built, with a total storage capacity of 1.1×10^8 m^3. The geographical distribution of major salt cavern oil storage facilities is shown in Fig.4 (Zhang et al., 2024).

Currently, more than 20 countries worldwide are using salt cavern technology for oil storage, including the United States, Canada, China, Russia, Germany, France, and 36 other countries. According to statistics, 90% of the United States' oil reserves, 50% of Germany's, and 30% of France's are stored in salt caverns (Liu et al., 2024).

2.2 Underground natural gas storage

2.2.1 Underground natural gas storage in depleted petroleum reservoir

Underground gas storage (UGS) facility utilizing depleted oil and gas reservoirs or partially exploited reservoirs with remaining recoverable reserves is known as a reservoir-type gas storage. It involves reinjecting natural gas into underground oil and gas reservoirs for storage, and extracting it when needed to meet seasonal and emergency demands for natural gas supply, as shown in Fig.5. Oil and gas reservoirs possess geological trapping structures that prevent further migration of hydrocarbons and facilitate their accumulation, such as anticlinal traps and fault traps, which effectively confine natural gas within specific areas. Additionally, reservoirs must have good physical properties, including high porosity and permeability. Porosity

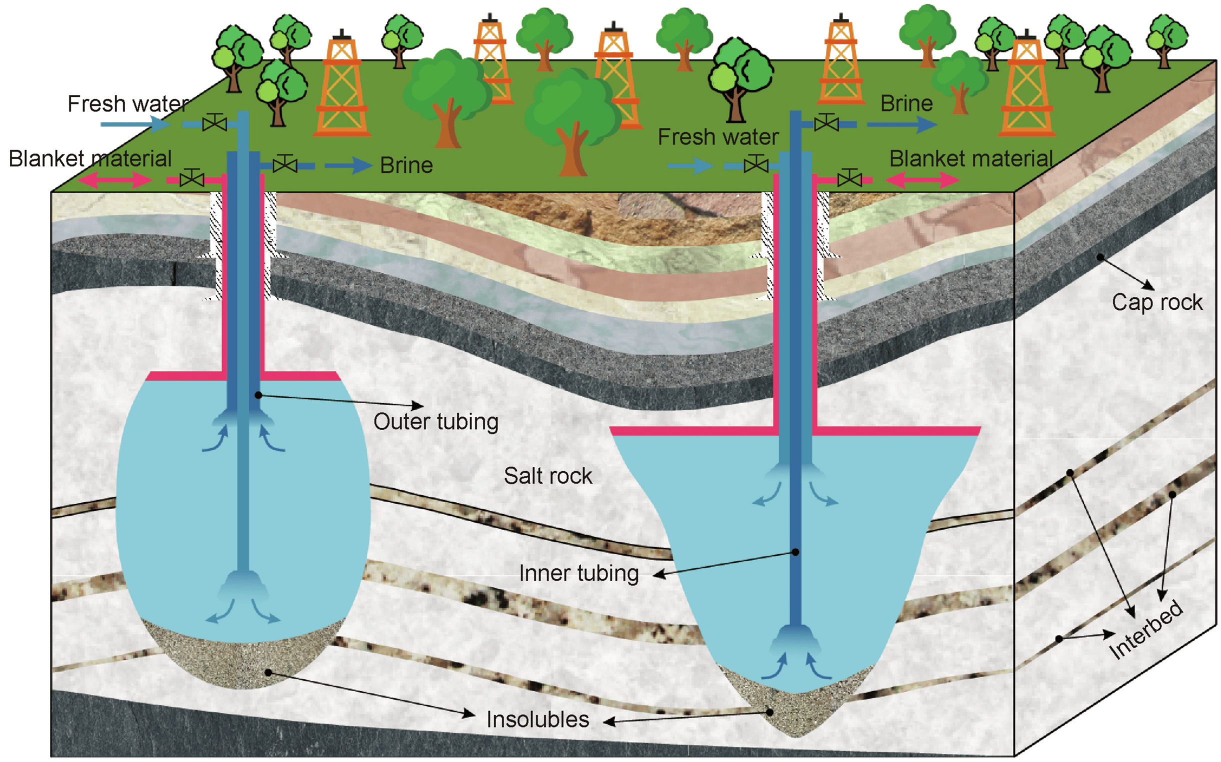

Fig. 3 Schematic diagram of salt cavern oil storage (Li et al., 2024)

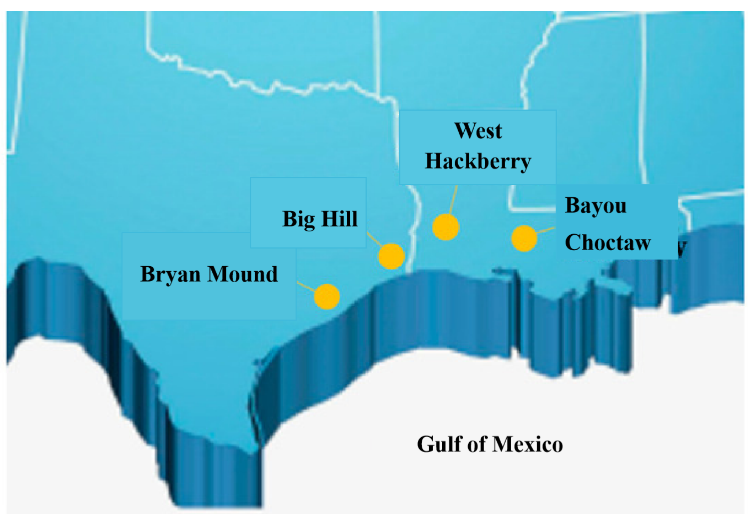

Fig. 4 Distribution of U.S. strategic oil storage (Zhang et al., 2024)

determines the storage capacity of the reservoir, while permeability affects the ease of gas injection and extraction. Generally, reservoirs with porosity greater than 10% and permeability greater than 1 mD are suitable for gas storage construction (Ma et al., 2022). Due to their favorable physical properties, natural geological trapping conditions, and large storage capacity, oil and gas reservoirs are preferred sites for gas storage facilities. Typically, reservoir-type gas storage facilities should be located close to natural gas consumption markets or major gas pipelines to reduce transportation costs and energy losses during transmission, thereby improving gas supply efficiency.

In 1915, Canada built the world's first underground gas storage facility, pioneering the use of depleted oil and gas reservoirs for natural gas storage. During this period, simple injection and production modes were mainly adopted, relying on natural structures to achieve seasonal peak shaving functions. Subsequently, European and American countries gradually expanded such facilities, forming a gas storage system mainly based on depleted gas reservoirs. These storage facilities became mainstream choices due to their low cost and reliable operation. More than 400 such facilities exist globally, accounting for over 75% of all underground gas storage facilities. The focus of applications at this time was on balancing seasonal gas demand fluctuations between winter and summer, as well as ensuring

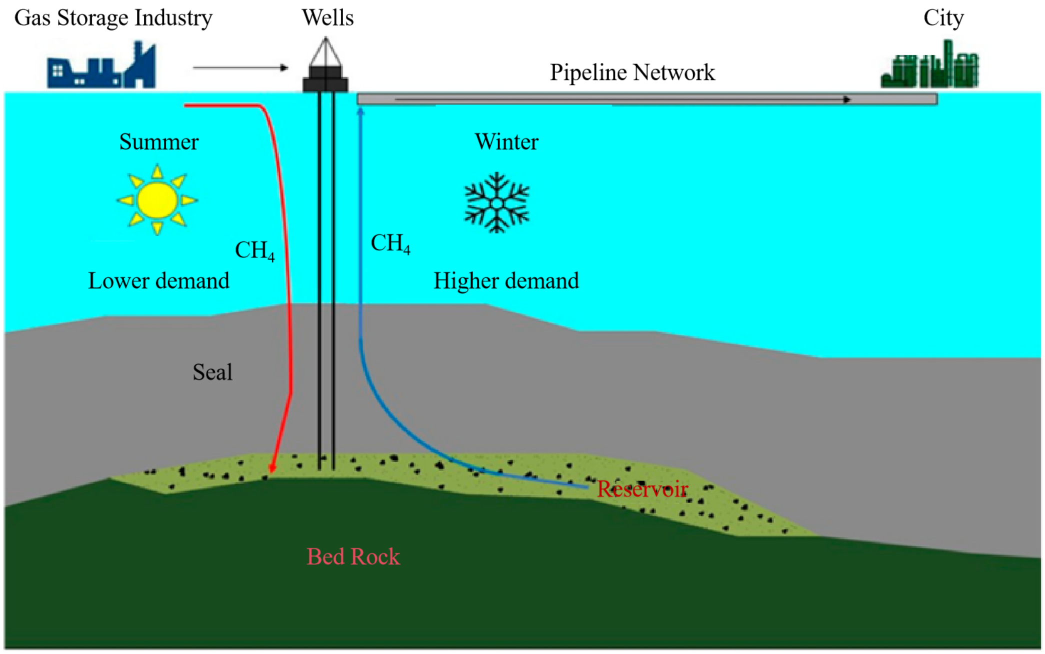

Fig. 5 UGS useful for creating strategic reserves of natural gas. On the left (red color): the CH_4 injection during the summer when demand is lower; while on the right (blue color): the methane withdrawal to meet winter's increased consumer demand (Fibbi et al., 2023).

emergency supply (Zheng et al., 2015).

China attempted to build gas storage facilities using depleted gas reservoirs from the late 1970s to the early 1990s, but progress stalled for a long time due to theoretical and technological limitations. It was not until 1999 when China's first commercial gas storage facility - the Dazhangtuo Gas Storage Facility in Dagang was fully constructed, marking the official start of localized development. Over the past 15 years, to address security risks arising from increasing dependence on foreign natural gas, China has incorporated gas storage capacity development into its strategic planning. A number of large-scale projects have been built and put into operation, including the Hutubi Gas Storage Facility in Xinjiang, the Xiangguosi Gas Storage Facility, the Shuang-6 Gas Storage Facility, and the Wen 23 Gas Storage Facility, creating multiple records in the process (Zheng et al., 2025).

2.2.2 Aquifer gas storage

An aquifer-type underground gas storage is an artificial gas reservoir formed by artificially injecting natural gas into suitable underground aquifers. This type of gas storage consists of water-bearing sand layers and an impermeable cover layer (such as an anticline or rock salt layer). The aquifer needs to have certain porosity and permeability to allow natural gas to displace the water and form a gas reservoir. Working gas refers to the gas that is stored and subsequently withdrawn during the storage cycle, while cushion gas is the gas that remains continuously in the storage or serves as a buffer layer between the working gas and water (Al-Shafi et al., 2023).

The construction of aquifer gas storage can be traced back to the mid-20th century. In 1946, the United States built the world's first aquifer gas storage facility, Doe Run Upper, in the Dujuan Formation at the border between Kentucky and Indiana. After decades of development, developed countries in Europe and America have accumulated extensive experience in site selection, evaluation, construction, and operation of aquifer gas storage facilities. They have developed a relatively complete technical system for converting aquifers into gas storage reservoirs, laying the foundation for the widespread application of aquifer gas storage technology.

Currently, aquifer gas storage has become the second largest underground gas storage method in the world, after depleted oil and gas reservoir storage. According to statistics from the International Gas Union (IGU), there are multiple operating aquifer gas storage facilities globally, which play a crucial role in natural gas storage and peak shaving. The main countries and regions constructing these facilities include the United States, Europe, and the Commonwealth of Independent States (CIS), where aquifer gas storage accounts for a significant proportion of their total working gas capacity.

The United States has the largest number of aquifer gas storage facilities in the world, primarily located in states such as Illinois, Indiana, and Iowa. For instance, the Hercher Galesville storage facility is a typical aquifer gas storage facility in the United States. France has the highest proportion of aquifer gas storage facilities globally, mainly distributed in the Paris Basin and Aquitaine Basin. The Beynes aquifer storage facility was France's first gas storage project, while Lussagnet is another significant aquifer storage facility. Germany is also one of the key countries in developing aquifer gas storage facilities. The Engelbostel aquifer storage facility was Germany's first aquifer gas storage project. Russia has achieved remarkable results in aquifer gas storage development. For example, the Kalugskoe storage facility near Moscow was Russia's first aquifer gas storage project, and the Kasimovskoe storage facility is currently the world's largest aquifer gas storage facility. In summary, aquifer gas storage facilities, as important natural gas storage and peak shaving facilities, have been widely applied and developed globally. With advancing technology and accumulated experience, aquifer gas storage facilities will continue to play a crucial role in the future.

2.2.3 Salt-cavern gas storage

The concept of using salt domes and salt layers for storage facility construction was first proposed by Germans and patented in 1916. The basic principle of salt cavern underground gas storage is to create a gas storage space by dissolving salt formations underground through water solution cavity creation (Wang et al., 2018). Taking the most common single-well double-pipe cavity creation method as an example, the process principle involves drilling a production casing into the salt layer, and then inserting the inner and outer cavity creation pipes within the production casing. According to the cavity design parameters, fresh water is injected into the well, dissolving the salt rock to form brine which is then discharged, as shown in Fig.6 (Zhang et al., 2023). Meanwhile, anti-solvent is injected into the annular space between the production casing and outer cavity creation pipe to control the upward dissolution rate, gradually forming the cavity from bottom to top. To control the cavity shape, the relative positions of the inner and outer pipe strings are continuously adjusted during the cavity creation process. The cavity shape is determined by monitoring salt extraction volume and using sonar cavity measurement. Once the designed shape is achieved, gas injection and brine discharge begin. After the brine is mostly extracted, gas injection continues until the design pressure is reached, at which point the well is shut in and the cavity creation is complete. Injecting fresh water into the inner cavity creation pipe while discharging brine through the outer pipe is called forward circulation; injecting fresh water into the outer pipe and discharging brine through the inner pipe is called reverse circulation.

In 1959, the Soviet Union built the world's first salt cavern gas storage facility, and this technology was rapidly adopted in Europe and America. The United States' first salt cavern gas storage facility was built in Marysville, Michigan in 1961. This storage facility began operation in 1968, with a working gas volume of 6×10^6 m^3 and pressure of 7.2 MPa. During the 1990s, the United States successively built more than 20 salt cavern gas storage facilities. By 2009, it had 31 salt cavern gas storage facilities, playing a significant role in peak shaving of natural gas consumption. Additionally, countries such as Canada, France, Germany, the United Kingdom, Denmark, and Poland all built multiple salt cavern gas storage facilities in the last century. As of 2009, there were 74 salt cavern gas storage facilities worldwide for natural gas storage, accounting for 11.7% of the total number of natural gas storage facilities. The total storage capacity was 229.42×10^8 m^3, with a working gas volume of 161.98×108 m^3, representing 70.6% of the total storage capacity (Liu et al., 2018).

2.3 Underground hydrogen storage

With the growing global demand for renewable energy, the importance of hydrogen energy has become increasingly prominent. The fluctuation issues in power generation from intermittent renewable energy sources such as wind and solar can be effectively addressed through hydrogen production via water electrolysis combined with underground hydrogen storage technology (Fu et al., 2020; Song et al., 2025). As a core technology for large-scale hydrogen energy storage, underground hydrogen storage facilities are of crucial significance in ensuring energy security, improving energy utilization efficiency, and promoting the development of the hydrogen energy industry chain. Compared with above-ground hydrogen storage, underground storage offers advantages such as larger energy storage capacity, longer storage duration, lower costs, and higher safety levels (Pan et al., 2022; Song et al., 2023). Since the 21st century, countries including the United States, France, Germany, Austria, the Czech Republic, Argentina, Spain, China, Romania, and Poland have respectively funded feasibility study projects for underground hydrogen storage facilities (Lord, 2009; Audigane et al., 2014; Bai et al., 2014; Iordache et al., 2014; Simon et al., 2015; Bunger et al., 2016; Tarkowski, 2017; Lewandowska-Smierzchalska et al., 2018; Heinemann et al., 2018; Song et al., 2024), with project distribution shown in Fig.7 (Muhammed et al., 2023).

As of now, there are 10 underground storage facilities worldwide used for storing pure hydrogen (purity above 95%) or low-purity H_2 (purity ranging from 10% to 62%), including three types: depleted oil and gas reservoirs, aquifers, and salt caverns (Ding and Wei, 2020). As shown in Tab.1, three aquifer storage facilities have been closed or converted to other purposes, leaving only two newly constructed depleted oil and gas reservoirs in Argentina and Austria for storing 10% purity H_2(Tarkowski, 2019; Muhammed et al., 2022). Low-purity hydrogen typically comes from coke gas in coal gasification processes, with a composition of: 25-60% hydrogen, small amounts of CH_4 (10-33%), CO/CO_2 (12-20%), and N_2 (<30%). Currently, the acceptable concentration of mixed hydrogen in industrial storage facilities ranges from 6% to 15%, which ensures that the gas energy does not decrease significantly while reducing the risk of pipeline rupture due to hydrogen embrittlement and other effects.

In recent years, China has successively launched three geological hydrogen storage projects, mainly including: the Pingdingshan Salt Cavern Underground Hydrogen Storage Demonstration Project in Henan, the Daye Cave Hydrogen Storage Demonstration Project in Hubei, and the Jintan Salt Cavern Hydrogen Storage Demonstration Project in Jiangsu.The Pingdingshan Salt Cavern Hydrogen Storage Demonstration Project in Henan commenced construction in November 2024 and plans to complete the pilot test of salt cavern hydrogen storage by September 2025. This project is jointly implemented by the Wuhan Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, and China Pingmei Shenma Group. The hydrogen for this project mainly comes from Henan Shenma Chlor-Alkali Chemical Co., Ltd. The selected salt layer is lo-

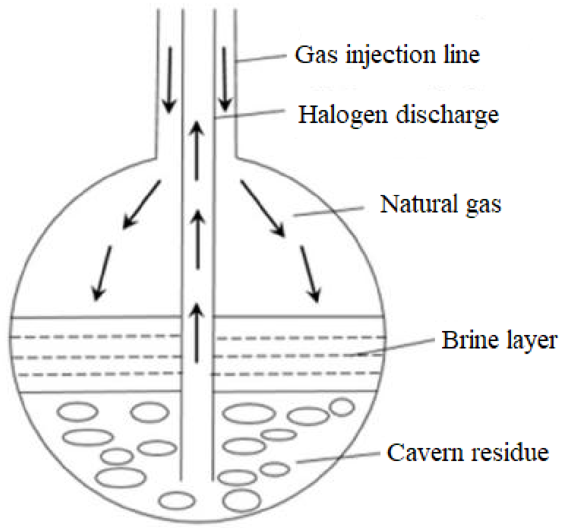

Fig. 6 Scheme of secondary gas injection for brine drainage (Fibbi et al., 2023).

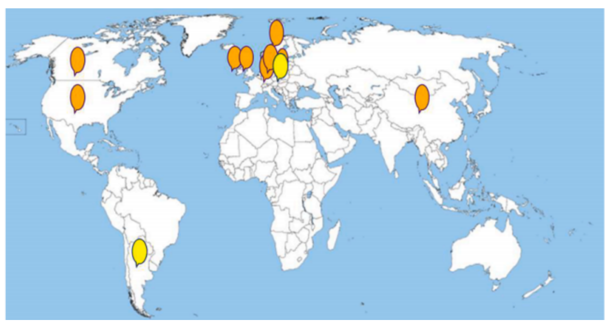

Fig. 7 Distribution of global depleted oil and gas reservoir-based hydrogen storage (Muhammed et al., 2023)
(Yellow markers represent operational hydrogen storage projects; Orange markers represent potential hydrogen storage sites)

cated approximately 1,030 m underground, with a designed drilling depth of 1,480 meters. The project utilizes salt caverns formed after brine extraction to inject hydrogen, planning to store 1.5 million cubic meters of hydrogen.The Daye Cave Hydrogen Storage Demonstration Project in Hubei commenced construction in December 2024. This project has achieved three ”global leading” achievements: it is the world’s first horizontal tunnel-type cave hydrogen storage project, has the largest single-tank hydrogen storage capacity (50,000 Nm³) globally, and leads globally in integrated cave hydrogen storage technology across the entire industry chain, which will bring significant and far-reaching impacts on the development of geological hydrogen storage.The Jintan Salt Cavern Hydrogen Storage Demonstration Project in Jiangsu has commenced construction in July 2025, planning to build two new sets of salt caverns, forming two hydrogen injection and production wells and two brine injection and discharge wells. It is expected to store 30 million cubic meters of hydrogen, serving as an engineering carrier for large-scale geological hydrogen storage testing and verification, to conduct cyclic hydrogen storage and release performance tests.

With the acceleration of global energy transition, underground hydrogen storage technology has gained increasing attention. In recent years, significant progress has been made in the research of depleted oil and gas reservoirs and aquifer hydrogen storage technologies. For example, depleted oil and gas reservoirs are considered as a major potential method for large-scale hydrogen storage due to their large storage space and good sealing properties (Zhou et al., 2022). Meanwhile, research on aquifer hydrogen storage technology focuses on how to control the gas-water interface and address challenges posed by microbial activities (Pan et al., 2023). Overall, underground hydrogen storage technology has evolved from a single salt cavern storage method to a diversified technical system, demonstrating broad application prospects in various energy scenarios.

2.4 Underground helium storage

As a rare and non-renewable strategic resource, helium plays an irreplaceable role in modern society. Its applications in high-tech industries are particularly prominent, as semiconductor manufacturing, fiber optic production, and aerospace technologies all rely on high-purity helium to ensure process accuracy and stability (Rapatskaya et al., 2020). Additionally, in the medical field, helium is widely used in the cooling systems of

Tab. 1 Global Underground Hydrogen Storage Facility Construction and Operation

Location	Geological Body Type	H_2 Purity (%)	Operating Conditions(MPa)	Burial Depth (m)	Storage Capacity (m^3)	Operator/Time
Teesside (UK)	Salt Dome	95	4.5	365	210,000	Sabic/1972 BP/2027
Clemens (USA)	Salt Dome	95	7-13.5	1,000	580,000	ConocoPhillips/1983-
Moss Bluff (USA)	Salt Dome	95	5.5-15.2	1,200	566,000	Praxair/2007
Spindletop (USA)	Salt Dome	95	6.8-20.2	1,340	906,000	Air Liquide/2014
Kiel (Germany)	Salt Dome	60	8-10	-	32,000	1971-
Ketzin (Germany)	Aquifer	62	-	200-250	1.3×10^8	1964-2000
Beynes (France)	Aquifer	50	-	430	3.3×10^8	1956-1972
Lobodice (Czech)	Aquifer	50	9	430	-	1960s-
Diadema (Argentina)	Depleted Reservoir	10	1	600-800	-	2015-
Underground Sun Storage (Austria)	Depleted Reservoir	10	7.8	1,000	-	2013-2017

magnetic resonance imaging (MRI) equipment, while the scientific research sector utilizes its unique physical properties for cryogenic experiments and high-end research such as particle accelerators(Song et al., 2025). With global economic development and technological progress, the demand for helium is showing a rapid growth trend. According to statistics, global helium consumption has been growing at an average annual rate of approximately 6% over the past decade. The demand for helium in medical, electronic, and aerospace fields has been particularly significant. For example, the increasing demand for MRI equipment in the medical industry is expected to result in 50% growth in global MRI installations by 2030 compared to 2020, which will directly drive a substantial increase in helium demand.

However, the supply of helium faces numerous challenges. Helium is primarily sourced from natural gas fields, where its concentration is extremely low, and global helium resources are highly unevenly distributed. Currently, approximately 75% of the world's helium supply comes from a few countries such as the United States, Qatar, and Algeria. The extraction and production process of helium is complex and costly, which also limits its supply growth.

To address the uncertainty of helium supply and ensure national helium security, establishing safe and efficient underground helium storage facilities has become a crucial measure to guarantee helium supply. Underground helium storage mainly utilizes underground spaces such as salt caverns and depleted oil and gas reservoirs as storage media. These storage methods have advantages such as large storage capacity, good sealing performance, and high safety. Among them, salt cavern helium storage facilities have the advantages of short construction time and lower costs; while depleted oil and gas reservoir helium storage facilities utilize existing oil and gas reservoirs for modification to achieve effective helium storage. For example, the United States established its National Helium Reserve as early as 1925, and after years of development, its reserve scale has continuously expanded. As of now, the storage capacity of the U.S. National Helium Reserve is approximately 850 million cubic meters, accounting for about 40% of the world's total helium reserves. The world's major underground helium storage facilities include: the Cleveland Salt Dome Helium Storage Facility in the United States, the Leuna Salt Dome Helium Storage Facility in Germany, and the Orenburg Salt Dome Helium Storage Facility in Russia. Other countries such as Russia, Japan, South Korea, and China are also actively building helium storage facilities to enhance their national helium reserve capabilities.

3 Carbon dioxide geological sequestration

Carbon Dioxide Geological Sequestration involves storing CO_2 in geological formations with good sealing properties. Currently, as in Fig.8, the reliable storage methods include CO_2 enhanced oil recovery and storage (CO_2-EOR), depleted oil and gas reservoir storage, saline aquifer storage, and coal seam storage.

3.1 Carbon dioxide storage in underground porous reservoir

3.1.1 CO_2-EOR and storage in oil reservoirs

CO_2-EOR refers to an environmental protection technology that involves injecting CO_2 into oilfields to enhance oil recovery while achieving underground storage. The principle of CO_2 flooding is mainly based on CO_2's ability to reduce crude oil viscosity, improve its fluidity, and make it easier to extract. After CO_2 injection, the volume of crude oil expands, increasing the driving force. CO_2 can extract light components from crude oil, further reducing viscosity. Under high-pressure conditions, CO_2 forms a miscible phase with crude oil, eliminating interfacial tension and improving oil displacement efficiency. Some CO_2 remains underground after oil recovery and achieves long-term storage through various mechanisms. This technology not only enhances oilfield recovery rates but also realizes geological storage of CO_2, offering significant environmental and economic benefits. The 1960s-1970s: The United States and the

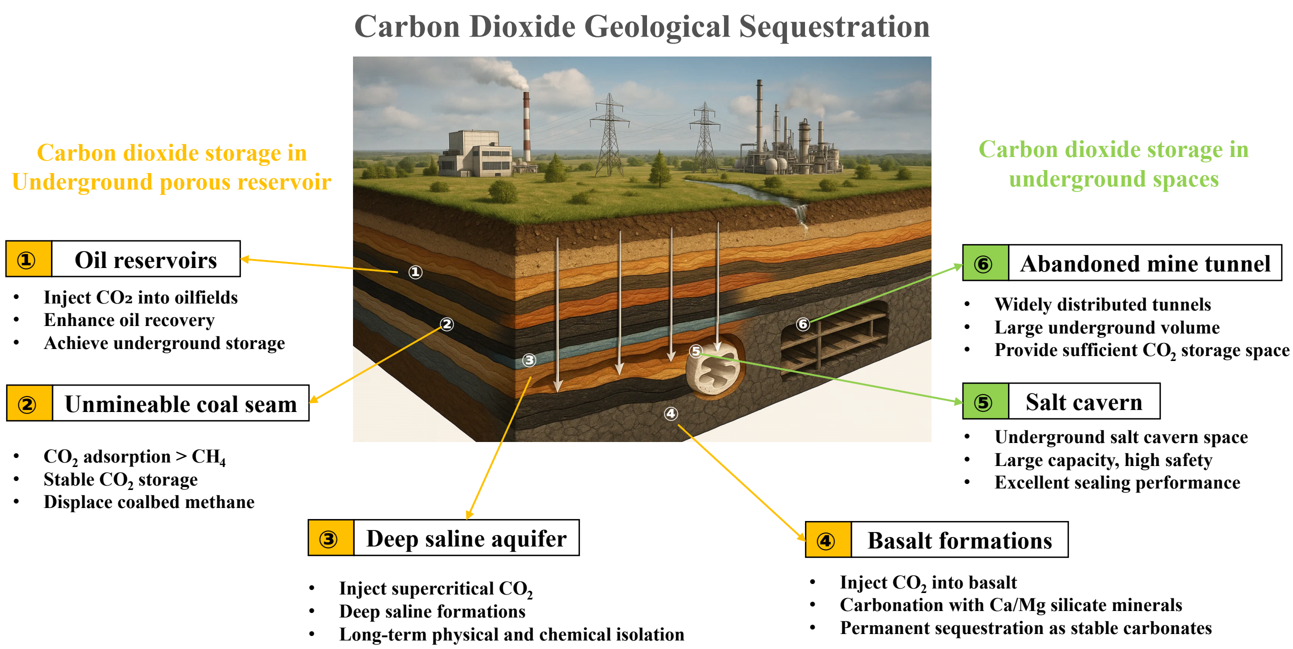

Fig. 8 Carbon dioxide geological sequestration

former Soviet Union began exploring carbon dioxide flooding technology. In 1972, the United States launched its first large-scale CO_2-EOR project, SACROC, which used carbon dioxide from natural gas fields for oil recovery and achieved remarkable results (Heinemann et al., 2018) In the 1980s-1990s: CCUS-EOR technology in the United States gradually matured, establishing a sophisticated commercialization system, which led to a significant increase in CO_2 flooding oil production. Canada launched a coal-to-gas capture CCUS-EOR project at the Weyburn oilfield, becoming one of the largest operational projects globally (Brown et al., 2016).

As early as the 1960s, China conducted pioneering CO_2-EOR tests in the Daqing Oilfield. Research and practice have never ceased since then. However, due to complex geological conditions and limitations in gas sources and compressor equipment, China's early CO_2-EOR technology developed slowly and remained in laboratory experiments and small-scale field testing phases. Pilot CO_2 flooding tests were successively carried out in oil and gas fields including Jiangsu, Zhongyuan, Daqing, and Shengli. Among them, the CO_2 huff and puff tests implemented at Well 48 in Fumin Oilfield, Jiangsu, and Well Cao-3 in Caozhe Oilfield, Subei Basin from 1996 to 1998 are considered China's earliest large-scale CO_2 flooding pilot tests.Entering the 21st century, China's CO2-EOR technology has developed rapidly, with major breakthroughs in CO_2 flooding and storage theories, as well as key core technologies. As of 2020, China has 9 operational CO_2-EOR projects and 1 project under construction. It has also built the first domestic CCS full-process demonstration project in Jilin Oilfield, which includes 5 CO_2 flooding and storage demonstration areas, 69 gas injection well groups, with an annual oil production capacity of 200,000 tons and annual CO_2 storage capacity of 300,000 tons. Xinjiang Oilfield conducted pioneering CO_2 flooding and storage tests in the Junggar Basin in 2009. Since 2012, it has successively conducted tests to enhance oil recovery and production through CO_2 flooding, CO_2 huff and puff, and tight oil CO_2 energy storage fracturing, cumulatively injecting 56,000 tons of CO_2, increasing oil production by 47,000 tons, and saving 23,700 cubic meters of steam, achieving good production results.

In 2021, China Petroleum & Chemical Corporation (Sinopec) launched a million-ton-level CCUS project. This project involves Qilu Petrochemical capturing CO_2, which is then transported to the Shengli Oilfield for enhanced oil recovery and storage. It is expected that over the next 15 years, a total of 10.68 million tons of CO_2 will be injected, achieving an increase in oil production of 2.27 million tons. By the end of 2023, China National Petroleum Corporation had deployed nearly 20 development tests in 11 oil and gas fields, with an annual CO_2 capture capacity of nearly 800,000 tons and injection capacity exceeding 2 million tons per year, accumulating a total of 7.23 million tons of CO_2 stored (Yang, 2024). Through continuous technological innovation and policy support, CO_2 EOR (enhanced oil recovery) and storage technology has moved from early-stage trials towards large-scale application, becoming a crucial method to achieve the goal of carbon neutrality.

3.1.2 CO_2 storage in unmineable coal seam

The adsorption potential well of CO_2 molecules on the coal seam surface is much larger than that of CH_4 molecules, which means that the adsorption of CO_2 on the coal surface is more stable (Jiang et al., 2006). Therefore, the adsorption capacity of the coal seam for CO_2 is much greater than that for CH_4. Injecting CO_2 into the coal seam can not only achieve its stable storage but also displace coalbed methane. Coal is a natural adsorbent for CO_2, and its adsorption capacity for CO_2 is about twice that for CH_4 (Ye et al., 2016). Moreover, while storing CO_2 in the coal seam, high - efficiency recovery of coalbed methane can be achieved, which has obvious economic advantages. In engineering, to prevent CO_2 from turning into a gaseous state during the storage process, it is usually injected in a super - critical state. Super-critical CO_2 with high density and low viscosity has strong dissolution, diffusion and penetration abilities, so the injection and stable adsorption can be completed more quickly. Since injecting CO_2 can enhance the recovery of coalbed methane, most CO_2 storage projects in coal seams are accompanied by the industrial purpose of high - efficiency coalbed methane recovery.

In 1998, Stevens et al. conducted a global assessment of the CO_2 storage potential in coal seams. Based on the assumption that CO_2 can displace the in - situ total amount of CH_4 at a volume ratio of 2:1, they estimated that the global CO_2 storage capacity in coal seams reaches 22.5×10^{10} tons (Stevens et al., 1998). In the same year, Parson et al. estimated that the CO_2 storage capacity of coal seams is approximately $(36.6 - 110) \times 10^{10}$ tons (Parson, 1998). In December 1993, the United States carried out the world's first field test of geological disposal of CO_2 in coal seams and enhanced coalbed methane recovery in the San Juan Basin (Gale, 2001). In 1995, a pure CO_2 injection test was conducted in the Allison coal seam of this basin, successfully achieving the joint production of coalbed methane from multiple wells. Approximately 3.35×10^5 t of CO_2 was injected into the coal seam at a depth of 900 m, and the recovery rate increased by about 18% (Busch, 2011). In 1997, Canada injected a mixture of CO_2 and CO_2, pure N_2, and pure CO_2 into the coal seams in the Alberta Basin, confirming that injecting pure CO_2 into coal seams is more conducive to coalbed methane production. Subsequently, Japan carried out pilot tests in Ishikari, Germany in Krczyn, Brandenburg, and Poland in the Silesian Coal Basin.

China started relatively late in CO_2 disposal in coal seams. Since 2002, a micro - pilot test of injecting CO_2 to enhance coalbed methane recovery and a single - well huff - and - puff test in deep coal seams were first carried out in Well TL-003 in the Qinshui Basin, Shanxi. Subsequently, multiple attempts were made in this basin in 2010 and 2013. It has been preliminarily confirmed that CO_2 injection can increase the methane recovery rate of coalbed methane wells and effectively store CO_2 (Ye et al., 2012). However, there are no actual engineering cases of using unmineable coal seams to store carbon dioxide He et al. (2022).

3.1.3 CO_2 storage in deep saline aquifer

Deep saline aquifer carbon dioxide storage involves injecting CO_2 in a supercritical state into deep underground saline formations, achieving long-term isolation through physical and chemical processes. As for the medium of CO_2 geological storage, saline aquifers are defined as porous and permeable reservoirs containing brine in the pores between rock particles. They are located below drinkable aquifers and widely distributed in sedimentary basins (Ma et al., 2024). Due to the influence of salinity and depth, groundwater in saline aquifers cannot be directly utilized by people. Therefore, to utilize saline aquifers for CO_2 storage, high-density gas under pressure must be injected into the pores of underground formations through injection wells to replace or dissolve the in-situ brine (Ke et al., 2023).

The mechanisms of CO_2 sequestration in saline aquifers include: (1) Structural trapping: Utilizing geological structures (such as anticlines and faults) to form physical traps, where CO_2 is confined within the geological formation; (2) Residual trapping: Capillary forces "lock" CO_2 within the rock pores, forming small gas bubbles that prevent upward migration; (3) Dissolution trapping: CO_2 dissolves into the formation water, increasing the brine's density and causing it to sink, thereby reducing the risk of escape; (4) Mineral trapping: CO_2 reacts with water to form carbonic acid, which further reacts with rock minerals (such as calcium and magnesium minerals) to produce carbonate minerals, achieving permanent solidification

Global research data shows that the storage potential of saline aquifers is more than ten times that of depleted oil and gas reservoirs and hundreds of times that of coal seams (Zhang et al., 2009). However, suitable sites for CO_2 storage in saline aquifers primarily involve selecting deep sandstone or carbonate formations with high porosity and permeability, overlain by low-permeability caprocks (such as mudstone or tight layers), forming natural "sealed containers" to prevent CO_2 leakage into shallow groundwater or the surface.

As of 2020, numerous large-scale saline aquifer storage projects have been implemented globally. Among them, Norway's Sleipner and Snøhvit, along with Algeria's In Salah, stand out as the most renowned cases due to their long operational duration, significant scale, high storage capacity, and demonstrated economic feasibility for commercial operation (Zhou et al., 2023).

Norway's Sleipner CCS project in the North Sea represents the world's first CO_2 sequestration initiative in saline formations. With the longest run time and substantial storage volume, it commenced injecting CO_2 into deep marine saline layers since 1996, serving as a critical research benchmark for understanding carbon dioxide confinement. Algeria's InSalah CCS project operates within a multi-field natural gas development managed by the In Salah Joint Venture, featuring an integrated CO_2 capture-and-storage demonstration component. Positioned at an elevation of 470 meters within the Sahara Desert, this low-productivity oilfield involves injecting captured CO_2 into Carboniferous sandstone reservoirs at Krechba at depths reaching 1,900 meters. Between 2004-2011, approximately 3.8×10^4 tons of CO_2 were successfully injected. The offshore Snøhvit field serves as another marine injection site at water depths averaging 330 meters—fully submerged during development. Here, after separation from methane streams (containing 5-8% CO_2) produced by Snøhvit, Albatross, and Askeladd fields via platforms operating at 80-meter depths, recaptured CO_2 is reinjected. Starting in 2008, plans call for total injections exceeding 23×10^6 tons over the project's 30-year life cycle.

China's sole deep saline aquifer geological storage endeavor, the Shenhua CCS Project, targets continental depositional strata comprising Paleozoic and Mesozoic permeable sandstones / carbonates spanning 11200 m^2. Comprising one injection well and two monitoring wells, it initiated injections in 2011. Ongoing surveillance confirms no leakage occurrence thus far.

3.1.4 CO_2 sequestration in basalt formations

The basic principle of CO_2 sequestration in basalt is to inject CO_2 into basalt, allowing it to undergo carbonation reactions with calcium - and magnesium - bearing silicate minerals in the rock to form stable carbonate minerals, thereby achieving permanent CO_2 sequestration. The potential for CO_2 sequestration in basalt is estimated to be between 100,000 and 250,000 gigatons. This method not only has high sequestration efficiency but also has almost no risk of leakage, so it is regarded as an ideal long term solution. There are three existing global demonstration projects for geological CO_2 sequestration in basalt: (1) Iceland's CarbFix Project: In this project, CO_2 and water are injected into basalt separately to ensure that CO_2 is completely dissolved in water, thus reducing the risk of leakage. Research shows that over 95% of the injected CO_2 was mineralized within two years, which proves the effectiveness of this method. (2) The Wallula Project in the United States: Nearly 10,000 tons of CO_2 were injected into basalt in this project. Sampling analysis two years later confirmed the mineralized sequestration of CO_2 . (3) The Nagaoka Project in Japan: Approximately 100,000 tons of super - critical CO_2 were injected into a volcanic sedimentary formation in this project. Fluid sampling analysis indicates that the expected mineral-fluid chemical reactions are taking place underground.

Theoretical research progress on CO_2 sequestration in basalt mainly includes the following aspects (Gao et al., 2023): (1) Mechanism of Carbon Sequestration in Basalt: Calcium-magnesium silicate minerals within basalt react with CO_2 to form carbonate minerals. This process not only sequesters CO_2 but also neutralizes solution acidity. Studies have ranked the sequestration capacities of common rock-forming minerals, revealing significant potential in olivine, pyroxene, serpentine, etc. Additionally, further research has been conducted on the mineralogical composition, pore distribution characteristics, and formation mechanisms of basalt. (2) Reaction Mechanism: The interaction between basalt and CO_2 involves multiple steps—dissolution of CO_2 in water, dissolution of rocks releasing metallic cations, and subsequent reaction between carbonate ions and metal cations to form carbonate minerals. Research indicates that reaction rates are influenced by factors such as salinity, temperature, pressure, pH values, fluid flow rates, and mineral surface area exposure. (3) CO_2 Sequestration Potential of Basalt: Basalt is extensively distributed across Earth, including oceanic crust and certain terrestrial regions. Studies identify key sites for CO_2 storage as oceanic plateau basalts, mid-ocean ridge basalts (MORB), and continental flood basalts. For example, Icelandic mid-ocean ridge basalts can absorb over one ton of CO_2 per 10 cubic meters; globally, MORB theoretically holds a sequestration capacity ranging from 100 to 250 trillion tons.

Implementing carbon dioxide sequestration in basalt still faces some scientific and technological challenges, such as difficulties in site selection, inaccurate estimation of storage capacity, and insufficient in-depth research on geochemical reactions and mineralization rates (Mwakipunda et al., 2024). It is necessary to strengthen relevant research to improve the efficiency and safety of CO_2 sequestration in basalt formations, reduce costs, and increase benefits.

China has carried out the country's first carbon sequestration test in basalt in Fujian Province. This project conducted the first in-situ field test of CO_2 sequestration in basalt in China and preliminarily evaluated the carbon sequestration potential of basalt in the coastal area of Zhangzhou. Through systematic data analysis, field surveys, on-site sampling, laboratory experimental analysis, and field tests, the project has basically identified the development and distribution characteristics of Cenozoic basalt in the area. It carried out the first in-situ field test of CO_2 sequestration in basalt in China and sequestered 24 kilograms of CO_2. It has preliminarily evaluated that the carbon sequestration potential of Cenozoic basalt in the coastal area of Zhangzhou can reach over 2 billion tons, and preliminarily delineated three prospective areas for CO_2 sequestration.

3.2 CO_2 storage in underground spaces

Underground carbon dioxide storage primarily utilizes abandoned underground spaces left by mining activities. These underground spaces mainly include: depleted salt caverns, abandoned gypsum mines, and deserted metal mine tunnels. By storing carbon dioxide in these underground spaces, it can be reserved for use as raw materials in chemical industries and other applications.

3.2.1 CO_2 storage in salt cavern

As an effective carbon emission reduction method, salt cavern CO_2 storage technology has received widespread attention. This technology utilizes underground salt caverns as storage spaces, offering advantages such as large storage capacity, high safety, and excellent sealing performance. It plays a crucial role in addressing climate change and achieving energy transition. When storing supercritical CO_2, salt caverns can maintain long-term stability and effectively prevent leakage. The high viscosity and low permeability characteristics of CO_2 itself further enhance the safety of storage in salt caverns (Liu et al., 2024).

Multiple countries worldwide have actively launched projects related to carbon dioxide storage in salt caverns (Popescu et al., 2021). For instance, Norway has developed large-scale carbon capture and storage (CCS) projects, permanently storing captured CO_2 in salt caverns under the North Sea, achieving significant results in both technology and operational models. In Canada's Alberta region, in-depth feasibility studies have been conducted on using salt caverns for CO_2 storage, laying a solid foundation for future project implementation. Additionally, the United States has several typical cases, such as the Petra Nova project, which inject captured CO_2 into oil fields or underground salt caverns for storage, achieving carbon emission reduction goals while promoting the development and application of relevant technologies.

China has also actively explored carbon dioxide storage technology in salt caverns. In regions such as Jiangsu and Shandong, relevant departments and enterprises have made full use of local salt cavern resources to carry out pilot projects for carbon dioxide storage and energy storage. These projects have not only verified the feasibility of salt cavern carbon dioxide storage technology in China but also accumulated valuable experience for future large-scale promotion and application. Through continuous optimization of technical solutions and operation modes, China's technological level in salt cavern carbon dioxide storage is gradually improving, providing strong support for addressing climate change and achieving energy transformation.

3.2.2 CO_2 storage in abandoned mine tunnel

The abandoned mine tunnels left by mines (such as coal mines, gypsum mines, and metal mines) serve as a special type of underground space resource, offering unique advantages and providing new possibilities for carbon dioxide storage. Firstly, abandoned mine tunnels are typically widely distributed with large spatial volumes, providing sufficient storage space for carbon dioxide. Secondly, these mine tunnels are mostly located in regions with relatively stable geological structures, and their surrounding rocks and roofs possess good sealing and stability properties, creating favorable conditions for safe carbon dioxide storage (Huo et al., 2024). Additionally, the reuse of abandoned mine shafts not only helps alleviate land resource pressure but also effectively reduces environmental problems and safety hazards caused by abandoned mine shafts. Therefore, studying the technical feasibility and economic viability of carbon dioxide storage in abandoned mine tunnels is not only an important supplement to traditional storage methods but also provides innovative ideas for comprehensive management of abandoned mines.

In recent years, research on abandoned mines as carbon dioxide storage sites has gradually increased, with existing studies mostly focusing on coal mines(Zhu et al., 2024), while research on abandoned metal mines is relatively limited. This is mainly because metal mines have significantly different geological characteristics from coal mines, such as surrounding rock stability and hydrological conditions, and the impact of these factors on storage effectiveness needs further investigation. Abandoned metal mine openings have widespread spatial distribution and complex structures, with their roadway layouts and cross-sectional shapes having significant impacts on carbon dioxide storage capacity and distribution. Additionally, geological structure types and hydrological conditions within metal mines are key factors determining storage feasibility. For example, stratum stability and permeability directly affect carbon dioxide injection and storage efficiency, while groundwater distribution may influence storage stability by altering chemical reaction rates(Ran et al., 2023). Abandoned metal mines typically contain large amounts of calcium-magnesium silicate minerals, which can undergo mineralization reactions with carbon dioxide to form stable carbonate precipitates. For instance, industrial solid wastes such as steel slag and gypsum are considered ideal mineralization materials due to their high reactivity and rich calcium-magnesium content(He et al., 2022). Indirect mineralization technology can significantly improve mineralization efficiency and obtain high-purity carbonate products through mild reaction conditions and efficient catalyst application. Moreover, chemical reaction types and products play important roles in storage stability. Research shows that mineralization reactions can not only fix carbon dioxide but also improve the geological environment within mine openings by reducing acidic substance content, thereby further enhancing storage safety. Although existing research has made progress in environmental management of abandoned metal mine openings, the assessment of their potential as carbon dioxide storage sites remains insufficient.

4 Underground compressed air energy storage and pumped hydro energy storage

As in Fig.9, Compressed Air Energy Storage (CAES) and Pumped Hydro Energy Storage (PHES) are also adopted for large-scale physical energy storage that utilizes air or water as the circulating working fluid.

4.1 Underground CAES

CAES is a large-scale physical energy storage technology that uses compressed air as the medium. It has attracted significant attention in the industry due to its many advantages, including low unit cost, long lifespan, safety, and environmental friendliness. During periods of low electricity demand, CAES stores excess electrical energy by compressing air. When needed, it releases the high-pressure air to generate electricity through expansion turbines. This technology can store intermittent renewable energy sources such as solar and wind power, or excess conventional electricity that exceeds grid supply(Xin et al., 2025). It can be used when grid supply is insufficient, playing a role in ”peak shaving and valley filling” to regulate the power grid. Additionally, it can solve the problem of ”curtailed wind and solar power” in renewable energy applications, making it of crucial significance for the utilization of renewable energy.

The basic principle of CAES power plants is based on the spatial and temporal transfer and conversion of energy. During periods of low electricity demand, when there is excess power in the grid, this technology utilizes this surplus electricity to drive compressors. The compressors draw in air and perform multi-stage compression, during which the air pressure increases continuously while the temperature rises significantly. The compressed high-temperature, high-pressure air is then transported and stored underground. Large-scale underground CAES power plants can be divided into two main categories based on storage space: cavern-type (including artificial hard rock caverns, abandoned salt caverns, abandoned mines, and karst caves, hereinafter referred to as CAES-C type) and porous reservoir-type (aquifers, depleted oil and gas fields, hereinafter referred to as CAES-A type).

4.1.1 Underground cave CAES

Underground chambers serve as storage spaces for compressed air. Therefore, they are typically located in areas with stable geological structures and good sealing properties, such as salt rock formations and hard rock strata. These rock layers have high compressive strength and low permeability, which effectively prevent compressed air leakage and ensure long-term stability of the storage space. Meanwhile, the scale of underground chambers can be designed according to energy storage requirements, meeting capacity needs of different scales. With the growing demand for efficient and clean energy storage technologies in the energy sector, non-afterburning CAES technology has emerged and gradually matured ((Zhang et al., 2024)). By effectively recovering and utilizing the heat generated during compression, this non-afterburning technology can drive the expander for power generation without burning fossil

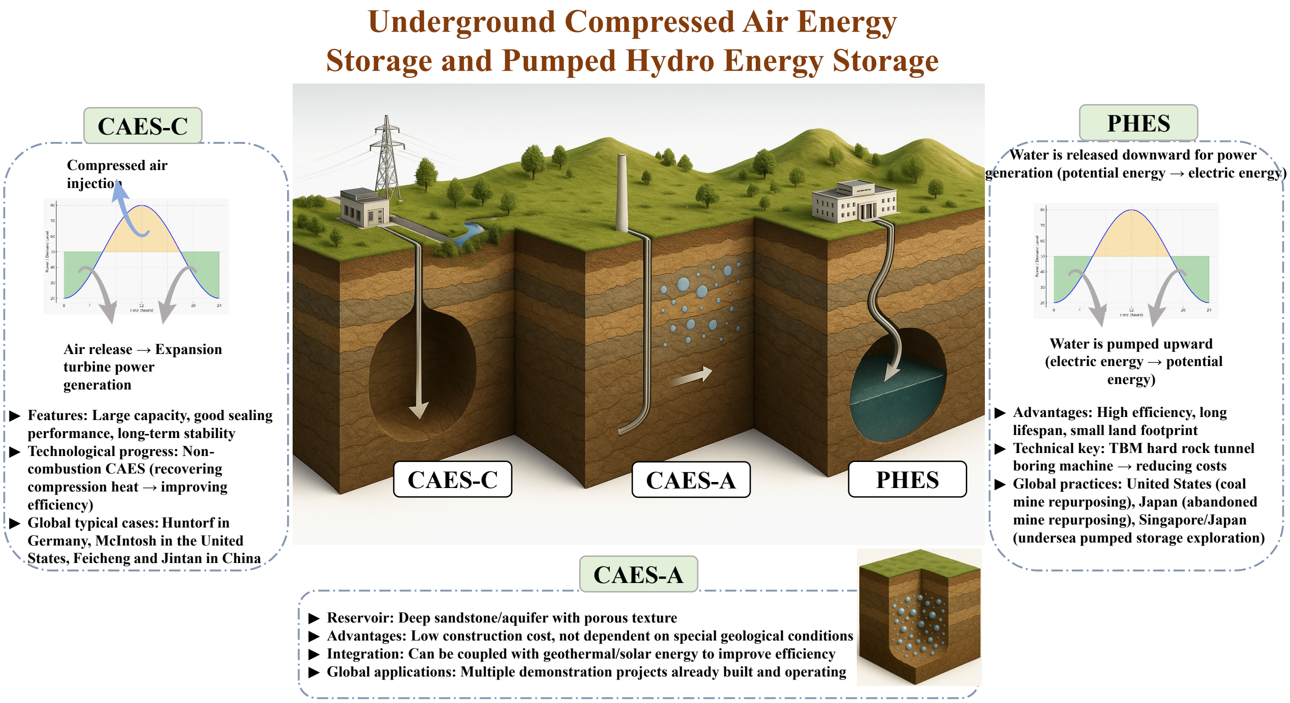

Fig. 9 Schematic of CAES and PHES

fuels during energy release, significantly improving system efficiency while substantially reducing environmental impact and enhancing environmental friendliness.

In recent years, underground chamber compressed air energy storage technology has achieved further optimization and widespread application. Compared to traditional gas storage methods, underground chambers offer advantages such as large space and good stability, which can provide greater energy storage capacity to meet the growing energy storage demands of power systems. Meanwhile, driven by continuous technological improvements, the efficiency of underground chamber CAES power plants has also been significantly enhanced, further strengthening their competitiveness in the energy storage market. The sealing and stability of underground chambers are crucial for the safe and stable operation of compressed air energy storage systems. To ensure the sealing of underground chambers, researchers have developed new sealing materials and construction techniques that can effectively prevent air leakage. Additionally, to address the potential impacts of geological structure changes on underground chambers, advanced reinforcement technologies such as grouting reinforcement and bolt support are employed to improve the stability of underground chambers and ensure system reliability during long-term operation.

Globally, underground chamber compressed air energy storage (CAES) power plant projects have been established to some extent (Rabi et al., 2023). As one of the pioneering countries in energy technology innovation, Germany's Huntorf power plant, which began operation in 1978, became the world's first commercial compressed air energy storage power plant. The plant utilizes abandoned salt caverns as gas storage space, compressing and storing air during periods of low electricity demand and releasing it for power generation during peak periods, playing an important role in the stable operation of Germany's power system . Similarly relying on underground salt cavern gas storage, the US McIntosh power plant has accumulated rich operational experience since its operation began in 1991, with its scale and efficiency being representative among early projects . In China, the construction of underground chamber compressed air energy storage power plant projects is also actively advancing. The Feicheng project in Shandong utilizes local abundant salt cavern resources to plan and construct a large-scale compressed air energy storage power plant, and has currently achieved significant results in technology research and engineering construction, serving as a demonstration project in this field in China. The Jintan area in Jiangsu has also conducted research and construction of compressed air energy storage projects leveraging its geological advantages, providing beneficial exploration for the development of domestic energy storage industry. These typical cases demonstrate that underground chamber compressed air energy storage power plants have good application potential in different regions, providing valuable experience for the promotion of subsequent projects(Li et al., 2018).

4.1.2 Porous reservoir type CAES

Porous reservoir-based CAES utilizes underground porous reservoirs (such as aquifers and sandstone formations) as gas storage spaces, eliminating the dependence on specific geological conditions required by traditional gas storage facilities and significantly reducing the construction costs of gas storage reservoirs (Sun et al., 2023). Research has shown that porous reservoir-based CAES technology can not only achieve large-scale energy storage but also improve overall system efficiency by coupling with other renewable energy sources (such as geothermal and solar energy). For example, a new type of compressed air energy storage system that couples U-shaped well underground aquifers with geothermal energy has been proven to effectively utilize geothermal energy in multiple working cycles, thereby improving the system's economy and environmental friendliness(Yuan et al., 2024). Therefore, porous reservoir-based compressed air energy storage technology is not only a promising energy storage method with great development potential but also provides new ideas and directions for the diversified development of future energy storage technologies.

Currently, multiple porous reservoir-based CAES demonstration projects have been built and put into operation globally(Guo et al., 2021). The construction background of these projects mainly stems from the urgent need for large-scale energy storage technologies and a deep understanding of the limitations of traditional energy storage methods. For example, a demonstration project is located in an area rich in natural porous reservoirs, aiming to verify the feasibility and economy of this technology in practical applications. The project adopts an advanced multi-well injection-production system, combined with an intelligent monitoring platform, to achieve real-time monitoring and optimal regulation of reservoir conditions. Its purpose is not only to demonstrate the potential of porous reservoir-based CAES technology but also to provide support for subsequent technology promotion through actual operation data. The successful implementation of these demonstration projects marks a significant breakthrough in this technology from theoretical research to practical application.

These demonstration projects have achieved remarkable results in actual operation, particularly in terms of energy storage efficiency and operational stability. According to operational data, the energy storage efficiency of this technology has reached over 55%, showing a significant improvement compared to traditional CAES technology. Moreover, by optimizing injection-production strategies and introducing intelligent control systems, the project has demonstrated good stability during operation, with reservoir pressure fluctuations controlled within reasonable ranges(Lu et al., 2023). These achievements not only verify the feasibility of porous reservoir-based CAES technology but also provide strong support for its widespread application in power peak shaving and renewable energy integration. Meanwhile, the successful experience of these demonstration projects has provided important reference for future technological improvement and large-scale promotion.

4.2 Underground PHES

Underground pumped storage technology is an energy storage method that realizes the mutual conversion of electrical energy and potential energy by utilizing underground space. Its core principle lies in the coordinated operation of underground reservoirs, power plants, and surface reservoirs to complete energy storage and release. Specifically, this technology creates water storage space through underground excavation, and together with the upper reservoir on the ground, pumps water from the lower reservoir to the surface reservoir during periods of low electricity demand, thereby converting electrical energy into potential energy(Hao, 2023). During peak electricity demand, potential energy is converted back into electrical energy through water release and power generation. This process not only effectively alleviates the peak-valley difference in power systems but also provides important support for large-scale integration of renewable energy. According to energy storage technology classifications, underground pumped storage belongs to mechanical energy storage, characterized by using water's gravitational potential energy for energy storage with high efficiency and long service life. Moreover, compared to traditional ground-based pumped storage power stations, underground pumped storage technology has significant advantages in reducing land resource occupation and environmental impact, making it one of the research hotspots in the energy storage field in recent years(Wu et al., 2021).

The concept of underground pumped storage technology was first proposed by Canadian scientist Reginald Aubrey Fessenden in 1917. He initially envisioned using underground space to solve the geographical constraints of conventional pumped storage technology. Despite the immaturity of electric motor technology at the time, Fessenden proposed a pumped storage solution directly driven by wind mechanical energy, laying the foundation for subsequent research. Entering the mid-20th century, with the growth of global energy demand and the rise of renewable energy development, underground pumped storage technology gradually gained attention. The United States, Russia, Japan, and other countries successively conducted related research. As an important means to address energy storage needs, underground pumped storage technology has received widespread attention and application globally. The United States, Russia, Singapore, and Japan are leading in underground pumped storage technology, with their technological development levels and practical experiences providing important references for the world. The United States has a long research history in underground pumped storage technology, with early projects primarily focusing on repurposing abandoned mines for low-cost energy storage. For example, a project in Colorado successfully converted an abandoned coal mine into an underground reservoir for pumped storage power station operation. This project not only effectively utilized existing underground space but also significantly reduced construction costs, becoming a global model for abandoned mine repurposing. Russia made breakthroughs in the application of underground hard rock tunnel boring machine technology, significantly improving the construction efficiency and economy of underground pumped storage power stations through advanced tunnel excavation techniques. Additionally, due to limited land resources, Singapore and Japan have actively explored the feasibility of underwater pumped storage technology. Singapore has initiated pilot projects to study how to build pumped storage systems using seabed space, while Japan has developed underground pumped storage technical solutions suitable for complex geological conditions, drawing on its extensive experience in geological disaster prevention. The practices of these countries demonstrate that the development of underground pumped storage technology depends not only on technological innovation but also on consideration of the differences in geographical environment and resource endowment.

From the end of the 20th century to the beginning of the

21st century, underground pumped storage technology entered a rapid development stage. During this period, key technologies achieved multiple breakthroughs. For example, the application of hard rock tunnel boring machines significantly reduced the cost and difficulty of underground engineering excavation, creating conditions for large-scale promotion of underground pumped storage technology. Meanwhile, several landmark projects were successively completed in various countries. For instance, a Japanese underground pumped storage power station successfully increased its energy storage capacity by utilizing abandoned mine shafts for transformation; while the United States built multiple efficiently operating underground pumped storage power stations through artificial excavation of underground spaces(Lu et al., 2023). The successful implementation of these projects not only verified the feasibility of underground pumped storage technology but also accumulated valuable experience for subsequent technological optimization.

4.3 Underground thermal energy storage

Underground thermal energy storage (UTES) technology is a technical solution that utilizes underground space as a thermal energy storage medium to achieve efficient energy utilization. Its core principle involves storing unstable thermal energy resources, such as solar energy and industrial waste heat, in underground media in the form of heat, which can be released when needed to meet heating or cooling demands(Zhang et al., 2024).This technology primarily relies on the thermal conductivity and heat capacity characteristics of underground media. Underground thermal storage technology not only effectively addresses the imbalance between renewable energy supply and demand but also provides clean and low-carbon solutions for building heating and district heating(Xiao et al., 2022).

The widespread application of underground thermal energy storage technology has had profound impacts on energy efficiency improvement and environmental enhancement. Firstly, this technology effectively addresses the imbalance between energy supply and demand by storing renewable energy sources such as solar energy and industrial waste heat, thereby enhancing energy utilization efficiency. Secondly, the application of underground thermal energy storage in building heating systems has significantly reduced the use of fossil fuels, thus lowering greenhouse gas emissions and providing crucial support for achieving global carbon neutrality goals(Wang et al., 2021). For example, district heating systems in countries such as Sweden and Germany have reduced millions of tons of CO_2 emissions annually by adopting deep aquifer thermal energy storage technology(Zhang et al., 2021). Furthermore, UTES technology has had positive impacts on energy structure and industrial layout, promoting the development of renewable energy industries and facilitating the improvement of related industrial chains.

The origin of underground thermal energy storage technology can be traced back to the mid-20th century. With the growth of global energy demand and preliminary exploration of renewable energy utilization, researchers began to focus on how to achieve efficient storage and utilization of thermal energy through underground spaces. Early attempts primarily focused on utilizing natural geological conditions for thermal energy storage. For example, Sweden took the lead in the 1980s by conducting pioneering research on large-scale underground cross-seasonal thermal storage systems. The research during this stage concentrated on verifying the feasibility of underground thermal storage technology, including the selection of storage media, assessment of heat exchange efficiency, and the preliminary framework construction of system design. After entering the 21st century, underground thermal energy storage technology has ushered in a critical period of rapid development. The key technological breakthroughs in this stage are mainly reflected in the optimization of thermal storage materials, improvement of system design, and integrated innovation of related technologies(Huang et al., 2020). In the field of thermal storage materials, researchers have proposed various modification and application schemes for high-performance thermal storage materials through in-depth analysis of the thermodynamic characteristics of different media such as soil, rock, and water, significantly improving thermal storage efficiency and stability . Meanwhile, in terms of system design, ground heat exchanger thermal storage technology and aquifer thermal storage technology have gradually matured, especially making important progress in the research and development of medium and deep ground heat exchanger heating technology. In addition, international research hotspots have gradually shifted to the development and utilization of hot dry rock geothermal resources, with related technologies such as deep drilling, reservoir fracturing, and high-temperature geothermal well design experiencing rapid development(Rui et al., 2024). These technological breakthroughs not only expand the application scenarios of underground thermal energy storage technology but also lay a solid foundation for subsequent technological optimization and promotion.

GTES technologies can be classified into various types based on the heat storage medium and system structure. The most common types include aquifer thermal energy storage (ATES) systems and ground heat exchanger (GHE) systems. ATES systems store thermal energy in underground aquifers, utilizing groundwater flow for heat transfer and distribution. This technology offers high energy storage density and excellent thermal conductivity, making it suitable for large-scale district heating projects . In contrast, GHE systems store heat directly in soil or other solid media through buried closed-loop pipe networks. Although soil has lower energy storage density, GHE systems offer flexible installation and minimal environmental impact, making them widely used in small to medium-sized building heating projects . Additionally, as an emerging technology, medium to deep GHE heating systems have gained widespread attention in recent years both domestically and internationally for their efficient heating capabilities utilizing deep geothermal resources(Xu et al., 2021). These different types of thermal storage systems exhibit significant differences in storage efficiency, application scope, and economic feasibility, requiring reasonable selection based on actual needs. Looking ahead, UTES technology will welcome new development opportunities in multiple dimensions. First, the deep integration with emerging technologies such as artificial intelligence and big data will bring intelligent monitoring and control capabilities to UTES systems, thereby further improving system efficiency and operational stability . Second, driven by carbon neutrality goals, growing policy support and market demand will provide strong impetus for the large-scale application of UTES technology(Li et al., 2022). Additionally, technological innovation will increasingly focus on research and development of thermal storage materials and system optimization to achieve higher energy density and lower costs. However, facing challenges such as geological complexity, high development costs, and environmental geological issues, advanced geological survey technologies, cost reduction strategies, and environmental monitoring and protection measures are still needed to address these challenges. Overall, UTES technology is expected to become one of the core technologies in the energy sector in the future, injecting new vitality into global energy transformation and sustainable development.

5 Underground storage of important materials

5.1 Underground granary

As a fundamental material for human survival, the storage safety of grain is directly related to national economic stability and social development. Underground granaries, as a special type of grain storage facility, have significant advantages in ensuring grain quality and extending storage time due to their unique characteristics of constant temperature, constant humidity, and airtight conditions(Wang et al., 2019).

The design and construction of underground granaries must consider not only structural safety but also the impact of storage environment on grain quality, thus making this research of significant theoretical and practical value. In China, the history of underground grain storage can be traced back to the Yangshao Culture period, when people stored grain by digging cellars(Yu et al., 2008). With the development of times, underground granaries have evolved from simple storage facilities into complex systematic projects integrating modern technology, intelligent management, and green storage concepts. Especially during the 1960s and 1970s, to meet wartime preparedness needs, China constructed large-scale underground granaries, promoting rapid development of underground grain storage technology. These granaries not only possess characteristics of concealment, durability, and fire resistance but also effectively utilize natural conditions of underground spaces to achieve low-temperature grain storage, thereby reducing grain loss and energy consumption(Li et al., 2015).

As a major global grain producer and exporter, the development path of underground grain storage in the United States is closely related to its agricultural modernization process. The construction of underground grain facilities in the United States has made full use of its unique natural conditions, including vast plain terrains, suitable climates, and abundant arable land resources. The Central Great Plains region, with its flat terrain and fertile soil, provides superior basic conditions for grain production and storage(Lan et al., 2024). Moreover, the United States attaches great importance to agricultural technology research and development, and application, continuously promoting the mechanization level of farmland supporting facilities through market mechanisms, which has laid a solid foundation for the technical upgrading of underground granaries. For example, American underground granaries widely adopt intelligent monitoring systems and automated control technologies to achieve precise regulation of grain storage environments, thereby effectively ensuring grain quality.

As a globally significant grain producer and exporter, Canada's underground grain storage development possesses unique regional characteristics and technological advantages. Underground grain storage construction in Canada primarily concentrates in the western regions, particularly Saskatchewan and Alberta, where abundant land resources and stable geological conditions provide a solid natural foundation(Abdurahman, 2023). Moreover, Canadian underground grain storage facilities emphasize adaptability to local climatic conditions in their design, such as utilizing deep underground storage structures to take advantage of constant underground temperatures, thereby reducing reliance on artificial cooling equipment and lowering operational costs. Additionally, Canada has made remarkable progress in intelligent management of underground grain storage, for instance, by installing sensor networks to monitor temperature, humidity, and gas composition of storage environments in real-time, and using data analysis techniques to optimize grain storage management decisions. These technological features enable Canadian underground grain storage facilities to demonstrate significant advantages in grain storage efficiency and safety(Valls, 2015).

5.2 Groundwater storage

Globally, the issue of water scarcity is becoming increasingly severe and has emerged as one of the major bottlenecks restricting socio-economic sustainable development. According to relevant research, the uneven distribution of water resources and frequent extreme weather events caused by climate change have further complicated this issue. As one of the countries with scarce water resources in the world, China's per capita water resources possession is only 28% of the world average, and the spatial and temporal distribution is extremely uneven. Especially in island areas and the northwest arid regions, issues such as irregular precipitation and poor groundwater endowment conditions are particularly prominent, leading to a sharp contradiction between fresh water supply and demand(Ye et al., 2022). Against this background, underground reservoir technology has gradually gained attention as an efficient means of water resources regulation and storage. This technology effectively addresses the issues of high evaporation loss and large farmland occupation associated with surface reservoirs by utilizing underground space for storing rainwater and flood resources or mine water. Meanwhile, it provides a solution for dealing with extreme weather events such as typhoons and heavy rainstorms(Tang, 2014). Therefore, the development of underground reservoir technology is not only a crucial approach to alleviating water scarcity but also a key measure to enhance regional disaster resilience.

The core of underground reservoirs lies in the supplementation and regulation of surface water resources through the water storage characteristics of underground aquifers. According to different water storage media, underground reservoirs can be classified into various types, including porous, fractured, and karst types, among which mixed-media underground reservoirs have attracted significant attention due to their complex hydrogeological conditions(Wen, 2024). The working principle of underground reservoirs mainly includes three key processes: surface water recharge, groundwater storage, and regulation and utilization. In this process, hydrogeological conditions such as aquifer permeability and groundwater level dynamics play a decisive role. Additionally, engineering geological investigation and analysis are equally essential; for example, the site selection of underground dams must fully consider bedrock stability and anti-seepage performance. The construction of underground reservoirs must be based on an in-depth understanding of regional hydrogeological and engineering geological conditions to ensure their long-term operational reliability and safety.

With the advancement of science and technology, underground reservoir technology has witnessed breakthroughs in key technologies, particularly in underground dam construction and recharge techniques. As crucial facilities for intercepting groundwater flow and raising groundwater levels, underground dams have evolved their construction techniques from initial simple grouting methods to sophisticated cutoff wall construction technologies. For example, Japan first attempted to construct underground dams using grouting method in the 1970s, and continuously improved construction techniques in subsequent practices, effectively solving the dam seepage problem. Meanwhile, the emergence of recharge technology provided important support for increasing the storage capacity of underground reservoirs. By injecting surface water or treated water resources into underground aquifers, recharge technology not only enhanced the water storage capacity of underground reservoirs but also improved groundwater quality and prevented seawater intrusion. These breakthroughs in key technologies greatly promoted the advancement of underground reservoir technology, laying a solid foundation for its widespread application.

With the maturity of key technologies, the application scope of underground reservoirs has gradually expanded from coastal areas to inland arid regions and other special scenarios. In coastal areas, underground reservoirs are mainly used for intercepting groundwater runoff, preventing seawater intrusion, and improving water quality. The successful practice of the Minami-Kyushu underground reservoir in Japan demonstrates that underground dams can effectively raise groundwater levels and achieve sustainable water resource utilization. In inland arid regions, underground reservoirs have become an important means to solve water shortage problems. For example, the Wulabo Depression underground reservoir and the Chaiwopu Basin underground reservoir in Xinjiang, China, have achieved joint regulation and storage of surface water and groundwater through recharge technology, significantly improving regional water resource utilization efficiency. Additionally, underground reservoir technology has been applied in island areas. Zhoushan Island, for instance, has effectively alleviated the supply-demand contradiction of freshwater resources on the island by combining excavated underground reservoirs with typhoon period rainwater storage. These diverse application scenarios not only demonstrate the flexibility of underground reservoir technology but also provide rich practical experience for its further development.

6 Underground disposal of nuclear waste and garbage

6.1 Underground disposal of nuclear waste

As an efficient and clean energy source, nuclear power plays a significant role in the global energy mix. With the continuous growth of global energy demand and increasing emphasis on environmental protection, nuclear energy is regarded as one of the key energy sources for achieving sustainable development goals due to its low carbon emission characteristics. However, the development of nuclear energy inevitably comes with the issue of nuclear waste. Nuclear waste mainly includes low-level radioactive waste, intermediate-level radioactive waste, and high-level radioactive waste, among which high-level radioactive waste has attracted significant attention due to its long-term radioactivity and toxicity. If these wastes are not properly managed, they will have profound impacts on the ecological environment and human health. Underground disposal of nuclear waste is considered one of the safest and most feasible treatment methods currently available. This method can maximize the isolation of radioactive substances from the biosphere, thereby effectively reducing the potential threat posed by nuclear waste to the environment and human health.

The development of underground nuclear waste disposal technology can be traced back to the 1940s, having evolved from early simple disposal methods to modern complex technological systems. In the early days, nuclear waste disposal primarily used trench burial methods, which were simple to operate but lacked scientific planning, making them prone to environmental pollution and radionuclide migration risks(Huang et al., 2017). With the rapid development of the nuclear industry, the amount of radioactive waste has been increasing, prompting scientists to explore safer and more sustainable disposal methods. After the 1950s, near-surface disposal and geological disposal gradually became mainstream technologies. Near-surface disposal is suitable for low-level radioactive waste with short half-lives, typically buried at depths of no more than 30 meters, featuring mature technology and lower costs.

Geological disposal is designed for nuclear waste with long half-lives and high radioactivity. Its core concept involves burying nuclear waste in rock formations hundreds or even thousands of meters underground, utilizing geological barriers to achieve complete isolation from the biosphere. Sweden, Finland, and France are leading in the research and application of geological disposal technologies. They have established relatively comprehensive site detection and evaluation systems and conducted systematic research on disposal engineering technologies(Guo et al., 2019). In contrast, China started research on geological disposal technologies relatively late. However, in recent years, it has made progress in disposal site selection and site evaluation, particularly accumulating valuable experience in hydrogeological and engineering geological surveys.

With continuous breakthroughs in key technologies, the underground disposal technology system for nuclear waste has gradually improved, forming a coordinated development model covering multiple links including site selection, design, and construction. In the site selection process, technical experts have comprehensively considered factors such as geological stability, hydrological conditions, and population distribution, establishing systematic site selection evaluation criteria. For example, the Beishan area in Dunhuang, Gansu Province, China, has been identified as a potential site for a permanent high-level radioactive waste disposal facility due to its superior geological conditions and extremely low population density. In the design phase, the concept of multi-barrier system has been widely applied, including the design of multi-layer protective structures such as disposal containers, buffer materials, and surrounding rock formations, aiming to maximize the delay of radionuclide migration. Additionally, significant progress has been made in engineering technologies during construction, with key processes such as chamber excavation and waste canister installation achieving high levels of mechanization and automation(Yu et al., 2022). The coordinated development of these aspects not only improves the overall efficiency of nuclear waste underground disposal but also provides more reliable technical support for long-term safety assessment.

6.2 Landfill

With the acceleration of global urbanization, the urban population continues to grow, leading to a sharp increase in municipal solid waste generation. According to relevant studies, the annual global urban waste generation has exceeded 2 billion tons and is increasing at a rate of approximately 3% to 5% per year. This rapid growth not only imposes tremendous pressure on urban environments but also becomes one of the significant challenges facing global sustainable development. As one of the most widely used waste disposal methods, underground landfill technology occupies a central position in the global waste management system(Jiang, 2023). Particularly in regions with relatively abundant land resources, underground landfilling is widely adopted due to its operational simplicity and cost-effectiveness. The UK first attempted to zone landfill sites in the 1930s and improved landfill conditions through simple engineering measures. In the 1940s, the United States proposed controlled municipal solid waste landfill technology, marking a shift from random dumping to standardized management of waste disposal(Bie et al., 2013; Zhang et al., 2013).

In the 21st century, landfill technology has made significant progress in standardization and systematization. Developed countries have gradually established a comprehensive technical system covering site selection, design, construction, operation, and environmental monitoring by continuously improving landfill design specifications. For example, landfill design specifications clearly stipulate the thickness of impermeable layers, material performance requirements, and layout requirements for gas collection systems, ensuring the long-term stable operation of landfills. During the mature stage of technology, the integrated application of underground waste landfill technology with other treatment technologies has become an important trend in diversified development. For example, the combined application of landfill and incineration technology can effectively reduce waste volume while achieving resource recovery and utilization. In addition, landfills accelerate the decomposition of organic matter in waste by introducing biodegradation technology, thereby shortening the stabilization period of landfills. This diversified development model not only expands the functions and benefits of landfill technology but also provides new ideas for its application in the context of sustainable development. Through synergistic effects with other technologies, underground waste landfill technology demonstrates greater potential in environmental protection and resource utilization.

7 Major scientific and technological challenges in geological storage engineering

Geological storage engineering refers to a comprehensive discipline that involves safely storing various substances (such as oil and gas, carbon dioxide, nuclear waste, etc.) in specific underground geological formations through engineering techniques. Its core lies in utilizing the Earth's internal spatial resources and physicochemical properties to achieve the dual objectives of efficient resource utilization and environmental protection. This technology not only involves the interdisciplinary theoretical foundation of geology, rock mechanics, fluid mechanics, but also covers the complete engineering process from site selection to long term monitoring.

7.1 Underground oil and gas storage

7.1.1 Reservoir seal integrity and stability

The reservoir sealing capacity of underground oil and gas reserves is one of the key factors ensuring storage safety and long-term effectiveness. However, accurately assessing reservoir sealing capacity faces numerous challenges, especially under complex geological conditions. For example, the presence of geological structures such as faults and fractures may significantly weaken the sealing performance of reservoirs, thereby increasing the risk of oil and gas leakage or external fluid intrusion(Zhang et al., 2018). The Caen port in France once built a 5 Gm^3 diesel storage facility using abandoned coal mine underground space. The key to its successful operation lies in the good stability and spatial sealing of surrounding rocks and roof strata. However, this case is not universally applicable because reservoir characteristics vary significantly under different geological conditions, making sealing assessment more complex. Additionally, China has not yet conducted underground coal mine space oil storage engineering practices, only verifying relevant theories at the pilot stage, indicating that reservoir sealing assessment technology still needs further improvement.

Another challenge in reservoir sealing assessment lies in how to accurately quantify the impact of geological structures on sealing performance(Hu et al., 2023). For example, the development degree of formation structural fractures, permeability, and changes in rock mechanical properties all have significant impacts on reservoir sealing performance. Reservoir sealing performance depends not only on its initial geological conditions but also on the significant influence of later human activities (such as mining disturbance). Therefore, when assessing reservoir sealing performance, it is necessary to comprehensively consider various factors, including geological structural characteristics, reservoir physical property parameters, and changes in the external environment. Although scholars both domestically and internationally have proposed multiple assessment methods, due to the complexity and diversity of geological conditions, existing assessment technologies still struggle to meet practical needs.

Reservoir stability assessment is another crucial technological challenge faced by underground oil and gas reserves. During long-term oil and gas storage, the stability of reservoir structures may be affected by various factors, including pressure changes, fluid migration, and chemical interactions. For example, cyclic pressure fluctuations within the reservoir may lead to fatigue damage in the rock matrix, potentially causing reservoir instability and even collapse risks(Yang et al., 2023). Additionally, the interactions between oil and gas, reservoir rocks, and fluids can alter the reservoir's physical and mechanical properties, further complicating stability issues.

The difficulty in reservoir stability assessment is also reflected in the prediction of long-term effects. As underground oil and gas reserves typically need to be exploited for decades or even longer, it is challenging to fully understand the behavioral characteristics of reservoirs over long timescales through short-term experiments or observations. For example, long-term fluid immersion in the reservoir may lead to gradual reduction of rock strength, and such changes are often insidious and accumulative, making them difficult to detect in the early stages. Furthermore, reservoir stability assessment needs to consider the uncertainties in the geological environment, such as the impacts of external factors like seismic activities and groundwater flow on the reservoir. These uncertain factors make reservoir stability assessment an extremely challenging task.

7.1.2 Interaction between oil-gas and reservoir

Chemical reactions between oil and gas, reservoir rocks, and fluids are one of the main causes of corrosion problems. During oil and gas storage, acidic gases (such as CO_2 and H_2S) in the reservoir may undergo chemical reactions with rock minerals, generating corrosive substances that can damage reservoir structures and equipment. For example, when CO_2 dissolves in formation water, it forms carbonic acid, which reacts with calcium carbonate in reservoir rocks, leading to rock dissolution and increased porosity. These chemical reactions not only reduce the sealing performance of the reservoir but may also trigger safety hazards such as oil and gas leakage(Zhao et al., 2024).

The mechanism and influencing factors of corrosion issues are highly complex. Corrosion rates are closely related to the chemical composition, temperature, pressure of fluids in the reservoir, and rock mineral composition. For example, under high-temperature and high-pressure conditions, the reaction rate between CO_2 and formation water significantly increases, leading to intensified corrosion. Additionally, the fluid mobility within the reservoir can also affect the corrosion process, as fluid flow accelerates the diffusion and transport of corrosive substances(Wei et al., 2022). Therefore, when designing and operating underground oil and gas storage facilities, potential corrosion risks must be fully considered, and corresponding protective measures should be taken.

Scaling in reservoirs caused by corrosion is another critical issue that requires special attention. Scaling phenomena are typically caused by the precipitation and deposition of inorganic salts, organic compounds, and microbial metabolites from oil and gas under specific conditions. For example, changes in temperature and pressure within reservoirs may lead to supersaturation of certain dissolved substances, resulting in solid precipitates. These precipitates not only block reservoir pores and pipelines but also affect oil and gas storage and production efficiency.

The causes and processes of scaling issues involve multiple aspects. First, the complexity of oil and gas components determines the diversity of scaling substances. For example, oil and gas with high concentrations of calcium and magnesium ions are more prone to forming scaling substances such as calcium carbonate and calcium sulfate in reservoirs. Secondly, the fluid mobility within the reservoir will also affect the scaling process. When the fluid velocity is low, scaling substances are more likely to deposit and adhere to the reservoir surface; conversely, when the fluid velocity is high, the deposition rate of scaling substances will decrease, but their distribution range may become more extensive. Moreover, microbial activity is also one of the important factors contributing to scaling issues, as organic acids and other substances produced by microbial metabolism may promote the formation and deposition of scaling materials. Therefore, research on scaling problems not only needs to focus on their causes and mechanisms but also requires the development of effective prevention and control technologies to improve the operational efficiency and safety of underground oil and gas storage facilities.

7.2 CO_2 geological storage

7.2.1 CO_2 transport

After carbon dioxide is injected underground, its migration path and speed are affected by various geological conditions, showing significant complexity. In different reservoir environments, such as saline aquifers, depleted oil and gas reservoirs, or deep coal seams, there are obvious differences in the migration behavior of CO_2. For example, in rocks with well - developed fractures, CO_2 tends to migrate rapidly along high permeability channels. In contrast, in dense rocks with low porosity, its diffusion rate decreases significantly. In addition, the heterogeneity of geological structures further increases the uncertainty of the migration path, which may lead to the accumulation of CO_2 in local areas or the formation of preferential flow channels. This complex migration behavior not only depends on the physical properties of the reservoir but is also jointly controlled by hydrodynamic processes, such as density - driven convection and multiphase flow interactions. Therefore, accurately describing the migration laws of CO_2 underground remains one of the significant challenges in current research.

The factors influencing the migration laws of carbon dioxide mainly include key parameters such as geological structures, pressure, and temperature. As the primary influencing factor, the geological structure determines the main paths and scope of CO_2 migration. For example, the presence of faults and fractures may serve as potential channels for CO_2 leakage, while the dip angle of the strata and fold structures will affect the gravity driven effect of the fluid. In addition, changes in pressure and temperature have a significant impact on the phase state and fluidity of CO_2. Under high pressure conditions, CO_2 usually exists in a supercritical state. Its density and viscosity characteristics make it easier to inject and store. However, as the pressure drops, CO_2 may undergo a phase change, leading to changes in its migration behavior. The role of temperature cannot be ignored either. A higher reservoir temperature will enhance the diffusion ability of CO_2 molecules, but it may also accelerate the chemical reaction with the surrounding rock, thus changing the physical property parameters of the reservoir. The interactions among these factors complicate the research on the CO_2 migration laws, which requires in - depth analysis by combining experimental and numerical simulation methods.

7.2.2 Reactions with surrounding rocks and long-term monitoring

The chemical reactions between carbon dioxide and surrounding rocks have a significant impact on the physical property parameters of the reservoir and caprock. Research shows that after CO_2 injection, the chemical properties of the pore fluid in the reservoir will change, which in turn leads to the dissolution of primary minerals and the precipitation of secondary minerals. For example, in rocks rich in silicates, the reaction between CO_2 and water generates carbonate ions. These ions combine with elements such as calcium and magnesium in the rock to form secondary minerals like calcite, thereby altering the porosity and permeability of the reservoir. This mineral transformation process not only affects the efficiency of CO_2 storage but may also pose a threat to the mechanical stability of the reservoir. In addition, chemical reactions can change the wettability of the rock surface, further influencing the distribution and migration behavior of multiphase flow(Wang et al., 2022). Therefore, a deep understanding of the interaction mechanism among CO_2 , water, and rock is crucial for optimizing geological storage schemes.

Long-term monitoring of the effectiveness of carbon dioxide sequestration faces numerous technical challenges, mainly in terms of monitoring accuracy, stability, and cost. Firstly, since CO_2 sequestration usually occurs in deep underground environments, traditional monitoring techniques struggle to meet high precision requirements. For example, although seismic monitoring can provide reservoir information over a large area, its resolution is limited and it cannot capture small scale changes. Secondly, the long term stability of monitoring equipment is also a key issue. The high pressure and high temperature conditions in the underground environment may have an adverse impact on the performance of sensors, leading to data distortion or equipment failure. In addition, the high monitoring cost restricts large scale application. Especially in commercial sequestration projects, economic feasibility has become one of the limiting factors. In recent years, emerging technologies such as wireless sensor networks and satellite remote sensing technologies have provided new solutions for long term monitoring, but their practical applications still need further verification and optimization.

7.3 Underground disposal of nuclear waste

7.3.1 Site selection

The selection of underground disposal sites for nuclear waste has extremely strict requirements for geological conditions, which is the foundation for ensuring the long - term safe containment of nuclear waste. Firstly, lithology is one of the key factors determining the suitability of a site. The ideal surrounding rock should have high stability and low permeability to prevent radioactive substances from diffusing into the biosphere through groundwater or other means. For example, granite, salt rock, and clay rock are often regarded as preferred types of surrounding rock due to their dense structures and low porosity. Secondly, tectonic stability is also a core factor that must be considered during the site - selection process. The presence of geological structures such as faults and fractures may damage the sealing performance of the nuclear waste repository, thereby increasing the risk of radioactive substance leakage. Research shows that the location and occurrence of faults have a significant impact on the safety of nuclear waste storage, especially in regions with frequent geological activities, and this impact is even more prominent(Bao et al., 2022). In addition, geological parameters such as the groundwater level distribution, formation pressure, and temperature gradient also need to be included in the comprehensive evaluation system to ensure the long - term and stable storage of nuclear waste in a complex geological environment.

Although the requirements for geological conditions in underground nuclear waste disposal are relatively clear, there are still many difficulties in the actual site - selection process. The primary issue is the scarcity of sites that meet the requirements. Since nuclear waste disposal needs to take into account multiple factors such as geological stability, hydrological conditions, and social acceptance, it is often difficult to find a site that meets all the criteria. For example, when Germany uses abandoned salt mines for the disposal of low and intermediate level radioactive waste, despite the good sealing and stability of the salt mines themselves, the site selection process still has to overcome the dual challenges of geological structural complexity and public opposition. In addition, low public acceptance is another issue that cannot be ignored. The construction and operation of nuclear waste disposal repositories often arouse concerns among nearby residents. Especially in the case of long term storage of radioactive substances, the public's fear of potential environmental risks and health threats complicates the site - selection work. Therefore, how to strike a balance between scientific evaluation and public participation has become an important issue that needs to be urgently addressed in the current site - selection work for underground nuclear waste disposal.

7.3.2 Isolation of nuclear waste from the biosphere and its thermal effects

Ensuring the long - term and effective isolation of nuclear waste from the biosphere is one of the core technological challenges in the underground disposal of nuclear waste. Achieving this goal relies on the construction of a multi - barrier system, including engineered barriers (such as waste packaging containers) and natural barriers (such as surrounding rocks). However, over time, these barriers may fail due to physical, chemical, or biological effects, leading to the leakage of radioactive substances. For example, the packaging materials for nuclear waste may corrode or age in the long term geological environment, thereby weakening their sealing performance. In addition, the interaction between groundwater and nuclear waste may also give rise to a series of complex problems. Research shows that the CO_2 -water-rock interaction can change the porosity and permeability of the surrounding rock, and such changes may pose a threat to the long term stability of the nuclear waste repository. Therefore, developing high - performance engineering materials and gaining an in-depth understanding of the interaction mechanism between groundwater and the surrounding rock are crucial for achieving long - term isolation of nuclear waste from the biosphere.

The impact of the heat generated during the decay of nuclear waste on the stability of the surrounding rock and the groundwater environment is another issue that requires significant attention. On the one hand, the heat can cause the temperature of the surrounding rock to rise, thereby altering its mechanical properties and thermal stress distribution. For example, under high - temperature conditions, the surrounding rock may undergo thermal expansion or thermal cracking, which in turn affects the sealing performance and structural integrity of the repository. On the other hand, the heat can also accelerate the rate of chemical reactions in groundwater, promoting the dissolution of primary minerals and the precipitation of secondary minerals, and further changing the porosity and permeability of the surrounding rock. These changes may not only weaken the isolation capacity of the surrounding rock but also pose potential threats to the surrounding ecological environment. To address this issue, researchers have proposed a variety of solutions. For instance, optimizing the design of the repository to reduce heat accumulation, or using artificial cooling systems to control the temperature of the surrounding rock. However, the practical applications of these technologies still need further verification and improvement, especially in terms of reliability and economic feasibility under long - term operating conditions.

7.4 Underground granaries

7.4.1 Temperature and humidity control

Underground grain depots are important facilities for long - term grain storage, and the stability of the temperature and humidity environment in them has a decisive impact on grain quality. However, fluctuations in temperature and humidity in the underground environment may lead to a series of storage problems, among which the most prominent ones are grain mildew and pest infestation. Research shows that grains are extremely sensitive to changes in temperature and humidity during storage. When the relative humidity exceeds 65%, the reproduction rate of molds increases significantly, which in turn leads to grain mildew. In addition, temperature fluctuations can also exacerbate the frequency and scale of pest infestations. For example, certain grain storage pests (such as Sitophilus zeamais and Tribolium castaneum) have the strongest reproductive ability in the temperature range of 20℃ to 30℃, and seasonal or local temperature changes in the underground environment may provide suitable living conditions for them. Such temperature and humidity fluctuations not only reduce the nutritional value of grains but may also produce harmful substances (such as aflatoxins), posing a potential threat to human health. Therefore, how to effectively address the impact of temperature and humidity fluctuations in the underground environment on grain storage quality has become one of the key technological issues in the construction and operation of underground grain depots.

The technical difficulties in achieving precise temperature and humidity control in underground grain depots mainly lie in the compatibility between the heat and moisture preservation characteristics of the underground space and the control equipment. Due to its special geological structure, the underground space generally has good heat and moisture preservation performance, but this natural characteristic also brings challenges to regulation. On the one hand, although the temperature and humidity in the underground environment change within a relatively small range, the response speed is slow, making it difficult for traditional control equipment to quickly adapt to the changing needs of the internal environment. On the other hand, while the airtightness of the underground space helps to reduce external interference, it also restricts air circulation, making the problem of uneven temperature and humidity distribution more prominent. In addition, the existing control equipment still has deficiencies in terms of energy consumption, accuracy, and stability. Especially during long - term operation, the equipment has a relatively high failure rate and the maintenance cost is expensive. Therefore, to develop an efficient temperature and humidity control technology suitable for underground grain depots, it is necessary to comprehensively consider the geological characteristics of the underground space and the technical parameters of the equipment to achieve a balance between precise control and economic feasibility.

7.4.2 Pest and disease control

The spread characteristics and patterns of pests and diseases in underground grain depots differ significantly from those in above - ground grain depots, mainly due to the special ecological conditions of the underground environment. Firstly, the airtightness and low - light conditions of the underground space inhibit the activities of some natural enemies of pests and diseases, thereby weakening the regulatory effect of the natural ecosystem. Secondly, the relatively stable temperature and humidity in the underground environment provide ideal living conditions for certain grain - storage pests and pathogens, enabling them to continuously reproduce and spread. For example, research shows that in the absence of effective control measures, the population density of pests in underground grain depots can reach a peak in a relatively short period, and the spread range is more concentrated. In addition, the spread routes of pests and diseases in underground grain depots also show diverse characteristics, including direct contact transmission between grain particles, air flow transmission, and transmission through attachment on the surfaces of storage equipment. These spread characteristics not only increase the difficulty of pest and disease control but may also lead to the rapid spread of local epidemics, posing a serious threat to food security.

The existing pest and disease control methods face numerous challenges when applied in underground grain depots. In particular, the pollution risk of chemical control to the underground environment cannot be ignored. Although chemical agents can quickly kill pests and pathogens, their residues may cause long term pollution to groundwater and soil environments, thereby affecting the ecological balance and human health. Moreover, due to the airtightness of underground grain depots, it is difficult for the volatilized chemical agents to be quickly discharged, which may lead to excessive residues being adsorbed on the surface of grains, further reducing the grain quality. Meanwhile, the application of biological control methods in underground grain depots is also restricted. Since the biodiversity in the underground environment is relatively low, the effects of introducing natural enemies or microbial agents are often less significant than those in above - ground grain depots. Therefore, how to develop efficient, environmentally friendly, and sustainable pest and disease control technologies based on the actual situation of underground grain depots is one of the important technological issues that need to be urgently addressed at present.

7.5 Underground reservoirs

7.5.1 Water resource protection

As an important form of water resource storage, the water quality safety of underground reservoirs is directly related to the reliability of the water supply system and the health of the ecosystem. However, underground reservoirs face a variety of potential pollution sources and risk factors, among which industrial and agricultural activities are one of the most significant threats. Wastewater and waste discharged during industrial production may enter the underground aquifer through seepage or improper disposal, leading to the accumulation of harmful substances such as heavy metals and organic pollutants. For example, leakage accidents in chemical enterprises or the discharge of untreated high concentration wastewater may cause long term pollution to the surrounding groundwater environment. In addition, fertilizers and pesticides widely used in agricultural activities are also important sources of groundwater pollution. These chemical substances migrate downward through the soil layer during rainfall or irrigation and eventually enter the underground reservoir, causing excessive levels of pollutants such as nitrates and phosphates. Especially in agriculturally intensive areas, the overuse of fertilizers and pesticides is particularly prominent, further increasing the risk of groundwater pollution. Therefore, identifying and controlling these pollution sources is a key challenge in ensuring the quality of water resources in underground reservoirs.

Formulating effective groundwater protection measures requires overcoming various technical challenges, especially the limitations of pollution monitoring and early - warning technologies. Currently, the commonly used groundwater monitoring methods mainly include chemical analysis, physical detection, and biological indicator assessment. However, these technologies all have certain deficiencies in practical applications. For example, traditional water quality sampling and analysis methods usually rely on manual operations, which are time consuming and difficult to achieve real time monitoring. This may result in the inability to promptly detect and handle pollution incidents. Moreover, the complexity and heterogeneity of groundwater flow make it difficult to accurately predict the diffusion paths of pollutants, thus increasing the difficulty of monitoring - point layout.

In recent years, although remote sensing technology and geophysical detection methods have been widely used in groundwater pollution monitoring, their accuracy and resolution are still insufficient to meet the requirements of refined management. For instance, although single - hole acoustic imaging technology can reveal the fine structure of the underground space to a certain extent, it still lacks sufficient sensitivity to the specific distribution and concentration changes of pollutants. Therefore, developing efficient and accurate pollution monitoring and early warning technologies and establishing a comprehensive groundwater protection system are important issues that urgently need to be addressed in the field of water - resource protection for underground reservoirs at present.

7.5.2 Groundwater level regulation

Water level regulation of underground reservoirs is a crucial step in achieving rational utilization of water resources and ecological protection. However, precise regulation faces numerous difficulties, mainly due to the complexity of groundwater flow and the uncertainty of hydrogeological parameters. Groundwater flow is influenced by multiple factors such as geological structures, lithological distribution, porosity, and permeability. Its movement patterns often exhibit high nonlinearity and spatio - temporal variability. For example, in karst areas with well - developed fractures, the flow paths of groundwater can be extremely complex, making it difficult for traditional numerical simulation methods to accurately describe its dynamic changes. In addition, there is also significant uncertainty in obtaining hydrogeological parameters. For instance, the determination of hydraulic conductivity and specific storage usually relies on field tests or empirical formulas, and the results may vary greatly depending on the sampling location or experimental conditions. This uncertainty not only affects the accuracy of water level regulation models but may also lead to mistakes in regulation decisions. Therefore, how to achieve precise regulation of groundwater levels under complex geological conditions remains one of the challenges in current research.

Rationally adjusting the water level of underground reservoirs according to water resource demand and ecological balance is a key challenge for achieving their sustainable utilization. Changes in the water level of underground reservoirs not only affect the water supply capacity but also have a profound impact on the surrounding ecological environment. For example, an excessively low water level may lead to ecological problems such as the degradation of surface vegetation and the drying up of wetlands, while an excessively high water level may cause adverse consequences such as soil salinization or land subsidence. Therefore, when formulating water level adjustment plans, it is necessary to comprehensively consider the water resource demand for social and economic development and the carrying capacity of the ecosystem. However, achieving this goal faces difficulties in multiple aspects. Firstly, water resource demand shows significant spatio temporal differences. How to optimize the allocation of water resources across different seasons and regions is a complex systematic project. Secondly, maintaining ecological balance requires long term monitoring and dynamic adjustment, but the existing monitoring technologies and regulation means are insufficient to meet this requirement. In addition, the public's awareness and participation in underground water resources are relatively low, which also increases the difficulty of implementing water level adjustment policies. Therefore, future research should focus on how to achieve scientific adjustment and sustainable utilization of the water level of underground reservoirs through technological innovation and institutional improvement.

7.6 Comparison and outlook of various application scenarios

7.6.1 Commonalities of technological issues

Although the application scenarios of geological storage projects vary, they all face a series of common challenges in technological issues. Firstly, the influence of geological conditions on various application scenarios is universal. Whether it is oil and gas storage or carbon dioxide sequestration, complex geological structures such as faults and fractures pose threats to the sealing performance and stability of the storage body. For example, in geological carbon dioxide sequestration, the properties of faults (development location, occurrence, geometric shape) have been proven to be one of the key factors affecting the leakage risk(Yang et al., 2023). Similarly, the strict requirements for site geological conditions in underground nuclear waste disposal also reflect the importance of the geological environment for storage safety.

Secondly, the need for long term monitoring is a common challenge in all application scenarios. Whether it is to ensure the stability of oil and gas reservoirs or to evaluate the long - term effectiveness of carbon dioxide sequestration, high precision and high stability monitoring technologies are required. However, existing technologies are often limited by cost, equipment lifespan, and the accuracy of data collection, making it difficult to meet actual needs.

In addition, the problem of the interaction between fluids and surrounding rocks also appears in multiple scenarios. For example, the chemical components in oil and gas may cause corrosion reactions with reservoir rocks, while the injection of carbon dioxide will change the physical property parameters (such as porosity and permeability) of the reservoir and caprock. These problems all involve complex mechanisms of multiphase flow-rock mechanics coupling.

7.6.2 Differences in technological issues

Although there are common challenges in various application scenarios, their unique scientific and technological issues cannot be ignored. Underground oil and gas storage mainly focuses on the evaluation of the sealing performance and stability of reservoirs, especially on how to accurately predict reservoir behavior under complex geological conditions. In contrast, geological carbon dioxide sequestration places more emphasis on the study of migration patterns and the impact of chemical reactions between carbon dioxide and surrounding rocks on reservoir physical properties.

Underground nuclear waste disposal faces more specific technological challenges, including how to achieve long - term and effective isolation of nuclear waste from the biosphere, and the impact of decay heat on the stability of surrounding rocks and the groundwater environment. The technological issues of underground grain depots mainly center around temperature and humidity control and pest and disease prevention. Solving these problems requires the development of suitable technologies in combination with the unique heat and moisture preservation characteristics of underground spaces.

For underground reservoirs, the application scenarios focus on water resource protection and water level regulation. The sources of groundwater pollution risk are diverse and difficult to predict, and it is quite challenging to precisely regulate the groundwater level. Therefore, the technological issues in different application scenarios show obvious differences, which also determine the uniqueness of research directions in each field.

7.6.3 Outlook on solution directions

In response to the technological issues in various application scenarios of geological storage projects, future research should focus on the following directions: Firstly, research and development of geological condition characterization and modeling technologies should be strengthened to improve the understanding and prediction of complex geological environments. For example, by introducing artificial intelligence and big data analysis technologies, the impact of geological structures on the behavior of storage bodies can be simulated more accurately.

Secondly, innovation in long term monitoring technologies is crucial. Future research should aim to develop low-cost, high-precision sensor networks and combine them with remote monitoring and real time data analysis platforms to enhance the efficiency and reliability of monitoring.

In addition, for the problem of the interaction between fluids and surrounding rocks, it is necessary to further deepen the mechanism research at the molecular level. In particular, the complex process of multiphase flow-rock mechanics coupling should be revealed through a combination of experiments and theories. In terms of specific application scenarios, underground oil and gas storage should focus on overcoming the technical bottlenecks in reservoir sealing performance evaluation; geological carbon dioxide sequestration needs to optimize injection plans and leakage risk control strategies; underground nuclear waste disposal should strengthen research on isolation materials and heat management technologies; underground grain depots should explore green and environmentally friendly pest and disease control methods; and underground reservoirs should improve the technical systems for pollution monitoring and water level regulation. Through the above mentioned multifaceted efforts, it is expected to provide solid technical support for the sustainable development of geological storage projects.

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Conflict of interest

The authors declare no competing interest.

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