IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Energy and Mining Engineering Group are shown in Table 1.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these 12 research fronts, "core materials of high safety and high energy-density batteries", "flexibility improvement of renewable energy power generation and power grid support theory", and "synthesis of ammonia by electrochemical nitrogen reduction in organic system" represent energy and electrical science, technology, and engineering research fronts; "research on spent fuel reprocessing and high-level radioactive material separation process", "research on nuclear waste glass properties", and "interaction mechanism between plasma and reactor materials" represent nuclear science, technology, and engineering research fronts; "3D fracture propagation model for hydraulic fracturing", "hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources", and "intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources" represent geology resources science, technology, and engineering research fronts; "induced mechanism and early warning method of rockburst in deep mining", "mechanism of carbon dioxide flooding recovery-capture and storage of crude oil", and "intelligent identification method for rock properties" represent research fronts of mining science, technology, and engineering.

The annual publication status of the core papers related to each front from 2016 to 2021 is shown in Table 1.1.2.

(1) Core materials of high safety and high energy-density batteries

The emergence of battery technology has changed our lives.

Table 1.1.1 Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Core materials of high safety and high energy-density batteries	177	10 783	60.92	2019.7
2	Research on spent fuel reprocessing and high-level radioactive material separation process	83	3 466	41.76	2017.8
3	3D fracture propagation model for hydraulic fracturing	239	4 020	16.82	2019.0
4	Induced mechanism and early warning method of rockburst in deep mining	214	3 374	15.77	2019.1
5	Flexibility improvement of renewable energy power generation and power grid support theory	188	3 058	16.27	2018.9
6	Synthesis of ammonia by electrochemical nitrogen reduction in organic system	20	930	46.50	2020.0
7	Research on nuclear waste glass properties	145	1 134	7.82	2018.8
8	Interaction mechanism between plasma and reactor materials	391	19 957	51.04	2017.6
9	Hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources	157	2 931	18.67	2019.0
10	Intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources	140	1 884	13.46	2018.7
11	Mechanism of carbon dioxide flooding recovery-capture and storage of crude oil	94	1 618	17.21	2019.0
12	Intelligent identification method for rock properties	119	2 608	21.92	2019.7

Table 1.1.2 Annual number of core papers published for the Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2016	2017	2018	2019	2020	2021
1	Core materials of high safety and high energy-density batteries	7	8	20	31	49	62
2	Research on spent fuel reprocessing and high-level radioactive material separation process	15	20	21	19	8	0
3	3D fracture propagation model for hydraulic fracturing	26	20	45	42	52	54
4	Induced mechanism and early warning method of rockburst in deep mining	21	20	35	37	44	57
5	Flexibility improvement of renewable energy power generation and power grid support theory	18	27	31	43	25	44
6	Synthesis of ammonia by electrochemical nitrogen reduction in organic system	0	0	0	5	9	6
7	Research on nuclear waste glass properties	18	22	24	23	27	31
8	Interaction mechanism between plasma and reactor materials	92	109	78	77	32	3
9	Hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources	22	17	21	21	35	41
10	Intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources	22	15	24	27	22	30
11	Mechanism of carbon dioxide flooding recovery-capture and storage of crude oil	5	16	12	19	24	18
12	Intelligent identification method for rock properties	2	8	15	17	30	47

It is a core component of electronic devices, electric vehicles, and smart grids. The energy density of existing lithium-ion batteries (LIBs) is close to its theoretical value, which is not adapted to the electric vehicle market. Safety issues have also become a significant obstacle hindering the development of battery technology in large-scale applications. Batteries are mainly composed of cathodes, anodes, and electrolytes. The energy density of batteries depends on the electrodes, whereas electrolytes determine their safety. The energy density of an electrode depends on voltage and capacity. To realize high energy- density cathodes, high-voltage cathode materials and high-capacity sulfur materials are being explored; concerning anodes, lithium metal anodes and silicon materials are being researched; finally, regarding electrolytes, solid-state electrolytes are being investigated. Solid-state electrolytes fundamentally solve safety problem of batteries, and they enable the use of high energy-density electrodes. Solid-state electrolytes can be divided into solid polymer electrolytes, solid inorganic electrolytes, and solid composite electrolytes. Solid composite electrolytes, which are actively researched for next-generation batteries, combine the advantages of good processability of polymer electrolytes and high ionic conductivity of inorganic electrolytes.

(2) Research on spent fuel reprocessing and high-level radioactive material separation process

Nuclear fuel reprocessing aims to separate fission products in the spent fuel with chemical treatment methods, recover and purify valuable fissionable substances such as ^{235}U and ^{239}Pu, and remake them into fuel elements for the further use in the nuclear power plant (thermal reactor or fast reactor). This can jointly improve the utilization ratio of nuclear fuel and greatly save uranium resources; it can also extract transuranic elements and fission products required to develop isotopes for application in medical treatment, aerospace, etc. Nuclear fuel reprocessing can be categorized into aqueous reprocessing and non-aqueous reprocessing, based on whether it is carried out in an aqueous medium or not. Aqueous reprocessing refers to the chemical separation and purification processes in aqueous solutions, such as precipitation, solvent extraction, or ion exchange; non-aqueous reprocessing refers to the chemical separation and purification methods in an anhydrous state, such as fluorination volatilization, high-temperature metallurgical treatment, high-temperature chemical treatment, liquid metal process, electrolysis of fused salts. Non-aqueous reprocessing has advantages in the treatment of high burnup spent fuel, especially in the reprocessing of fast reactor spent fuel. Research on “separation/transmutation” and “advanced nuclear fuel recycling” has been internationally conducted. In this case, the separation and recovery of minor actinides (MA) and long-lived fission products (LLFPs) from nuclear waste is a key step. Compared with existing spent fuel reprocessing and disposal methods, the integrated process of spent fuel reprocessing and high-level waste liquid separation is simpler and more economical, produces less secondary waste, and can better meet the separation requirements of advanced nuclear fuel recycling.

(3) 3D fracture propagation model for hydraulic fracturing

Hydraulic fracturing is a reservoir reconstruction technology that communicates natural fractures by pumping high displacement fluid into a formation to generate artificial fractures in the reservoir. Owing to the introduction of idealized assumptions concerning fracture geometry in the fracture height direction, the traditional two-dimensional and quasi-three-dimensional hydraulic-fracturing numerical models cannot describe the propagation process of the actual hydraulic fracturing. In a three-dimensional hydraulic fracturing model, the geometric constraints of the fracture are removed. Consequently, a more practical fracture design scheme can be obtained. At present, three-dimensional hydraulic-fracturing models can be divided into plane three-dimensional models and non-plane three-dimensional models. In a plane three-dimensional model, it is assumed that the hydraulic fracturing can only expand in the original fracture plane, while a non-plane three-dimensional model relaxes this condition and can simulate the non-plane deflection of the hydraulic fracturing. In a three-dimensional hydraulic-fracturing model, the crack propagation mode is more complex, and a mixed propagation mode is often coupled with three basic modes. Therefore, new crack propagation criteria need to be adopted. Hence, the fracture morphology of three-dimensional models is more complex than that of two-dimensional models and requires a new algorithm to accurately capture the crack front and calculate the stress field at the crack tip. In addition, problems addressed by two-dimensional models, such as the influence of in-situ stress, filtration effect, reservoir heterogeneity, and fracturing mode, on the expansion of hydraulic fractures, migration of proppant still need to be further developed in three-dimensional models.

(4) Induced mechanism and early warning method of rockburst in deep mining

Rockburst is a phenomenon in which the elastic deformation potential energy accumulated in rock mass is suddenly and violently released under certain conditions, resulting in rockburst and ejection. It is a serious dynamic disaster. With the increase of mining depth, rockburst in coal mines is becoming increasingly dangerous. Research on the underlying mechanism of rockburst disasters, as well as on monitoring, early warning, and prevention and control technology, is increasingly important for safe coal mining. The main research topics in this field include dynamic response and catastrophe mechanisms of deep coal mine rockburst, intelligent monitoring of early warning theory and technology for the deep coal mine rockburst, and mechanisms and methods for prevention and control of deep coal mine rockburst. Regarding the underlying mechanism of rockburst, a new approach is based on the analysis of the sudden change mechanism of strain energy release of surrounding rock. Concerning rockburst early warning technology, future research lines will be based on integration of artificial intelligence algorithms, such as data mining and big data processing and analysis, to realize intelligent monitoring and early warning of rockburst disasters, and multi-field multi-dimensional perception.

(5) Flexibility improvement of renewable energy power generation and power grid support theory

The development of renewable energy generation, such as wind and solar power, is a promising approach for China to facilitate a clean and low-carbon transition of the energy and power industry and achieve the “30·60” carbon neutrality goal. Different from conventional electricity generators with continuous and controllable power output, the features of renewable generation are strong volatility and weak controllability. This fundamentally changes the physical form and operation mode of power systems. With the rapid development of centralized and distributed renewable generation, as well as the gradual decommissioning of thermal power units, the uncertainty continues to increase in both the generation and consumption sides of power systems, and flexible regulation resources are becoming increasingly scarce. The power supply-demand balance and secure economic operation of power systems are facing unprecedented challenges. It is of utmost importance to investigate the theory and key technologies for flexibility improvement of renewable generation and power grid support, and for improvement of wide-area and efficient integration of a high proportion of renewable generation. Related research topics include mechanisms, operation strategies, and market mechanisms of flexibility balance in power systems; techno-economic analysis of the flexible transformation of thermal generation units and their conversion to regulating units; transient voltage support technology for large-scale wind and solar power generation systems; stability control technology of large-scale wind and solar power generation system; coordinated planning and operation of multi-period and multi-type energy storage technologies; and hierarchical aggregation, coordinated control, and distributed transaction of massive heterogeneous demand-side resources.

(6) Synthesis of ammonia by electrochemical nitrogen reduction in organic system

Ammonia is the second most produced commodity in the world. Motivated by the global shift toward sustainable energy, ammonia synthesis by electrochemical nitrogen reduction reaction (NRR) has attracted wide attention and is regarded as a promising alternative to traditional Haber-Bosch process. The electrochemical NRR can be performed in aqueous and organic systems and the later usually have higher Faradaic efficiency. Among the investigated modes of NRR, a lithium-mediated process in organic electrolytes distinguishes itself by outstanding ammonia yield rate and Faradaic efficiency. The lithium-mediated process takes place in three steps. Electrodeposition of metallic lithium first occurs, and then lithium-nitrogen based compound is produced by spontaneous reaction with reactive lithium. Based on this, the ammonia is formed by the protonation reaction. The performance of organic lithium-mediated systems is directly correlated with characteristics of lithium depositions. The study of lithium-mediated NRR is mainly focused on optimization of electrolytes, including the selection of proton donor, lithium salt, and additive. The highest reported current density and Faradaic efficiency are approximately 1 $A\cdot cm^{-2}$ and 100%, respectively, which are even better than the targets set by the REFUEL program of the US Department of Energy (current density is 0.3 $A\cdot cm^{-2}$; faradaic efficiency is 90%; energy efficiency is 60%). Before practical use, higher energy efficiency and better durability must be accomplished.

(7) Research on nuclear waste glass properties

The safe treatment and disposal of high-level radioactive waste liquid is a common challenge faced by all countries in the world, and it is also one of the key factors restricting the sustainable development of the nuclear industry. Glass solidification is currently the only industrially applied high-level waste liquid treatment method in the world. Glass has a short-range-ordered and long-range-disordered network structure, and most of the nuclides in the periodic table can enter the network of the glass. Therefore, Glass solidification used for treatment of high-level waste liquid have been extensively studied by scholars domestically and abroad, involving aluminosilicate glass, phosphate glass, silicate glass, and borosilicate. Phosphate glass has a relatively low melting temperature and are easy to prepare; however, they are seriously corrosive to other equipment. To date, only Russia has adopted phosphate glass solidification. Silicate glass contains more SiO_2, although it has good anti-leaching performance. However, its solidification process is relatively complicated, and the solidification of high-level waste liquid with high cesium content is poor. Borosilicate glass has the advantages of good stability, simple preparation process, high mechanical strength, and large waste packaging capacity. It has become a solidified material widely used in the treatment of high-level waste liquid. Borosilicate glass is the substrate of choice. The first vitrification plant in China has now entered the operation stage, and research on the solidification behavior and anti-leaching performance of glass solidified bodies is of great significance for the safe production, temporary storage, and disposal of such bodies.

(8) Interaction mechanism between plasma and reactor materials

Controlled fusion energy is the ideal clean energy source of the future. Currently, the most likely method to achieve controlled thermonuclear fusion is magnetic confinement fusion. Solving the material problem of tokamak devices and future reactors is a key issue to realize magnetic-confinement fusion energy. The solution strongly depends on the deep understanding of the processes and mechanisms of plasma-wall interactions (PWIs), which occur mainly in the boundary plasma beyond the outermost closed magnetic surface of the tokamak field, also known as the scrapped-off layer (SOL), and in the region of the plasma-facing material in direct contact with the SOL. PWIs directly determine the operation safety of fusion devices, development process of wall material components, and future wall lifetime. The understanding of the various physical processes and underlying mechanisms of PWIs and their effective control is one of the most important aspects in the realization of future fusion energy. The International Tokamak Physics Activity (ITPA) Working Group on scraped-off layer/divertor (SOL/Div) is dedicated to identifying the PWI issues and coordinating joint efforts at international scale. The results will have important implications for the design, manufacture, and operation of future fusion demonstration plants and commercial reactors. Currently, the main research directions include selection of plasma-facing materials, basic physical processes of boundary plasma, surface damage and structural effects under plasma irradiation, impurities and dust, and wall conditioning. Although a lot of research work on PWI process has been conducted domestically and abroad, there are still many issues to be solved; for example, the data on atomic-molecular processes in boundary plasma are not perfect, and the behavior of particle transport and redeposition is not completely clear. In view of the urgent demand for PWI-related data for national fusion projects and ITER, it is necessary to conduct comprehensive and in-depth basic research on PWIs both domestically and abroad as soon as possible.

(9) Hydrogen-carbon cycle process in deep earth and its relation to oil and gas resources

The long-term hydrogen-carbon cycle in deep earth is closely related to the short-term hydrogen-carbon cycle on the earth's surface. As the "processing plant" of the earth material cycle, the plate subduction zone is a window for understanding the deep earth. However, its internal complexity also restricts the understanding of the "generation, transportation, and accumulation" process of the earth's deep material. The exchange of material and energy between the ocean-sphere, lithosphere, and atmosphere is strengthened in the subduction "plant". Volatile components such as H_2O and CO_2 are brought into the mantle along with crustal sediments in the subduction zone. The products of deep-seated action are recycled into and out of the crust through the magmatic system of island arc volcanoes and rift basins, deep sea, and hydrothermal systems. By clarifying the link and correlation between plate subduction processes, deep geological processes, and inorganic origin oil and gas resources, the dynamics and material energy exchange mechanism across the lithosphere, and the possibility of independent accumulation of inorganic origin oil and gas can be revealed. In the future, the work in this research field will focus on various sedimentary basins in the east of China that are under the influence of the subduction zone. By analyzing the direct or indirect relationships between these basins and deep geological processes, the interaction and dynamic mechanisms between the ocean-sphere, lithosphere, and atmosphere under the framework of the subduction "plant" will be revealed, and the resource effect of material-energy exchange between the lithosphere and asthenosphere will be clarified. Meanwhile, the hydrocarbon cycle process under organic-inorganic interaction between the ocean-sphere, lithosphere, and atmosphere, as well as the enrichment mechanism of inorganic origin oil and gas, and geothermal and other resources under plate subduction background can be clarified. Thus, the evaluation standard of inorganic-origin oil and gas resources and selection method of enrichment area can be established.

(10) Intelligent prospecting and comprehensive quantitative research for continental potash and lithium resources

Terrestrial potassium-lithium salts are formed in a terrestrial sedimentary environment. At present, China's potassium salt resource industry is based on modern terrestrial salt lakes mainly located in the Qaidam basin. Recently, Paleocene-Neogene deep-brine-type terrestrial potassium-lithium salts in western Qaidam have been discovered. The future trend of this type of resource-industry development is to carry out intelligent mineral search and comprehensive quantitative research.

Big data, artificial intelligence, blockchain, and other new technologies will be used to conduct efficient and intelligent collaborative research on key technologies for deep-brine potassium-lithium resources. In particular, new technologies will be applied to achieve deep data mining and multi-dimensional intelligent evaluation of deep-brine potassium-lithium resources. Therefore, it is of great significance to support intelligent mineral search and comprehensive quantitative research on deep-brine potassium-lithium resources and safeguard the national strategic resource security.

The next steps are as follows. First, using potassium and lithium exploration combined with seismic and logging data for oil and gas exploration will allow mapping the distribution of the reservoir brine layer. Second, well investigation and water release tests will be conducted to obtain hydrogeological parameters of the aquifer section, determine the water richness, brine composition, aquifer permeability coefficient (K), specific yield (m), storage coefficient (S), coefficient of recharge from precipitation (a), irrigation infiltration coefficient (b), evaporation limit depth of diving (D), and other key parameters for resource evaluation. Third, core calibration or nuclear magnetic logging will be used to identify original and movable water saturations. Fourth, tectonic and lithium-bearing reservoir phase models will be created to obtain comprehensive well data, seismic data, and various types of results. Fourth, a phase-control and trend-control constraint modeling method, reservoir property model, and the use of intelligent means will be combined to achieve batch-computing quantitative evaluation of potassium and lithium resources.

(11) Mechanism of carbon dioxide flooding recovery-capture and storage of crude oil

Carbon dioxide-enhanced oil recovery with carbon capture and storage technology refers to the injection of captured carbon dioxide into low-permeability reservoirs to achieve carbon dioxide burial and storage while enhancing the recovery of oil. This technology is a win-win solution to help reduce carbon emissions and enhance the production from oil and gas wells, which is of great significance for China to enhance "carbon peaking and carbon neutrality goals". Carbon dioxide flooding technology was first developed in the USA in the early 1950s. By now, the carbon dioxide injection capacity amounts to 68 million tons/year and has become the main method of enhanced recovery in low-permeability and very-low-permeability blocks in the USA. There are abundant low-permeability oil reserves in China that approximately represent half of the total resources. However, the reservoir conditions of the onshore low-permeability reservoirs are complex and feature special crude oil properties. Likewise, existing carbon dioxide flooding technology is complicated. Carbon dioxide capture and transportation incur high cost, and carbon dioxide is difficult to bury, which limits the scale of carbon dioxide flooding storage. Therefore, it is urgent to explore mechanisms of carbon dioxide flooding and carbon capture and storage for the low-permeability reservoirs in China. The main research areas include efficient carbon dioxide capture technology, secure carbon dioxide transport technology, carbon dioxide enhanced oil recovery technology, and efficient carbon dioxide storage mechanism. Understanding of the mechanism of carbon dioxide flooding recovery-capture and storage of crude oil, and accelerating the widespread promotion of carbon dioxide flooding and carbon capture and storage technology in China's onshore low-permeability reservoirs will lead to important contributions to the optimization of energy structures and realization of "carbon peaking and carbon neutrality goals".

(12) Intelligent identification method for rock properties

Rock lithology classification identification is the primary task of underground engineering. This identification is the basis of quantitative analysis of rock engineering geology and an important aspect in geological safety evaluation. The main research areas in lithology identification mainly includes physical methods, such as ultrasonic, rebound index, density, and other physical test methods; mathematical and statistical methods, such as statistics, analysis, and comparison of the main elements of stratum rocks; and lithology intelligent identification methods. These development trends show that intelligent recognition methods are more dependent on sample data, and the generalization ability of models is easily affected when the sample data are insufficient; moreover, the classification error of rock lithology is larger when only a single feature type of the rock is considered, such as image optical features. Therefore, it is also necessary to analyze other physical features or properties of the rock to improve the classification accuracy. Coupling rock image recognition models and rock audio intensity regression models achieves rapid recognition of rock lithology and effectively improves the generalization ability and accuracy of models. Combined with the recognition results of comparative expert methods, it assists engineers to make the correct classification of rock properties.

1.2 Interpretations for four key engineering research fronts

1.2.1 Core materials of high safety and high energy-density batteries

Safety and energy density are two obstacles hindering the development of the battery industry. Batteries are mainly composed of cathodes, anodes, and electrolytes. The energy density of batteries depends on the electrodes, and electrolytes determine the safety of batteries. LIBs, the most extensively employed battery system, are essentially a rocking-chair battery in which lithium ions are intercalated back and forth between the positive and negative electrodes. As early as 1990, Sony Company commercialized the first LIBs. The development of batteries has shaped our lives. It is a core component of electronic devices, electric vehicles, and smart grids. The most widely used anodes of LIBs are graphite and lithium titanate. Carbonate electrolytes are typically employed, and the positive electrodes are oxides such as lithium iron phosphate, lithium cobalt oxide, and lithium nickel cobalt manganese oxide.

The energy density of electrodes is determined by voltage and capacity. The main research areas in high energy-density cathodes are high-voltage cathode materials and high-capacity sulfur materials; in anodes, the main research areas are lithium metal anodes and silicon materials. High-voltage cathode materials include lithium-rich manganese-based cathodes, lithium nickel manganese oxides, and high-voltage lithium cobalt oxides; high-capacity cathode materials are mainly sulfur cathodes. The cost of cathode materials accounts for more than 40% of the total cost of batteries. Ideal cathode materials featuring both high capacity and high voltage still need to be explored. Lithium-metal and silicon anodes have been extensively studied both in academia and industry in recent years. However, dendrite problems for lithium-metal anodes and long-cycling problems for silicon anodes at large scale hinder their commercialization. A possible tradeoff involves the use of Si/C composite anodes. Besides, the overall capacity of Si/C composite anodes can be improved by adding a certain proportion of silicon material.

The main research area in electrolytes is the development of solid-state electrolytes. These electrolytes can fundamentally solve the safety problem of batteries. In addition, they enable the use of high energy-density electrodes. Solid-state electrolytes can be categorized into solid polymer electrolytes, solid inorganic electrolytes, and solid composite electrolytes. On the one hand, solid polymer electrolytes have good processing ability, wide electrochemical window, and excellent stability. On the other hand, they are severely impeded by their limited ionic conductivity and transference number at room temperature. The ionic conductivities of inorganic solid electrolytes have reached values close to those of liquid electrolytes, but their poor stability and huge interfacial impedance with electrode materials seriously hinder their application. Composite solid electrolytes combine the advantages of polymer electrolytes and inorganic electrolytes. They are expected to achieve a breakthrough in the technology of all-solid-state battery industry if the solid interface between electrolytes and electrodes and the active loading of electrodes can be improved.

In the engineering research front of “core materials of high safety and high energy-density batteries”, the top three countries in terms of the number of core papers published (Table 1.2.1) are China, the USA, and Germany, all of which have been cited more than 60 times. Among the Top 10 countries with the most published papers, the

Table 1.2.1 Countries with the greatest output of core papers on “core materials of high safety and high energy-density batteries”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	154	87.01	9 718	63.10	2019.6
2	USA	18	10.17	1 673	92.94	2019.3
3	Germany	10	5.65	1 183	118.30	2019.3
4	Australia	9	5.08	805	89.44	2019.7
5	Canada	8	4.52	984	123.00	2019.4
6	Singapore	5	2.82	410	82.00	2019.6
7	South Korea	5	2.82	152	30.40	2019.8
8	Japan	5	2.82	63	12.60	2020.4
9	Spain	2	1.13	676	338.00	2018.5
10	Saudi Arabia	2	1.13	65	32.50	2021.0

USA and China have more cooperation, followed by China and Australia (Figure 1.2.1). The institutions that produce a large number of core papers include Chinese Academy of Sciences, Central South University, and Huazhong University of Science and Technology (Table 1.2.2). Among these 10 institutions, Chinese Academy of Sciences has more cooperation with the Tsinghua University (Figure 1.2.2). In the amount of citing core papers, the top three countries are China, the USA, and South Korea (Table 1.2.3). The main output institutions of citing core papers are Chinese Academy of Sciences, Zhengzhou University, and Central South University (Table 1.2.4).

Material innovation is indispensable for new developments in the battery industry. Concerning lithium batteries, cathode materials will evolve from high-voltage cathode materials to low-cost high-capacity sulfur cathodes, and anode materials will evolve from Si/C composite anodes to pure silicon anodes and finally to lithium metal anodes. Electrolytes will evolve from solid composite electrolytes to all-solid-state inorganic electrolytes. Terminal all-solid-state high-voltage lithium metal batteries or lithium-sulfur batteries are expected to be used in electronic devices, electric vehicles, and smart grids. Figure 1.2.3 shows the roadmap of the engineering research front of “core materials of high safety and high energy-density batteries”.

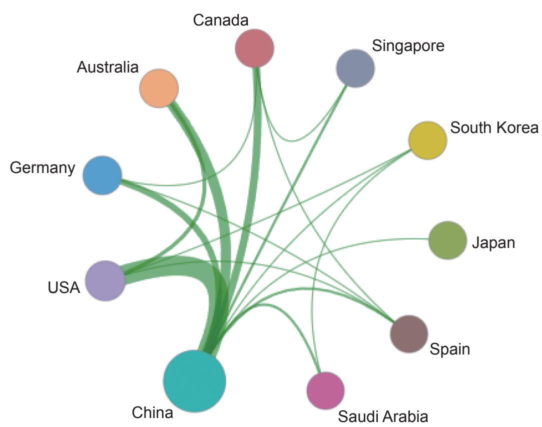

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “core materials of high-safety and high energy-density batteries”

Table 1.2.2 Institutions with the greatest output of core papers on “core materials of high safety and high energy-density batteries”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	26	14.69	1 639	63.04	2019.1
2	Central South University	10	5.65	109	10.90	2020.9
3	Huazhong University of Science and Technology	9	5.08	349	38.78	2019.0
4	Beijing Institute of Technology	8	4.52	328	41.00	2019.8
5	Tsinghua University	6	3.39	916	152.67	2019.5
6	The Hong Kong Polytechnic University	6	3.39	531	88.50	2019.3
7	Wuhan University of Technology	6	3.39	460	76.67	2018.8
8	Zhengzhou University	6	3.39	215	35.83	2020.7
9	Fudan University	5	2.82	2 759	551.80	2017.6
10	Nankai University	5	2.82	618	123.60	2019.2

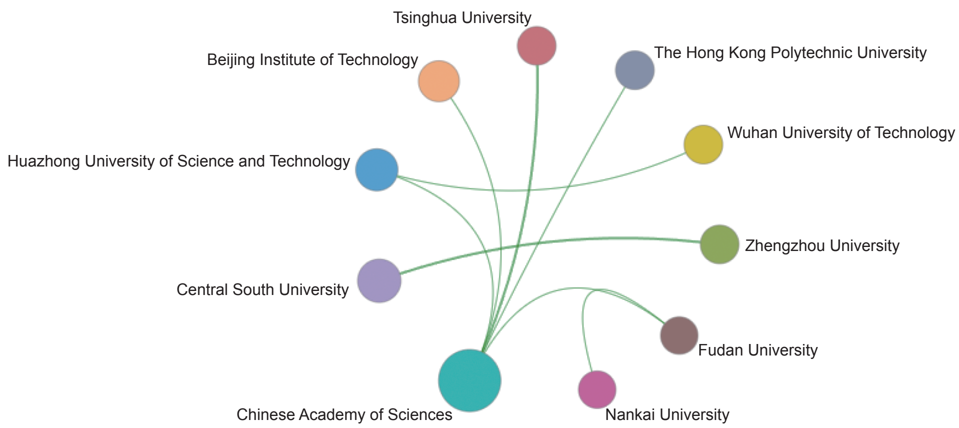

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “core materials of high safety and high energy-density batteries”

Table 1.2.3 Countries with the greatest output of citing papers on “core materials of high safety and high energy-density batteries”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	6 177	63.87	2020.1
2	USA	866	8.95	2020.1
3	South Korea	498	5.15	2020.3
4	India	408	4.22	2020.2
5	Australia	385	3.98	2020.1
6	Germany	377	3.90	2020.3
7	Japan	233	2.41	2020.1
8	Singapore	221	2.29	2020.1
9	UK	213	2.20	2020.3
10	Canada	178	1.84	2020.1

Table 1.2.4 Institutions with the greatest output of citing papers on “core materials of high safety and high energy-density batteries”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	742	29.22	2020.2
2	Zhengzhou University	244	9.61	2020.3
3	Central South University	241	9.49	2020.6
4	Tsinghua University	204	8.03	2020.2
5	University of Science and Technology of China	191	7.52	2020.2
6	Nankai University	184	7.25	2020.2
7	City University of Hong Kong	161	6.34	2020.2
8	Huazhong University of Science and Technology	161	6.34	2020.0
9	Tianjin University	150	5.91	2020.2
10	Beijing Institute of Technology	135	5.32	2020.4

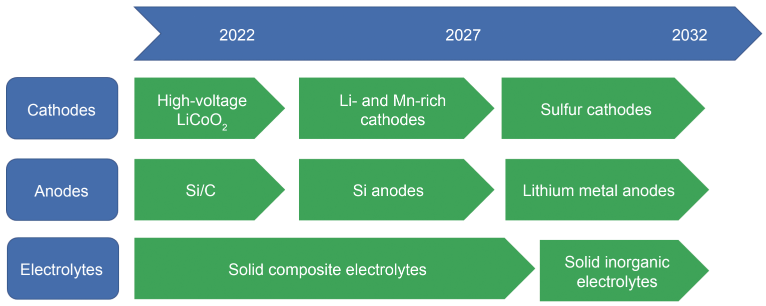

Figure 1.2.3 Roadmap of the engineering research front of “core materials of high safety and high energy-density batteries”

1.2.2 Research on spent fuel reprocessing and high-level radioactive material separation process

(1) Spent nuclear fuel reprocessing research

World-wide industrial-scale spent fuel reprocessing has a history of more than 40 years. A total of 17 countries have developed spent fuel reprocessing and built 32 reprocessing plants, including intermediate and experimental devices. The total reprocessing capacity is approximately 4 800 tons/year. Britain and France are the world leaders in terms of large-scale commercial spent fuel reprocessing.

The development of spent fuel reprocessing in China has gone through two stages: production reactor reprocessing and power reactor reprocessing. This development has been basically determined by the three-stage idea of “pilot scale–demonstration scale–large commercial scale”. The successful thermal commissioning and operation of the pilot plant shows that China has mastered the core technology of power-reactor spent fuel reprocessing, which is a milestone. The reprocessing industrial demonstration plant is expected to be completed in 2023, when China will have industrial-scale spent fuel reprocessing capability. China will complete the technology integration during the “14th Five-Year Plan” period. As a whole, it will have the ability to independently design and build large-scale post-processing plants.

In terms of technology development trends, spent fuel reprocessing methods can be categorized into two types: aqueous reprocessing and non-aqueous reprocessing, according to the state of the spent fuel being processed in the main stage. Aqueous reprocessing is mostly based on the PUREX process, whereas non-aqueous reprocessing uses electrolytic melting of halogen salts to separate fissionable material and fission products. Considering the differences in the spent fuel reprocessing objects and improvement in fuel consumption, the mainstream development directions of aqueous reprocessing are as follows. First, improving the separation efficiency of U and Pu, strengthening the separation of Np and Tc, and improving and strengthening the control of ^{14}C and ^{129}I radioactive gas emissions. Second, to reduce the toxicity and volume of the final radioactive waste, MA and LLFP require “separation/transmutation”. In addition to the improvement of the conventional spent fuel reprocessing—PUREX process, the concept of “advanced spent fuel reprocessing” has been proposed internationally in terms of the “separation/transmutation” of MA and LLFP. It includes separation-based and transmutation-based spent fuel reprocessing technologies. Concerning fast reactor and accelerator technology, separation can be realized through two schemes, namely “total separation” and “spent fuel reprocessing—high-level waste liquid separation”. In addition, the design concept, key equipment, instrument control, waste management, nuclear safety, and other aspects of reprocessing plants are constantly improving and developing.

Non-aqueous reprocessing mainly includes halogenated volatilization, pyrometallurgy, and electrolytic refining. Electrodeposition and electrolytic refining are generally considered to be the most promising, feasible, economical, and reliable non-aqueous reprocessing technologies. As such, they have been widely studied internationally. At present, most countries are still in the laboratory research stage in terms of non-aqueous reprocessing. Only the USA has completed laboratory-scale and engineering-scale simulation experiments, and is preparing for pilot-scale thermal experiments.

(2) Research on separation of high-level waste liquid

The USA, France, Russia, Japan, and China have proposed their own high-level waste liquid separation processes. In the 1990s, Russia built a pilot-scale facility (UE-35) for separation of high-level radioactive waste using CCD-PEG (chlorinated cobalt dicarbollide and polyethylene glycol) in Mayak to recover Sr and Cs from high-salt waste liquid. At present, only the USA has completed research on high-level waste liquid separation technology from laboratory to engineering scale. The high-level waste liquid separation plant was built at the Savannah River National Laboratory, and over 4 000 cubic meters of high-level waste liquid have been treated there by June 2016.

Since the 1980s, Tsinghua University in China has conducted research on the separation technology of high-level radioactive waste liquid, and proposed a separation process with independent intellectual property rights. At present, experimental research on the separation of high-level waste liquid of power reactor is being carried out, setting a solid foundation for thermal verification and application of high-level waste liquid separation technology, and meeting the conditions for engineering applications.

Concerning technology development trends, the separation process of transuranic elements (TRU) includes American TRUEX-TALSPEAK (Transuranic Extraction Process-Trivalent Actinide Lanthanide Separation by Phosphorous reagent Extraction from Aqueous Komplexe) and its improved process, American ALSEP (Actinide Lanthanide Separation Process) process, French DIAMEX-SANEX (DIAMide Extraction-Selective Actinide Extraction) process, European GANEX (Group Actinide Extraction) process, Japanese ARTIST (Amide-based Radio-Resources Treatment with Interim Storage of Transuranics) process, and Russian dibutyl zirconium phosphate extraction process. The Sr and Cs separation process includes the Russian CCD-PEG process, French CSSEX process, American FPEX (Fission Product Extraction) process, and Japanese extraction chromatography process.

In China, the trialkylphosphine oxide (TRPO) process for separating actinides, crown ether process for separating strontium, and calixarene crown ether process for separating cesium have been proposed. At present, China has basically completed research on the separation process and equipment of high-level waste liquid, and is investigating on thermal experimental verification of the separation process of high-level waste liquid in power reactors. China aims to master the engineering technology by 2030 and then realize industrial applications of high-level waste liquid separation.

As shown in Table 1.2.5, the top four countries in terms of the number of core papers published on this research topic are China, the USA, the UK, and Germany. Among them, China occupies the first place, with more than 30%. The USA, the UK, and Germany exceed 10%. It can be seen from Table 1.2.6 that the top six institutions in terms of the number of core papers on this research topic are the Chinese Academy of Sciences, The University of Manchester, Sichuan University, Forschungszentrum Julich, National Nuclear Energy Laboratory, and Eidgenössische Technische Hochschule Zürich.

As shown in Figure 1.2.4, China, the USA, Japan, Germany, the UK, France, and Spain pay more attention to cooperation among countries in this field. The number of published papers in the USA is relatively large, mainly in cooperation with China, France, Germany, the UK, and Japan. As shown in Figure 1.2.5,

Table 1.2.5 Countries with the greatest output of core papers on "research on spent fuel reprocessing and high-level radioactive material separation process"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	25	30.12	1 067	42.68	2017.8
2	USA	14	16.87	800	57.14	2017.6
3	UK	12	14.46	459	38.25	2017.8
4	Germany	10	12.05	348	34.80	2017.7
5	Spain	8	9.64	512	64.00	2017.0
6	France	7	8.43	373	53.29	2018.1
7	Japan	6	7.23	354	59.00	2017.7
8	India	4	4.82	136	34.00	2018.8
9	Canada	4	4.82	133	33.25	2017.8
10	Switzerland	4	4.82	124	31.00	2019.5

Table 1.2.6 Institutions with the greatest output of core papers on “research on spent fuel reprocessing and high-level radioactive material separation process”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	5	6.02	168	33.60	2018.0
2	The University of Manchester	4	4.82	104	26.00	2018.0
3	Sichuan University	3	3.61	136	45.33	2017.3
4	Forschungszentrum Julich	3	3.61	134	44.67	2018.3
5	National Nuclear Laboratory	3	3.61	129	43.00	2018.3
6	Eidgenössische Technische Hochschule Zürich	3	3.61	98	32.67	2019.3
7	University of Texas at Austin	2	2.41	229	114.50	2018.0
8	Hokkaido University	2	2.41	147	73.50	2017.5
9	Japan Science and Technology Agency	2	2.41	147	73.50	2017.5
10	Massachusetts Institute of Technology	2	2.41	121	60.50	2017.5

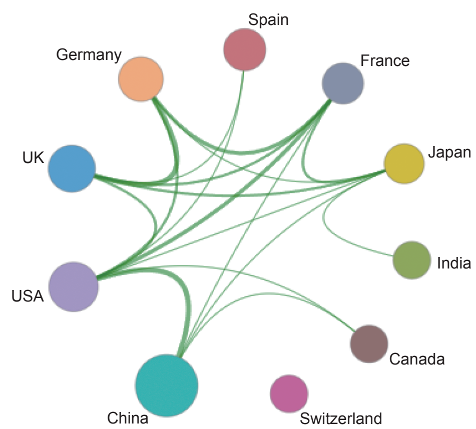

Figure 1.2.4 Collaboration network among major countries in the engineering research front of “research on spent fuel reprocessing and high-level radioactive material separation process”

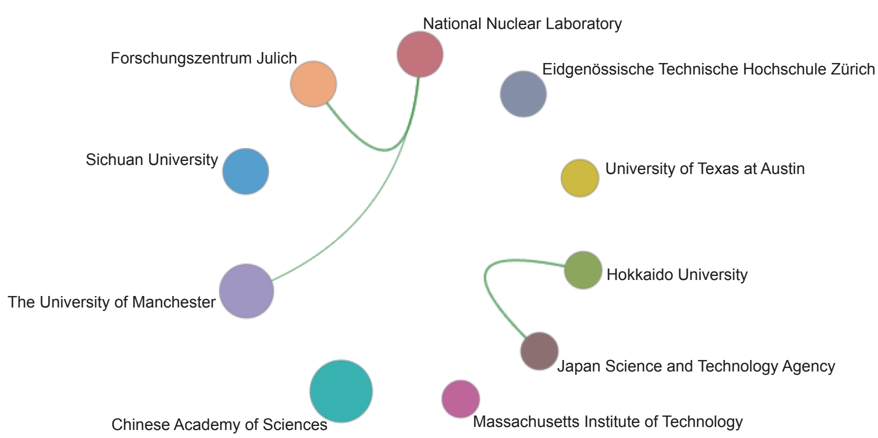

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “research on spent fuel reprocessing and high-level radioactive material separation process”

The University of Manchester, Forschungszentrum Julich, and National Nuclear Energy Laboratory also cooperate.

Table 1.2.7 shows that China, which is the main output country, accounts for 32.28%, whereas the USA accounts for 20.47%. As shown in Table 1.2.8, the institutions with the main output of citing papers are Chinese Academy of Sciences, Chongqing University, Qingdao University of Science and Technology, Tsinghua University, University of New South Wales, University of Texas at Austin, and Shandong University of Science and Technology. Among them, Chinese Academy of Sciences, Chongqing University, and Qingdao University of Science and Technology all account for more than 10% on average.

From the above data analysis, it can be concluded that China and the USA are at the forefront of the world in the number of core papers on "research on spent fuel reprocessing and high-level radioactive material separation process", and the number of the output of citing core papers by institutions in China is relatively large.

With different reprocessing objects and the improvement of fuel burnup, the mainstream development direction of aqueous reprocessing is to strengthen the separation of Np and Tc on the basis of improving the separation efficiency of U and Pu. To reduce the toxicity and volume of the final radioactive waste, it is necessary to perform "separation/ transformation" on MA and LLFP. Separation technology can be realized through two schemes, namely "total separation" and "spent fuel reprocessing—high-level waste

Table 1.2.7 Countries with the greatest output of citing papers on "research on spent fuel reprocessing and high-level radioactive material separation process"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	123	32.28	2019.2
2	USA	78	20.47	2018.8
3	Australia	31	8.14	2018.9
4	France	24	6.30	2018.8
5	Germany	24	6.30	2018.8
6	Italy	21	5.51	2019.0
7	Spain	20	5.25	2018.6
8	UK	19	4.99	2018.8
9	India	19	4.99	2018.7
10	Japan	12	3.15	2018.5

Table 1.2.8 Institutions with the greatest output of citing papers on "research on spent fuel reprocessing and high-level radioactive material separation process"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	11	12.94	2018.7
2	Chongqing University	9	10.59	2019.0
3	Qingdao University of Science and Technology	9	10.59	2018.9
4	Tsinghua University	8	9.41	2018.5
5	University of New South Wales	8	9.41	2019.0
6	University of Texas at Austin	8	9.41	2018.6
7	Shandong University of Science and Technology	8	9.41	2019.0
8	Consejo Superior de Investigaciones Científicas	6	7.06	2018.5
9	Massachusetts Institute of Technology	6	7.06	2018.3
10	The Hong Kong Polytechnic University	6	7.06	2019.3

liquid separation". Most countries are still in the laboratory research stage in terms of non-aqueous reprocessing. Only the USA has completed laboratory-scale and engineering-scale simulation experiments, and is preparing for pilot-scale thermal experiments. By 2025, the spent fuel reprocessing industrial demonstration plant will be completed and put into stable operation, conduct special work on reprocessing scientific research, and have the ability to independently build large reprocessing plants. By 2030, the objectives are to carry out further pilot-scale thermal verification of the high-level waste liquid separation process and master the engineering technology. By 2035, the objectives are to realize special scientific research technology of spent fuel reprocessing and master the core technology of large-scale spent fuel reprocessing plants. China will independently construct a large-scale reprocessing plant. By 2050, research on advanced aqueous reprocessing technology will be conducted, verification of non-aqueous reprocessing technology and demonstration of non-aqueous reprocessing projects will be realized, and advanced and complete reprocessing process and radioactive waste treatment along with disposal technologies and industries will be established. Figure 1.2.6 shows the roadmap of the engineering research front of "research on spent fuel reprocessing and high-level radioactive material separation process".

1.2.3 3D fracture propagation model for hydraulic fracturing

Since the 1950s, research on fracture propagation models for hydraulic fracturing has been conducted both analytically and numerically. PKN (Perkins-Kern-Nordgren), KGD (Khristianovic-Geertsma-de Klerk), and Penny are three classical hydraulic fracturing models that were developed in early stages. In the 1980s, with the progress of computational solid mechanics technology, fracture propagation models that consider the phase change of fracturing fluid and reservoir heat exchange were gradually developed. In 1983, Cleary established a 3D fracture propagation model for hydraulic fracturing that included singular integral equations to describe the deformation of rock, and finite element methods to simulate the fluid flow in the fracture. This model is used to analyze the effect of stress difference and bedding on fracture propagation and can be directly used in fracture design. Several researchers, including Settari, Hongren Gu, and Donsov, have developed various 3D fracture propagation models for hydraulic fracturing that account for proppant, heat transfer, and fracturing fluid compressibility using finite differences, a finite element mesh, and implicit level set algorithms. The research objective is to closely combine the characteristics and actual conditions of hydraulic fracturing, achieve a comprehensive description of hydraulic fracture geometry, and master the law of hydraulic fracturing. Many countries around the world have conducted extensive research on 3D fracture propagation model for hydraulic fracturing. In particular, China and the USA have made the most remarkable efforts and published most of the core papers. Statistical data (Table 1.2.9 and Figure 1.2.7) show that China and the USA are the countries that pay most attention to the research on 3D fracture propagation model of hydraulic fracturing and produce most relevant core papers. Chinese core papers amount to 143, accounting for 59.83% of the total number of papers, whereas American papers amount to 90, accounting for 37.66%. Together, both countries account for 97.49% of the global production. The main institutions in terms of core papers related to 3D fracture propagation model for hydraulic fracturing also comprise mostly universities and research centers in China and the USA. The data (Table 1.2.10 and Figure 1.2.8) show that there are 6 Chinese universities and 3 American universities in the Top 10. Among them, China

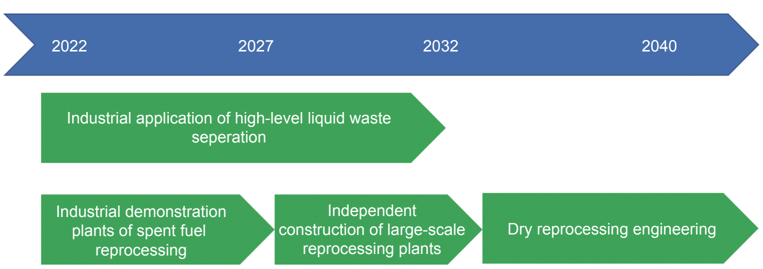

Figure 1.2.6 Roadmap of the engineering research front of "research on spent fuel reprocessing and high-level radioactive material separation process"

Table 1.2.9 Countries with the greatest output of core papers on "3D fracture propagation model for hydraulic fracturing"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	143	59.83	2 128	14.88	2019.3
2	USA	90	37.66	2 151	23.90	2018.6
3	Canada	18	7.53	160	8.89	2019.2
4	Australia	14	5.86	331	23.64	2018.9
5	Germany	11	4.60	580	52.73	2018.8
6	Russia	7	2.93	19	2.71	2018.6
7	UK	6	2.51	65	10.83	2019.5
8	Vietnam	4	1.67	369	92.25	2019.2
9	France	4	1.67	92	23.00	2017.8
10	Switzerland	3	1.26	204	68.00	2019.0

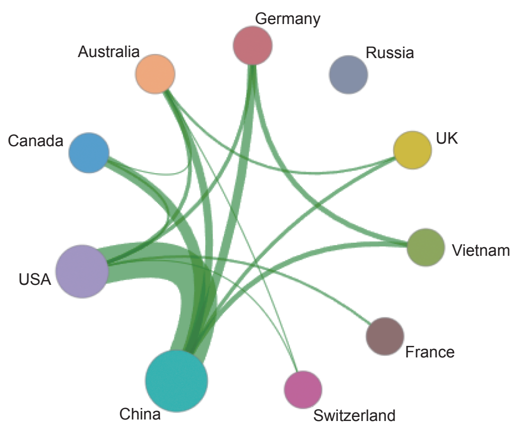

Figure 1.2.7 Collaboration network among major countries in the engineering research front of "3D fracture propagation model for hydraulic fracturing"

Table 1.2.10 Institutions with the greatest output of core papers on "3D fracture propagation model for hydraulic fracturing"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Petroleum	32	13.39	432	13.50	2019.3
2	Southwest Petroleum University	28	11.72	281	10.04	2019.2
3	Texas A&M University	22	9.21	456	20.73	2019.4
4	University of Texas at Austin	20	8.37	869	43.45	2017.6
5	China University of Petroleum East China	12	5.02	160	13.33	2019.2
6	University of Oklahoma	10	4.18	135	13.50	2019.1
7	Chongqing University	10	4.18	76	7.60	2019.5
8	Tongji University	8	3.35	431	53.88	2019.2
9	China University of Mining & Technology	8	3.35	167	20.88	2019.2
10	Commonwealth Scientific and Industrial Research Organisation Energy Centre	7	2.93	228	32.57	2018.6

University of Petroleum (Beijing) has 32 papers, accounting for 13.39% of the total number of papers, and Texas A&M University has 22 papers, accounting for 9.21% of the total number of papers. These are the institutions that present the largest production of core papers in China and the USA. Likewise, China and the USA are also the countries producing most citing papers on 3D fracture propagation model for hydraulic fracturing (Tables 1.2.11 and 1.2.12). Chinese citing papers amount to 1 676, accounting for 55.77%, while the citing papers from USA are 617, accounting for 20.53%. Together, both countries account for 76.3% of the global production. Among the Top 10 universities, 8 are from China and 2 from the USA. The above data clearly demonstrate that China and the USA pay attention to 3D hydrofracture propagation model as a cutting-edge engineering research topic.

Domestic research on 3D fracture propagation model for hydraulic fracturing started earlier. To date, different studies have revealed factors that influence models. A large amount of simulations has been realized using tools such as the ABAQUS large calculation software. However, the development speed is notably slow, mainly because 3D fracture propagation model for hydraulic fracturing involves coupling several complex problems. Strong knowledge of mathematics and mechanics related to coupling is required. In the next 5 to 10 years, 3D fracture propagation model research will still be focused on the mechanisms underlying influence factors such as proppant, heat transfer, fluid compressibility, three-phase flow, and hydraulic and natural fractures. Verification of 3D fracture propagation model by a large number of physical simulation experiments will be required. After ensuring the accuracy of model prediction and achieving reliable high-

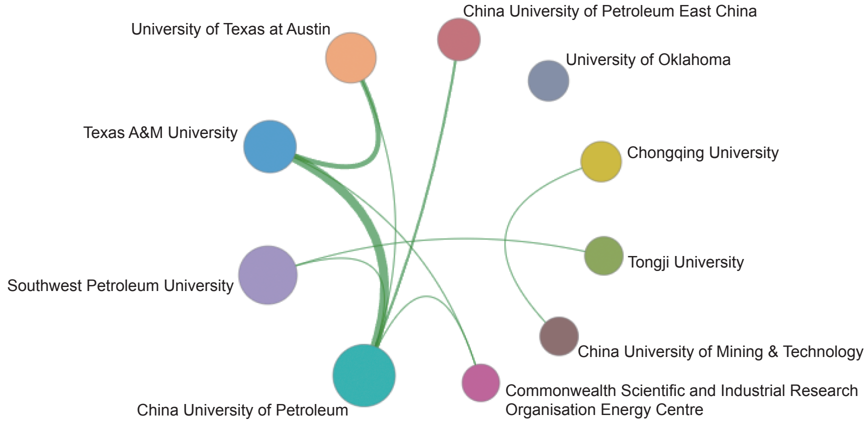

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “3D fracture propagation model for hydraulic fracturing”

Table 1.2.11 Countries with the greatest output of citing papers on “3D fracture propagation model for hydraulic fracturing”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 676	55.77	2020.0
2	USA	617	20.53	2019.7
3	Canada	136	4.53	2019.9
4	Australia	134	4.46	2019.8
5	Germany	104	3.46	2020.0
6	UK	95	3.16	2019.9
7	Iran	60	2.00	2019.9
8	Russia	58	1.93	2019.9
9	France	51	1.70	2019.6
10	India	38	1.26	2020.1

performance computer and software, multi-factor coupled model software will be developed to carry out high-precision 3D hydraulic pressure fracture prediction, setting a theoretical basis for hydraulic fracturing technology transformation. Figure 1.2.9 shows the roadmap of the engineering research front of "3D fracture propagation model for hydraulic fracturing".

1.2.4 Induced mechanism and early warning method of rockburst in deep mining

Rockburst is a phenomenon in which the elastic deformation potential energy accumulated in rock mass is suddenly and violently released under certain conditions, resulting in rockburst and ejection. It is a serious dynamic disaster. With the increase of mining depth, rockburst in coal mines is becoming increasingly dangerous. Research on the mechanism of rockburst disaster, monitoring, early warning and prevention, and control technology is increasingly important for safe coal mining.

At present, among the main coal-producing countries in the world, China faces the most deep mining conditions, and the most serious potential harm from rockburst. To improve the monitoring, early warning, and control level of rockburst, China has conducted extensive scientific research on the induced mechanism and early warning methods of rockburst in deep mining. The country with the highest output of core papers in this field is China, which has produced 78.5% of the core papers, followed by Canada and Australia (Table 1.2.13). Portugal has the highest citation frequency with 35.67 times (Table 1.2.13). Institutions with high output of core papers are mainly Chinese universities, among which China University of Mining and Technology, Shandong University of Science and Technology and University of Science and Technology Beijing occupy the top three in the output of core papers in this field (Table 1.2.14). Among the countries with greatest paper output, China and Australia have more cooperation, followed by China and Canada, China and the USA (Figure 1.2.10). Among the institutions, China University of Mining and Technology and Shandong University of Science and Technology, University of Science and Technology Beijing and North China Institute of Science and Technology have the closest cooperation (Figure 1.2.11). The top two countries with greatest output of cited core papers are China and

Table 1.2.12 Institutions with the greatest output of citing papers on "3D fracture propagation model for hydraulic fracturing"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Petroleum	314	22.57	2020.0
2	Southwest Petroleum University	198	14.23	2019.8
3	China University of Petroleum East China	139	9.99	2019.9
4	China University of Mining & Technology	138	9.92	2020.0
5	Chinese Academy of Sciences	116	8.34	2020.1
6	University of Texas at Austin	101	7.26	2019.2
7	Chongqing University	97	6.97	2020.1
8	Texas A&M University	95	6.83	2019.7
9	China University of Geosciences	73	5.25	2020.0
10	Tongji University	61	4.39	2020.0

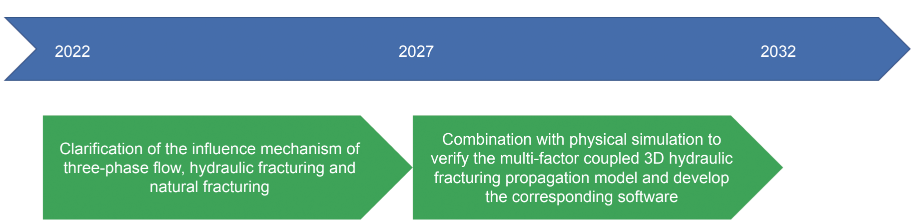

Figure 1.2.9 Roadmap of the engineering research front of "3D fracture propagation model for hydraulic fracturing"

Table 1.2.13 Countries with the greatest output of core papers on "induced mechanism and early warning method of rockburst in deep mining"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	168	78.50	2 860	17.02	2019.2
2	Canada	21	9.81	516	24.57	2018.5
3	Australia	18	8.41	486	27.00	2019.1
4	USA	12	5.61	153	12.75	2018.8
5	Poland	11	5.14	82	7.45	2018.9
6	Czech Republic	9	4.21	117	13.00	2018.0
7	Russia	6	2.80	16	2.67	2017.7
8	South Africa	4	1.87	27	6.75	2018.8
9	Portugal	3	1.40	107	35.67	2018.0
10	Japan	3	1.40	32	10.67	2019.3

Table 1.2.14 Institutions with the greatest output of core papers on "induced mechanism and early warning method of rockburst in deep mining"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Mining and Technology	43	20.09	720	16.74	2018.7
2	Shandong University of Science and Technology	28	13.08	536	19.14	2019.0
3	University of Science and Technology Beijing	21	9.81	230	10.95	2019.3
4	Central South University	10	4.67	322	32.20	2019.9
5	North China Institute of Science and Technology	10	4.67	153	15.30	2019.4
6	Anhui University of Science and Technology	10	4.67	92	9.20	2020.0
7	China University of Mining and Technology-Beijing	9	4.21	147	16.33	2019.6
8	Xi'an University of Science and Technology	9	4.21	58	6.44	2020.1
9	Chinese Academy of Sciences	8	3.74	112	14.00	2019.4
10	Czech Academy of Sciences	7	3.27	109	15.57	2018.3

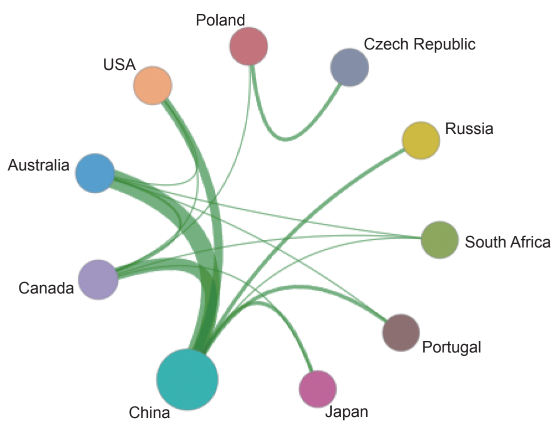

Figure 1.2.10 Collaboration network among major countries in the engineering research front of "induced mechanism and early warning method of rockburst in deep mining"

Australia, accounting for over 80%; the average citation year is 2020 (Table 1.2.15). The top three institutions with greatest output of cited core papers are China University of Mining and Technology, Central South University, and Shandong University of Science and Technology, accounting for 53.07% (Table 1.2.16).

Concerning the occurrence mechanism and prevention technology of rockburst, current research mainly focuses on the dynamic response and catastrophe mechanism of deep coal mine rockburst, intelligent monitoring and early warning theory and technology of deep coal mine rockburst, and prevention and control mechanism and method of deep coal mine rockburst. Regarding the mechanism of rockburst, a recent breakthrough is the study of the mechanism of rockburst by analyzing the sudden change of strain energy release of surrounding rock. With respect to research directions of rockburst early warning technology, artificial intelligence algorithms, such as data mining and big data processing and analysis, are being integrated to realize intelligent monitoring and early warning of rockburst disasters and multi-field multi-dimensional perception. Conducting in-depth research and making breakthroughs in the field of induced mechanism and early warning methods of rockburst in deep mining will help to release deep mineral resources and fulfill the objective of realizing sustainable development of energy and resources in the future. Figure 1.2.12 shows the roadmap of the engineering research front of "induced mechanism and early warning method of rockburst in deep mining".

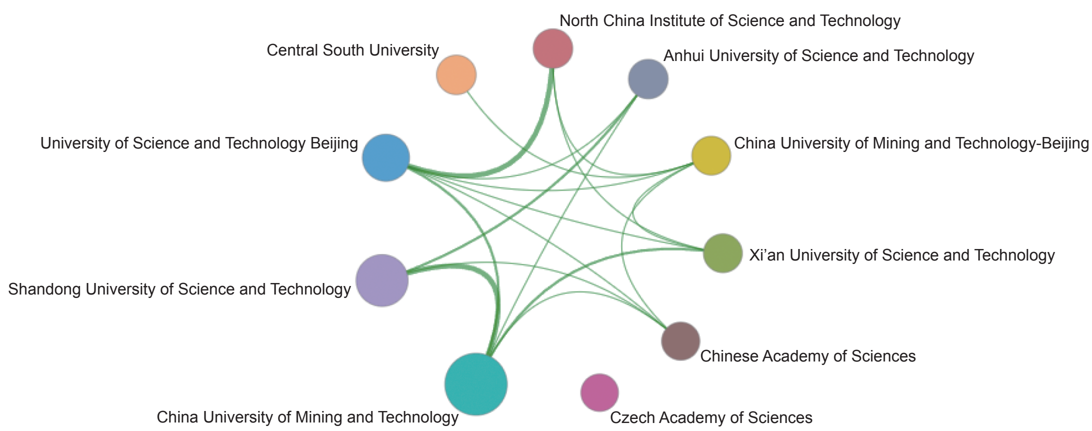

Figure 1.2.11 Collaboration network among major institutions in the engineering research front of "induced mechanism and early warning method of rockburst in deep mining"

Table 1.2.15 Countries with the greatest output of citing papers on "induced mechanism and early warning method of rockburst in deep mining"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 073	74.49	2020.2
2	Australia	164	5.89	2020.1
3	Canada	102	3.67	2019.9
4	USA	101	3.63	2019.9
5	Iran	73	2.62	2020.2
6	Vietnam	62	2.23	2020.5
7	Poland	59	2.12	2020.3
8	UK	42	1.51	2020.0
9	Russia	41	1.47	2020.2
10	Malaysia	37	1.33	2020.4

Table 1.2.16 Institutions with the greatest output of citing papers on "induced mechanism and early warning method of rockburst in deep mining"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Mining and Technology	469	25.93	2019.9
2	Central South University	265	14.65	2020.4
3	Shandong University of Science and Technology	226	12.49	2019.9
4	Chongqing University	145	8.02	2020.0
5	China University of Mining and Technology-Beijing	130	7.19	2020.3
6	University of Science and Technology Beijing	122	6.74	2020.1
7	Henan Polytechnic University	101	5.58	2020.3
8	Northeastern University	97	5.36	2020.3
9	Anhui University of Science and Technology	94	5.20	2020.4
10	Chinese Academy of Sciences	85	4.70	2020.0

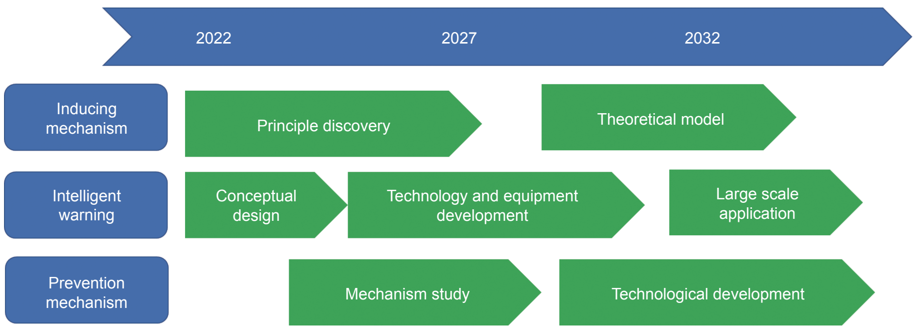

Figure 1.2.12 Roadmap of the engineering research front of "induced mechanism and early warning method of rockburst in deep mining"

2 Engineering development fronts

2.1 Trends in Top 12 engineering development fronts

The Top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 2.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these 12 engineering development fronts, "large scale wind solar complementary power generation and stable grid connection technology", " fast and flexible peak shaving technology for coal-fired units", and "ammonia-fuelled engine technology" represent the engineering development front of energy and electrical science; "multipurpose new concept micro nuclear reactor", "technical system for high-level radioactive waste repository and disposal", and "tritium production technology by nuclear fusion" represent the engineering development front of nuclear science, technology, and engineering; "high precision prediction system for shale oil and gas production capacity", "high-precision intelligent 3D visual exploration system", and "intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources" represent the engineering development front of geology resources science, technology, and engineering; "research and development of looking-around and looking-ahead while-drilling technology", "research and development of efficient fracturing technology for shale reservoirs", and "coal mine layer long borehole fracturing, permeability enhancement and extraction technology" represent the engineering development front of mining science, technology, and engineering.

The disclosure of core patents involved in each development front from 2016 to 2021 is presented in Table 2.1.2.

Table 2.1.1 Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Large scale wind solar complementary power generation and stable grid connection technology	70	89	1.27	2018.6
2	Multipurpose new concept micro nuclear reactor	60	150	2.50	2018.6
3	High precision prediction system for shale oil and gas production capacity	145	589	4.06	2019.5
4	Research and development of looking-around and looking-ahead while-drilling technology	128	344	2.69	2017.9
5	Fast and flexible peak shaving technology for coal-fired units	157	124	0.79	2019.8
6	Ammonia-fuelled engine technology	70	53	0.76	2020.3
7	Technical system for high-level radioactive waste repository and disposal	140	172	1.23	2018.7
8	Tritium production technology by nuclear fusion	94	110	1.17	2018.5
9	High-precision intelligent 3D visual exploration system	129	311	2.41	2018.8
10	Intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources	162	336	2.07	2018.9
11	Research and development of efficient fracturing technology for shale reservoirs	190	766	4.03	2019.3
12	Coal mine layer long borehole fracturing, permeability enhancement and extraction technology	192	329	1.71	2019.5

Table 2.1.2 Annual number of core patents published for the Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	2016	2017	2018	2019	2020	2021
1	Large scale wind solar complementary power generation and stable grid connection technology	9	6	19	9	19	8
2	Multipurpose new concept micro nuclear reactor	13	6	9	9	5	18
3	High precision prediction system for shale oil and gas production capacity	9	23	27	19	27	40
4	Research and development of looking-around and looking-ahead while-drilling technology	29	30	29	12	20	8
5	Fast and flexible peak shaving technology for coal-fired units	2	11	18	19	42	65
6	Ammonia-fuelled engine technology	2	2	2	2	16	46
7	Technical system for high-level radioactive waste repository and disposal	18	22	23	21	27	29
8	Tritium production technology by nuclear fusion	17	17	14	9	14	23
9	High-precision intelligent 3D visual exploration system	23	15	18	14	20	39
10	Intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources	16	17	29	32	28	40
11	Research and development of efficient fracturing technology for shale reservoirs	9	20	24	40	41	56
12	Coal mine layer long borehole fracturing, permeability enhancement and extraction technology	8	9	31	31	50	63

(1) Large scale wind solar complementary power generation and stable grid connection technology

Wind power and solar power are naturally complementary. Wind-solar-storage complementary power generation systems formed with energy storage systems can overcome the volatility and randomness of wind and solar resources, smooth overall power fluctuations in the large-scale wind-solar bases, and ensure the stable operation of new energy high-penetration power system. In recent years, with the continuous increase of the proportion of wind and solar power generation, wind and solar hybrid power generation has evolved towards high voltage levels and multi-station coordination. In addition, the forms of energy storage used for coordination and complementarity are also changing to green and low carbon; this is the case of large-scale hydrogen storage and pumped storage stations. The key technologies involve in the large-scale wind-solar-storage hybrid power generation system including site selection and capacity determination of wind farms, photovoltaic power stations and energy storage power stations; wind-solar-storage coordinated control, dispatch and economic operation technology; the active power grid supporting technology of wind-solar-storage hybrid power generation system; unplanned and off-grid seamless switching technology of wind-solar-storage hybrid power generation system; stable control technology of wind-solar-storage hybrid power generation system.

In the future, the focus of large-scale wind-solar-storage hybrid power generation will be, among other topics, on the development of active grid-supporting technology, unplanned grid-connected and off-grid seamless switching technology, and broadband oscillation suppression to support the steady operation of high–energy-penetration-rate power systems.

(2) Multipurpose new concept micro nuclear reactor

International Atomic Energy Agency (IAEA) generally refers to a reactor with a power generation below 10 MW and with modular features as a micro nuclear reactor. Micro nuclear reactors are neither miniaturized versions of large nuclear power plants nor prototype reactors to verify technical feasibility. They are innovative reactors with advanced technical features that can provide megawatt-level energy in innovative application scenarios according to user needs. Micro nuclear reactors have broad application prospects and unique advantages with respect to other energy sources. They are also one of the important supports for the realization of national strategies. IAEA and major international nuclear energy countries have recognized the development prospects of micro nuclear reactors and strongly supported their development. The USA, Canada, and the UK have developed technical routes for micro nuclear reactors and provided long-term policy and financial support. The USA has studied the challenges faced by key activities of micro reactor deployment, such as technology development and license application, engineering design procurement and construction, and fuel cycle. They have also put forward suggestions. By cooperating with users, project approval units, nuclear safety review units, technology development units and operating units, it is planned to build and operate at least one micro nuclear reactor demonstrator by the end of 2027.

(3) High precision prediction system for shale oil and gas production capacity

Productivity prediction is an important part of the theoretical system of petroleum development. Whether the prediction result is reliable is one of the core factors that affects the asset evaluation and development scheme design. Commonly used methods for shale oil and gas productivity prediction include numerical simulation, decline analysis, and analytical models. Researchers have conducted extensive research in aspects such as numerical model building, modern production performance, data analysis, and inter-well interference risk prediction, aiming to explore the influence of factors such as fractures, cluster spacing, pore media, compaction, and fluid phase state on productivity. However, shale reservoirs are characterized by complex lithology, diversity hydrocarbon occurrence with large pore-scale span, and complex development processes such as horizontal well and volume fracturing, which lead to deviation between productivity prediction results and actual production. Therefore, it is urgent to develop a high-precision system suitable for shale oil and gas productivity prediction. Four possible trends are expected: ① continuously deepen and improve the research on shale oil and gas occurrence characteristics and seepage mechanism to set a solid foundation for realizing reliable prediction of shale oil and gas production; ② use artificial intelligence technology to analyze big data of geological parameters and engineering parameters in order to explore the main control output factors, establish correlation models, and predict the output; ③ develop non-deterministic prediction methods of shale oil and gas productivity, combine uncertain mathematical theory and physical methods, and establish uncertain production capacity analytical models or numerical models to realize production prediction; ④ physical simulation and theoretical research on three-dimensional development of shale oil and gas by horizontal wells to promote the realization of systematic theoretical research on methods of production prediction for three-dimensional development.

(4) Research and development of looking-around and looking-ahead while-drilling technology

Measurement while drilling (MWD) refers to technology that realizes real-time measurement and upload of drilling trajectory information and geological parameters during the drilling process. Look-ahead-while-drilling and look-around-while-drilling technologies can be used for geosteering and evaluation of the oil and gas content of complex wells and complex formations. They have become a hot topic in industry. Foreign look-ahead-while-drilling and look-around-while-drilling technologies have been greatly developed, Schlumberger, Halliburton, and other companies have developed various technologies. The detection distance of the look-around-while-drilling technology can reach 60 m, whereas the detection distance of the look-ahead-while-drilling technology can reach 30 m. China's current oil and gas exploration and development are gradually turning to deep and ultra-deep complex formations, deep sea, and unconventional reservoirs, thereby setting more demanding requirements for drilling. Look-ahead-while-drilling and look-around-while-drilling technologies are expected to become key to improve the drilling-encounter ratio and oil and gas production. At present, China has made progress in some stages, but as a whole, these technologies are still lagging behind those of foreign countries. The main research directions are development of downhole test instruments, test process improvement, data transmission and storage, data analysis and interpretation, etc. The development trend of look-ahead-while-drilling and look-around-while-drilling technologies is to reduce costs, increase efficiency, and improve the level of intelligence. This can be used for geosteering and reservoir depiction while-drilling, which are expected to become an important part of smart oilfield and intelligent drilling and of great practical and strategic significance for building a solid foundation of oil and gas resources for China's energy security.

(5) Fast and flexible peak shaving technology for coal-fired units

Rapid and flexible peak shaving of coal-fired units is a coal-fired power generation technology with capabilities of rapid response and safe and stable operation at low loads according to the load change command of the power grid. For countries/regions that use coal-fired power generation at large scale, this technology is the only one, and consequently key, to increase the proportion of renewable energy power generation and ultimately achieve carbon neutrality.

Renewable energy has the characteristics of fluctuation, intermittence, and uncertainty. Besides, there is a significant space-time difference between the supply of renewable energy and energy consumption of terminal users. Therefore, to ensure the safety of the power grid and stable supply of energy, it is necessary to rely on coal-fired units for rapid and flexible peak shaving in an extensive period of time as long as the energy storage technology remains immature and expensive. The main technical development directions include: ① ultra-low load pulverized coal boiler combustion technology and circulating fluidized bed combustion technology under various coal qualities; ② hydrodynamic safety and reliability, and economy of coal-fired units, under ultra-low load and varying load operation; ③ rapid start and stop technology of coal-fired units; ④ rapid response mechanism of unit load and coupling technology of coal-fired units and various energy storage systems; ⑤ influence of rapid load change of coal-fired units on heating surface materials; ⑥ full-load ultra-low emission technologies and carbon dioxide emission reduction assessment of coal-fired units; ⑦ economic and efficient thermal power decoupling technology and wide load peak shaving technology for thermal power coal-fired units. The core indicators of fast and flexible peak shaving technology are the response speed to the load change command of the power grid. The development trend is a progressively faster peak shaving speed, in which the supercritical unit reaches above 5% PE/min (rated load/min), and the subcritical unit reaches above 8% PE/min (rated load/min).

(6) Ammonia-fuelled engine technology

Fossil fuel-based engines, which are commonly used in power generation, land transportation, ship power, aerospace industry, and other sectors, are one of the major contributors to carbon dioxide emissions. Ammonia, a carbon-free fuel, is viewed as a viable approach to minimize carbon emissions with respect to traditional carbon-based fuels. However, the combustion of ammonia may encounter some issues, including poor stability and misfire due to high self-ignition temperature and slow flame propagation speed. In addition, the emissions of nitrogen oxides (NO_x) from ammonia engines is generally high because the fuel molecule itself contains nitrogen, which also hinders the development of ammonia to substitute engine fuels.

Dual-fuel technology, which combines ammonia with high-reactivity additives to improve combustion stability, is a potential path to the realization of ammonia-fueled engines. Compared with other high-reactivity fuels, hydrogen has the advantage of being another carbon-free fuel that can be produced online through ammonia cracking. High-efficiency catalytic techniques that convert ammonia into hydrogen is gaining attention. However, owing to the strong diffusivity of hydrogen and high latent vaporization heat of ammonia, the concentration and temperature distribution of ammonia-hydrogen fuel in the engine combustion chamber is often highly inhomogeneous. Therefore, a proper fuel injection strategy to achieve a reasonable distribution of ammonia fuel in the engine and effectively control the combustion phase is a key technology to be accomplished. Although the addition of high-reactivity fuels such as hydrogen improves the combustion stability of ammonia, it also increases the combustion temperature and therefore increases NO_x emissions. Under fuel-rich conditions, NO_x emissions may reduce to a certain extent, but it simultaneously leads to other problems such as poor combustion economy and increased unburned ammonia emissions. Therefore, it is imperative to couple after-treatment methods such as selective catalytic reduction (SCR) and ammonia slip catalyst (ASC) in ammonia-fueled engines to reduce NO_x and unburned ammonia emissions.

In general, single ammonia-fuelled engine technology is still facing many challenges. To achieve the efficiency and emission optimization of ammonia fueled engines, several advanced technologies should be realized, including: ① fast and efficient ammonia on-line cracking to produce high-reactivity hydrogen; ② proper fuel injection strategies, such as high-temperature rich-fuel jet through pre-chamber and multi-stage injection in the main chamber considering the existence of strong turbulences; ③ moderate or intense low oxygen dilution (MILD) combustion, which allows high temperature and low-oxygen concentration to simultaneously reduce NO_x emission and enhance combustion stability; ④ a strategy to prevent pre-ignition and knocking of ammonia-hydrogen fuel in large space of marine engines; ⑤ after-treatment system, such as SCR and ARC (Ammonia Slip Catalysts), with wide operation window and high conversion efficiency for NO_x and unburned ammonia emissions.

(7) Technical system for high-level radioactive waste repository and disposal

The safe disposal of high-level radioactive waste is a major issue for the sustainable development of nuclear energy and environmental protection. High-level radioactive waste is a special waste with strong radioactivity, high toxicity, long half-life, and heat. Safe disposal is extremely difficult and faces a series of challenges involving science, technology, engineering, humanities, and sociology. In response to this problem, most nuclear-armed countries have carried out a large number of fruitful research and development studies based on the formulation of laws and regulations. They have established management systems, implemented agencies, and financed mechanisms. They have also developed long-term plans and underground laboratories as well as other R&D platforms to ensure safe disposal of waste. Since the research and development of geological disposal of high-level radioactive waste began, in the 1960s, extraordinary achievements have been made in geological disposal site selection and evaluation, engineering barriers, repository design and construction technology, underground laboratory construction and experiments, and safety evaluation research. The most prominent countries in the implementation of repository engineering are Finland, France, and Sweden. Core technologies include site evaluation; high-precision hydrogeological parameter measurement systems; fracture network simulation; ultra-low-concentration radionuclide migration evaluation; engineering barrier design and manufacturing; disposal container design; evaluation and manufacturing; safety evaluation; ultra-long-term and ultra-large-scale safety evaluation simulation; key equipment development (such as disposal pit excavation, waste container placement), and high-precision and high-reliability hydrological parameter testing system.

(8) Tritium production technology by nuclear fusion

Tritium plays an important role in the military, energy, industry, and scientific research fields, among others. Natural tritium is extremely rare and difficult to utilize and is often produced through man-made means such as gas pedals and nuclear fission reactors. Compared to other approaches, nuclear fusion reactions can directly produce high-energy neutrons and have more advantages in tritium production. Tritium production by nuclear fusion is a process that uses the nuclear reaction of high-energy neutrons with Li-6 to produce tritium. It also extracts and purifies the tritium in a safe and inclusive manner. The main directions involved in the development of fusion tritium technology include design and fabrication of tritium-producing cladding for nuclear fusion reactors, tritium extraction, separation and purification, and safe containment. According to tritium production efficiency requirements, the tritium-producing blanket of nuclear fusion reactors can be designed as a conventional or hybrid blanket: a conventional blanket presents clean features but tritium production efficiency needs to be improved. One of the goals of the ITER, currently under development, is to test tritium production in a tritium breeder blanket. Likewise, the main objective of China's proposed China Fusion Engineering Test Reactor (CFETR) is to achieve tritium self-sustainability through tritium production in the blanket. A hybrid blanket is chain-amplified by introducing fission fuel to the neutron yield. This can achieve efficient tritium production but is less clean. Tritium extraction, separation, and purification and safe inclusion technologies are critical factors that affect tritium self-sustainability. Therefore, the development of fusion-tritium production technology still needs to focus on tritium-production blanket design, fabrication, and verification, tritium-permeation retention reduction, tritium extraction and separation and purification efficiency, and safe inclusion of tritium operation.

(9) High-precision intelligent 3D visual exploration system

A high-precision intelligent 3D visual exploration system refers to a prospecting system with enhanced precision based on artificial intelligence technology for comprehensive exploration data related to mineral exploration, such as those employed in geophysics, multispectral and hyperspectral remote sensing, infrared spectral detection, and geochemistry and geology, under the guidance of the theory of mineral deposits. It includes hardware and software. The main research line is to continuously improve the accuracy of exploration through the development of sensor hardware technology and software algorithms. Hardware development is mainly focused on high-performance sensors, reliable performance of core chips, data acquisition accuracy, and power. Software development consists mainly in algorithmic innovations for deep-seated ore prospecting information mining. Finally, 3D exploration is realized through independent and controllable artificial intelligence prospecting and exploration software. Future development trends are as follows: ① constant improvement of the performance of hardware related to exploration for more accurate collection of geological exploration information; ② higher exploration precision of all types of information for in-depth excavation, especially in the proposed target area; ③ artificial intelligence encapsulation of expert knowledge to realize simple and user-friendly interfaces; ④ latest exploration data displayed in real-time 3D visualization systems.

(10) Intelligent identification and comprehensive evaluation technology of a new type of polyhalite potash and bearing lithium brine resources

Potassium salt is a strategic mineral resource related to food security that has been classified as a large and scarce strategic mineral by China. Lithium salt is also a new strategic energy mineral, and its foreign dependence remains high, which seriously threatens the national security of mineral resources. The difficulties in exploring deep potassium/lithium salt resources in China are mainly multiple resource endowment states (solid and liquid phases), complex late tectonic deformation, and strong non-homogeneity of brine reservoirs, which have hindered the achievement of breakthroughs for a long time.

To date, there are no international evaluation criteria for new deep miscellaneous halite potash and lithium-rich brines. Intelligent identification and comprehensive resource evaluation technology of new potassium halite and lithium-rich brines are established on the basis of long-term practice. They take advantage of the geophysical and drilling data characteristics of new deep miscellaneous halite potash ores: high gamma, high potassium, high resistance, low thorium, low uranium, and large well diameter. They also establish "three high, two low, and one large" comprehensive logging identification technologies. For the geological characteristics of lithium-rich potash brines, "three high, four low (high neutron porosity, high acoustic time difference, high gamma energy spectrum potassium, low natural gamma, low natural potential, low resistivity, low density)" logging comprehensive intelligent identification technology is established. Combined with massive 3D seismic data to carry out planar intelligent identification prediction, new deep miscellaneous halite potash and lithium-rich brine layers can be found, obtaining information on the depth, thickness, mineral content, and porosity of brine reservoirs in the target layer. On this basis, the necessary parameters for the evaluation of deep potash/lithium resources are obtained and a comprehensive evaluation is completed. This technology was first created by Zheng Mianping's team in the Xuanhan area of northeast Sichuan and achieved a major breakthrough in deep potassium/lithium resource exploration. This technology is helpful to break the bottleneck of comprehensive evaluation of deep sea-phase potassium and lithium resources in China.

The next step is to improve the prediction accuracy, increase the landmark parameters, improve the existing set of deep geological exploration technologies, and create relevant norms for deep solid and brine salts. The objective is to promote the formation of the first large-scale "comprehensive industrial base of lithium and potassium resources in the marine phase" in China, and produce pioneering results domestically and abroad.

(11) Research and development of efficient fracturing technology for shale reservoirs

Shale is dominated by micro-nano pore throats, and the brittle mineral content is generally greater than 35%. Fracturing is the core technology to shorten the seepage distance of oil and gas and realize the economic exploitation of shale. Shale reservoir reconstruction is required to form interlaced fracture networks and has become the industry consensus. Horizontal well staged multi-cluster fracturing is the main technology for reservoir reconstruction. In recent years, the number of stages, clusters, and sand addition in fracturing design has been increasing. Likewise, the proportion of sliding water fracturing has been gradually increased and the spacing of fracturing and clusters has been shortened. Different from the stable tectonic conditions in the North American Plain, the shale strata in China have poor continuity and strong segmentation. Domestic shale development cannot copy the mode of multi-well staged network fracturing. Therefore, it is necessary to form a full-well fracture network mode to achieve high yield with fewer wells. Maximizing the distribution of fracture networks is key for efficient fracturing, but it faces the following challenges, among others: non-synchronous initiation of fractures, formation of main fractures, and inter-fracture interference and fracture steering near the wellbore zone. In view of the above problems, the research directions mainly include the following technologies: branch well fracturing, high-speed channel fracturing, variable displacement fracturing, repeated fracturing, synchronous fracturing, zipper fracturing, steering fracturing, and small well spacing three-dimensional development. Each fracturing process has its own limitations. Only by realizing an integrated reservoir solution that matches geology and engineering, optimal reservoir reconstruction volume can be achieved and efficient development of shale oil and gas in China can be promoted.

(12) Coal mine layer long borehole fracturing, permeability enhancement and extraction technology

With the deepening of coal mining in China, the proportion of high gas and low permeability coal seam expands constantly. In this new situation, the problem of gas control and efficient extraction needs to be solved urgently. Anti-reflection extraction and extraction technology based on long drilling holes in coal seam uses directional drilling machines to construct horizontal long drilling holes in coal seam and capsule hole sealers to seal holes in sections. Fracturing fluid is thus delivered to the sealing hole section through a high-pressure sealing drill pipe to perform sectional fracturing on coal body. This can effectively change the development of coal seam fractures, increase the permeability of coal seam, and greatly increase the drilling concentration and flow rate. The main research directions are the development of deep-hole fracturing tool strings, optimization of fracturing proppant, development of downhole fracturing pump with high pressure and large flow rate, and exploration of gas-liquid collaborative fracturing technology. In the future, anti-reflection extraction technology based on long borehole fracturing in underground coal mines will greatly improve the efficiency of gas advanced control in coal mine areas and shorten the time of gas extraction reaching the standard. Current conventional hydraulic anti-reflection measures such as hydraulic slit, cavitation, and punching are expected to be replaced. The realization of anti-reflection extraction of low-permeability coal seam will lead to faster, efficient, and energy-saving characteristics.

2.2 Interpretations for four key engineering development fronts

2.2.1 Large scale wind solar complementary power generation and stable grid connection technology

Owing to the randomness and volatility of wind and solar power output, direct grid connection will have an impact on the power system. To ensure the stable operation of the power grid, related companies often restrict the grid connection of wind and photovoltaic power generation through dispatching means or provide backup services by thermal power units. Although the stable operation of the system is thus ensured, the abandonment of wind and light has caused serious waste. Wind power and photovoltaics have certain complementarity. Integrated wind-solar-storage power generation combined with energy storage devices constitutes a high-quality power source under the action of intelligent regulation technology. The coordination of wind-solar complementary power generation and energy storage can improve the consumption rate of wind-solar resources and stabilize the power supply capacity. Denmark, the UK, and other European countries with rich wind resources have planned a large number of wind-solar-storage integrated power plants in coastal areas. Denmark's Eurowind Energy has planned the deployment of more than 1 GW of wind-solar-storage onshore energy centers and considered the use of hydrogen electrolysis as large-scale energy storage. General Electric has built a 380 MW large-scale wind-solar-storage project in Oregon, and Australia's Walcha Energy has built a 4 GW wind-solar-storage project in New South Wales (NSW). The earliest wind-solar-storage hybrid power generation project in China was a 54 MW/100 kWp wind-solar hybrid power plant built by Huaneng Nanao in December 2004. With the national policy biased towards renewable energy generation, integrated wind-solar-storage power generation technology has been fully developed and applied. Limited by the geographical layout, most of the wind-solar-storage hybrid power generation systems in China are distributed in northwest and coastal areas with sufficient solar or wind resources. In the future, wind-solar-storage power generation will be jointly planned and designed with transmission systems. China's first 10- million-kilowatt-level wind-solar-storage-transmission multi-energy complementary integrated energy base was officially launched in Gansu in 2021. China Energy Engineering Group Co., Ltd., China Energy Investment Corporation, Shanxi International Energy Group Co., Ltd., Beijing Energy Holding Co., Ltd., China Power Investment Corporation and State Nuclear Power Technology Corporation, and other 15 central and state-owned enterprises have signed 27 wind-solar-storage projects, with a total project planning scale of 42.49 GW.

At present, as shown in Table 2.2.1, the top three countries in terms of patent production in this field are China, India, and South Korea. China has published 63 related patents, accounting for 90% of the public disclosure. There are 6 related patents published in India, accounting for 8.57%. There is 1 relevant patent published in South Korea, accounting for 1.43%. China has the highest patent citation frequency and average citation frequency, 86 and 1.37 respectively, and the citation frequency ratio is 96.63%. There is no cooperation among countries. According to Table 2.2.2, the major institutions of patent output are State Grid Corporation of China, Hohai University, Sungrow Power Supply Company Limited. State Grid Corporation of China and Zhuji Dongbai Power Installation Engineering Company Limited have carried out related engineering cooperation, as shown in Figure 2.2.1.

In the next 5–10 years, large-scale photovoltaic-wind-storage hybrid power generation systems will become an important component to ensure safe operation and support the stability of voltage and frequency of power systems. Considering both the capacity of consumption and active support of the power grid is the key development direction of future photovoltaic-wind-storage hybrid power generation systems, involving the following key technologies:

1) Large-scale photovoltaic-wind-storage hybrid high-proportioned absorption technology to smooth the output

Table 2.2.1 Countries with the greatest output of core patents on "large scale wind solar complementary power generation and stable grid connection technology"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	63	90.00	86	96.63	1.37
2	India	6	8.57	3	3.37	0.50
3	South Korea	1	1.43	0	0.00	0.00

Table 2.2.2 Institutions with the greatest output of core patents on "large scale wind solar complementary power generation and stable grid connection technology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	State Grid Corporation of China	8	11.43	18	20.22	2.25
2	Hohai University	2	2.86	3	3.37	1.50
3	Sungrow Power Supply Co., Ltd.	2	2.86	1	1.12	0.50
4	Shanghai University of Engineering Science	1	1.43	13	14.61	13.00
5	Nantong University	1	1.43	7	7.87	7.00
6	Nanjing Institute of Technology	1	1.43	6	6.74	6.00
7	Harbin Electric Co., Ltd.	1	1.43	5	5.62	5.00
8	Guangdong Electric Power Design Institute	1	1.43	4	4.49	4.00
9	Huaxia Wuwei Cultural Industries Co., Ltd.	1	1.43	4	4.49	4.00
10	Zhuji Dongbai Power Installation Engineering Co., Ltd.	1	1.43	4	4.49	4.00

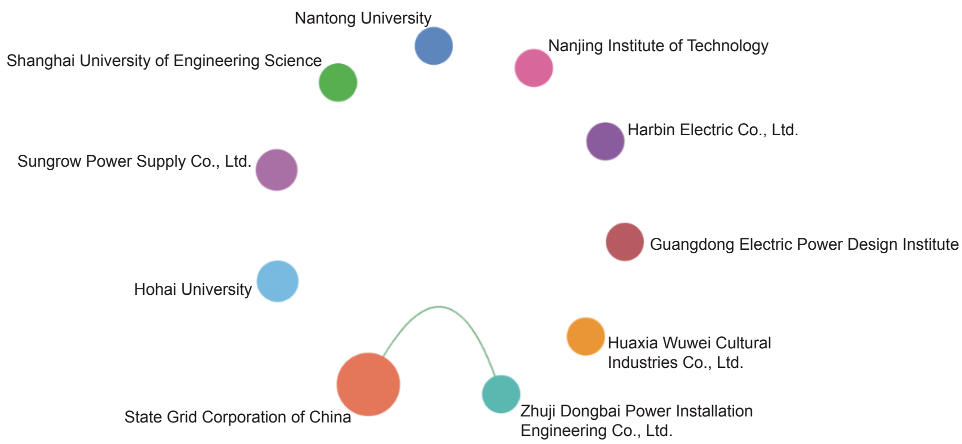

Figure 2.2.1 Collaboration network among major institutions in the engineering development front of "large scale wind solar complementary power generation and stable grid connection technology"

fluctuations of new energy sources, compensate the power prediction error, reduce the wind and light curtailment rates, and increase the number of new energy grid connections and the delivery capacity.

2) Grid-connected technology of photovoltaic-wind-storage with inertial control. Dynamic disturbance control technology represented by virtual synchronous machine control and variable droop control dynamically adjusts to incorporate the frequency and voltage of bus bar for improving the fault ride-through capability of new energy.

3) High-energy-density and high-reliability energy storage systems to improve the manufacturing process, operation ability, and safety performance of single equipment components such as energy storage battery, battery management system, and energy storage converter.

Under the background of building a new type of power system with new energy as the main body in China, the proportion of renewable energy generation in China will increase from 30% to 50%, or even higher. Large-scale photovoltaic-wind-storage hybrid power generation and stable grid-connected technology will become the core technologies of energy construction in the future. The new photovoltaic-wind-storage project will reach more than 50 million kilowatts. In the future, China will build a photovoltaic-wind-storage power generation base, photovoltaic-wind-storage hybrid base, wind-photovoltaic-hydrogen-storage complementary base, and other related projects.

Figure 2.2.2 shows the roadmap of the engineering development front of “large scale wind solar complementary power generation and stable grid connection technology”.

2.2.2 Multipurpose new concept micro nuclear reactor

Micro nuclear reactors are neither miniaturized versions of large nuclear power plants nor prototype reactors to verify technical feasibility. They are innovative reactors with advanced technical features that can provide megawatt-level energy in innovative application scenarios according to user needs. To meet user needs in innovative application scenarios, the design of micro nuclear reactors must consider multiple factors, such as safety improvement, simplification of on-site construction, flexible deployment, and simplified operation. Moreover, this design generally has innovative technical characteristics: high inherent safety; easy modularization and expansion; transportability; ease of deployment; autonomous operation.

Micro nuclear reactors can meet flexible and diverse energy needs for multiple nuclear energy innovation fields and can provide small-capacity or distributed green and clean power and heat sources for remote islands and mining areas, border posts and bases, and other important remote areas. They can also provide emergency relief after disasters or to war victims. They can provide emergency or backup power after damage to important infrastructures. As an energy module with high capacity density, small size, and reduced maintenance during operation, a micro nuclear reactor can provide long-endurance autonomous operation power for important applications such as deep-sea exploration and space exploration; it can also be used as high-energy density equipment. Providing a long-life power supply with flexible deployment has been a research and development hot topic in the international nuclear energy industry in recent years.

As early as in the 1960s and 1970s, the USA and the Soviet Union had developed micro nuclear reactors for space exploration and military bases; this ended with the end of the Cold War. Around 2015, leveraging key technological breakthroughs of space heat pipe reactors in the USA and the emergence of new demands for land-based nuclear power sources, micro nuclear reactors have become a research and development hot topic in the world, revealing the characteristics of a diversity of reactor types and system configurations.

At present, the micro nuclear reactors disclosed domestically and abroad include high-temperature gas-cooled reactors, heat pipe reactors, sodium-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, and light water reactors. In addition to power generation capabilities, various micro nuclear reactors are designed with transport and mobility in mind. In general, when designing micro nuclear reactor thermoelectric conversion systems and waste heat removal systems, compact and lightweight designs are especially considered, and transportability is a key objective to be fulfilled as much as possible. Specifically, factors such as the choice of reactor vessel, reactor type, fuel type and enrichment, reflector material, and control rods and drums affect the size of the reactor vessel and thus the transportability of the reactor design. For thermoelectric conversion systems, compact heat exchangers and Rankine cycles, supercritical carbon dioxide, nitrogen, and helium closed or open Brayton cycles are mainly used. Concerning waste heat removal systems, natural circulation or thermal radiation/thermal conduction transfers the core heat to the periphery. The heat is then dissipated through passive air cooling or metal fins.

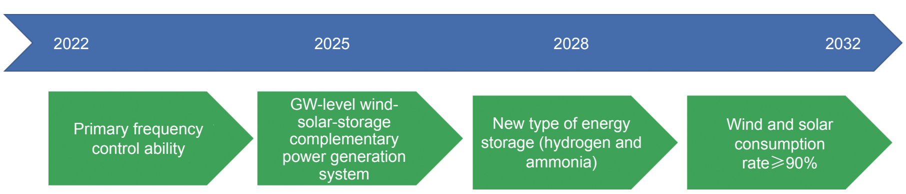

Figure 2.2.2 Roadmap of the engineering development front of “large scale wind solar complementary power generation and stable grid connection technology”

As shown in Table 2.2.3, the countries with the largest number of core patents in this research topic are China, the USA, and South Korea. Among them, the proportion of core patents in ① China exceeds 60%, ② the USA and South Korea both exceed 14%, and ③ other countries are less than 2%. There is no cooperation among countries. It can be seen from Table 2.2.4 that the institutions with the largest number of core patents in this research topic are Xi'an Jiaotong University, Xi'an Thermal Power Research Institute, Westinghouse Electric Company, South China University of Technology, and Nuclear Power Institute of China. They have a proportion exceeding 4% on average. As shown in Figure 2.2.3, the cooperation among institutions in this field is mainly domestic.

Most of the domestic and abroad micro nuclear reactors are currently in key technology research stage. The first demonstration and verification tests are expected to be conducted after 2025–2027. According to the technological development trends in large nuclear power plants in China and the innovative technical characteristics of small and micro nuclear reactors, the technological development trends in micro nuclear reactors are to improve the inherent safety, compact and lightweight design, easy transportation, and ease of deployment for users, and use flexibility. After further analysis, the identified key technologies include: new fuels (such as accident-resistant fuels), main circuit integration, new thermoelectric conversion, passive safety systems, intelligent operation and maintenance, and coupling of nuclear energy and other energy sources. Different micro nuclear reactors are employed for development and verification of the above-mentioned key technologies and equipment based on the reactor characteristics and technological maturity. Figure 2.2.4 shows the roadmap of the engineering development front of "multipurpose new concept micro nuclear reactor".

Table 2.2.3 Countries with the greatest output of core patents on "multipurpose new concept micro nuclear reactor"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	39	65.00	65	43.33	1.67
2	USA	9	15.00	80	53.33	8.89
3	South Korea	9	15.00	1	0.67	0.11
4	Switzerland	1	1.67	4	2.67	4.00
5	Germany	1	1.67	0	0.00	0.00
6	Japan	1	1.67	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "multipurpose new concept micro nuclear reactor"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Xi'an Jiaotong University	5	8.33	8	5.33	1.60
2	Xi'an Thermal Power Research Institute	4	6.67	3	2.00	0.75
3	Westinghouse Electric Company	3	5.00	22	14.67	7.33
4	South China University of Technology	3	5.00	8	5.33	2.67
5	Nuclear Power Institute of China	3	5.00	3	2.00	1.00
6	Shenzhen Alpha BioPharm Co., Ltd.	2	3.33	13	8.67	6.50
7	Yunnan Jici Institute of Regenerative Medicine	2	3.33	13	8.67	6.50
8	Liaoning Dahua Guorui New Materials Co., Ltd.	2	3.33	11	7.33	5.50
9	TerraPower Limited Liability Company	2	3.33	11	7.33	5.50
10	China Aerospace Academy of Systems Science and Engineering	2	3.33	1	0.67	0.50

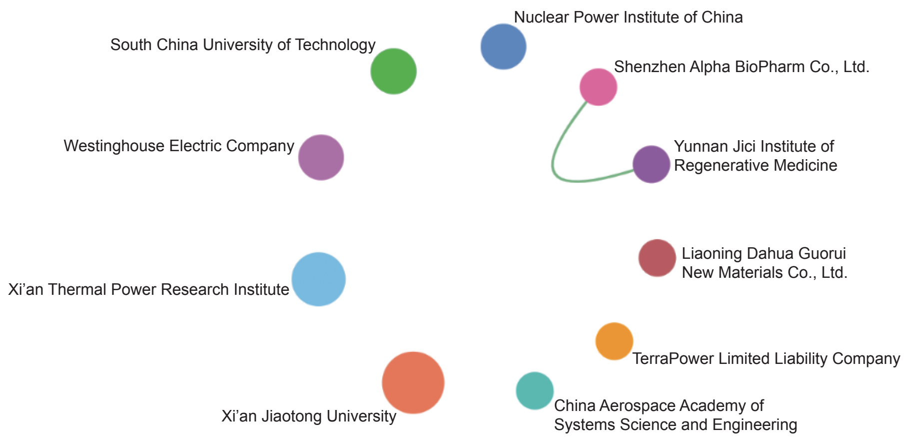

Figure 2.2.3 Collaboration network among major institutions in the engineering development front of "multipurpose new concept micro nuclear reactor"

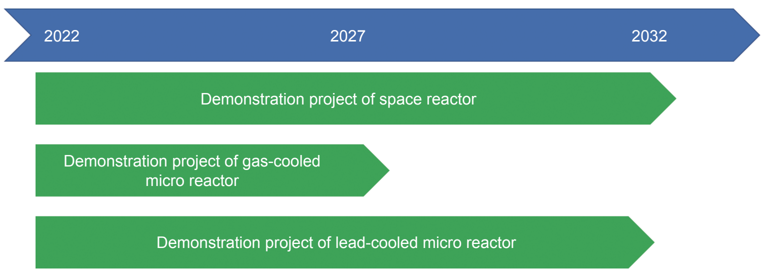

Figure 2.2.4 Roadmap of the engineering development front of "multipurpose new concept micro nuclear reactor"

2.2.3 High precision prediction system for shale oil and gas production capacity

Predictivity is an important prerequisite for shale oil and gas resource evaluation and development scheme designs. An accurate estimate of production capacity and output is key for shale oil and gas development and can provide effective support for scientific arrangement and deployment of various tasks, formulation of reasonable production systems, and realization of sustainable development. The characteristics of ultra-low porosity, low permeability, and multi-stage fracturing of shale reservoirs give rise to unsteady flows in long production cycles of oil and gas wells. No conditions exist to achieve quasi-steady flow for production capacity testing. The production decline law is not clear, especially in later stages. Strong fracturing reconstruction makes shale fracture systems complex and difficult to identify. It is also difficult to select multiple sets of production capacity prediction models, and uncertain numerical simulation is caused by the uncertainty of the flow mechanism. Therefore, the prediction of shale oil and gas production capacity is difficult and highly uncertain. Conventional prediction methods are not adaptable to shale oil and gas. It is appropriate to pay attention to mine production data, build the relationship between production capacity and geological engineering parameters, strengthen dynamic analysis, and integrate multiple prediction methods to build a high-precision prediction system.

At present, China is the main producing country of patents in the development frontier of "high precision prediction systems of shale oil and gas production capacity", with 120 patents, accounting for 82.76%. South Korea and the USA rank second and third with 12 and 10 pieces, accounting for 8.28% and 6.90%, respectively (Table 2.2.5). The largest patent-output institution is China. There is no cooperation among countries. Among the Top 10 institutions in terms of output, nine are oil and gas-related Chinese companies or universities. Among them, China Petroleum and Chemical Corporation rank first with 32 patents, accounting for 22.07% (Table 2.2.6). China's oil and gas related companies and universities cooperate closely. The most cooperative institutions are Sichuan Changning Natural Gas Development Co., Ltd. and

Chengdu Chuanyou Ruifei Technology Co., Ltd. (Figure 2.2.5).

In the next 5–10 years, high-precision prediction systems for shale oil and gas production capacity will mainly have two key development directions: first, deepening the understanding of shale oil and gas geology and engineering theory; second, establishing a comprehensive evaluation method and prediction model for shale oil and gas production capacity (Figure 2.2.6). These directions can be divided into the following four topics: ① deepening and improving the research on the occurrence characteristics and flow mechanism of shale oil and gas, and setting a solid foundation for promoting the reliable prediction of shale gas production capacity; ② using artificial intelligence technology to carry out big data analysis of geological parameters and engineering parameters, exploring the main control factors of production, establishing relevant relationship models, and finally predicting production; ③ conducting research on prediction methods of uncertain production capacity, and combining uncertain mathematical theory and physical methods to derive an analytical or numerical model of uncertain production capacity to realize prediction of uncertain production capacity; ④ developing physical simulation and theoretical research on three-dimensional development of shale oil and gas horizontal wells, promoting the generation of systematic research results on production capacity evaluation methods for three-dimensional development of shale oil and gas horizontal wells. Considering the actual conditions and uncertain factors of shale oil and gas reservoir development,

Table 2.2.5 Countries with the greatest output of core patents on “high precision prediction system for shale oil and gas production capacity”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	120	82.76	485	82.34	4.04
2	South Korea	12	8.28	39	6.62	3.25
3	USA	10	6.90	63	10.70	6.30
4	France	1	0.69	2	0.34	2.00
5	Australia	1	0.69	0	0.00	0.00
6	Saudi Arabia	1	0.69	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “high precision prediction system for shale oil and gas production capacity”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Petroleum & Chemical Corporation	32	22.07	129	21.90	4.03
2	Southwest Petroleum University	21	14.48	73	12.39	3.48
3	PetroChina Co., Ltd.	20	13.79	125	21.22	6.25
4	China University of Petroleum-Beijing	9	6.21	17	2.89	1.89
5	Chongqing University of Science & Technology	6	4.14	32	5.43	5.33
6	Sichuan Changning Natural Gas Development Co., Ltd.	4	2.76	1	0.17	0.25
7	Yangtze University	3	2.07	15	2.55	5.00
8	China University of Geosciences (Beijing)	3	2.07	9	1.53	3.00
9	Korea Institute of Geoscience and Mineral Resources	3	2.07	8	1.36	2.67
10	Chengdu Chuanyou Ruifei Technology Co., Ltd.	3	2.07	0	0.00	0.00

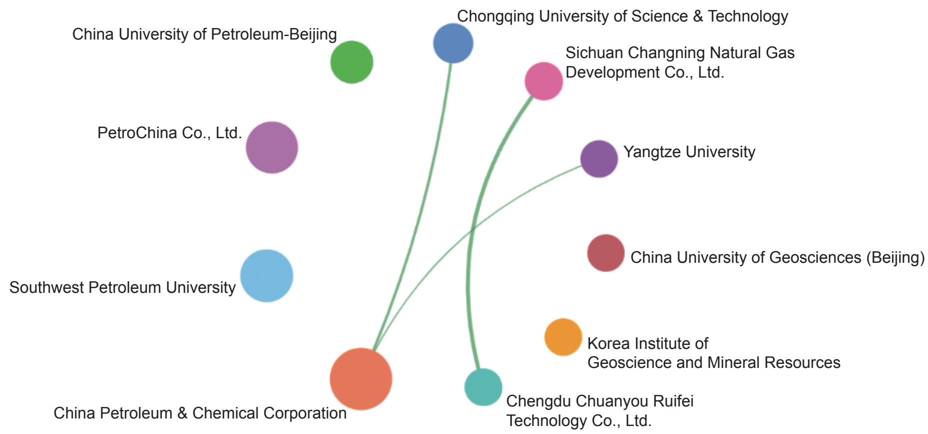

Figure 2.2.5 Collaboration network among major institutions in the engineering development front of "high precision prediction system for shale oil and gas production capacity"

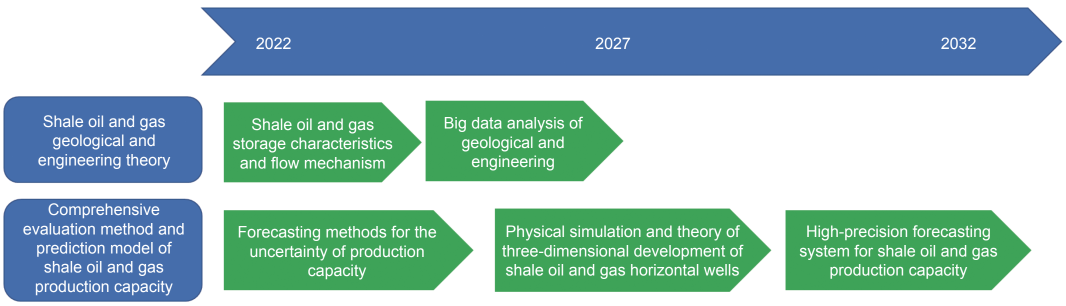

Figure 2.2.6 Roadmap of the engineering development front of "high precision prediction system for shale oil and gas production capacity"

comprehensive evaluation methods and prediction model of shale oil and gas production capacity can be used to achieve an accurate prediction of production capacity and provide scientific guidance for promoting the increase of reserves, production, and economic development of continental shale oil and marine shale gas in China.

2.2.4 Research and development of looking-around and looking-ahead while-drilling technology

Measurement while drilling (MWD) refers to the technology that realizes real-time measurement and upload of drilling trajectory information and geological parameters during the drilling process. Look-ahead-while-drilling and look-around-while-drilling technologies can be used for geosteering and evaluation of oil and gas content of complex wells and formations. It has become a hot topic in the industry. Look-ahead-while-drilling technology makes use of logging instruments to detect the stratigraphic interface of an unexplored formation in front of a drill bit. The detection direction is the same as that of wellbore/drilling, mainly used for geosteering. Look-around-while-drilling technology makes use of logging instruments to detect fluid and formation boundaries as well as other formation information in a long range from the wellbore. In this case, the detection direction is perpendicular to the wellbore direction, mainly used for reservoir description and formation evaluation.

Foreign look-ahead-while-drilling and look-around-while-drilling technologies have been greatly developed. Schlumberger, Halliburton, and other companies have developed Geosphere, Earthstar, IriSphere and other technologies. The detection distance of the look-around-while-drilling technology can reach 60 m, whereas the detection distance of the look-ahead-while-drilling technology can reach 30 m. China's current oil and gas exploration and development is gradually turning to deep and ultra-deep complex formations, deep sea, and unconventional reservoirs, which puts forward higher requirements for drilling. Look-ahead-while-drilling and look-around-while-drilling technologies are expected to become key to improve the drilling-encounter ratio and oil and gas production. In 2006, China set up the "Research on Seismic While Drilling Technology" project in the National High-tech R&D Program (863 Program), and made a certain breakthrough in the vertic seimaic profiling (VSP). In 2014, Greatwall Drilling launched GW-LWD (BWRX) with a detection distance of 2–3 m, thereby reaching the international advanced level. In 2016, Bohai Drilling Engineering Co., Ltd. (BHDC) launched the Azimuth Detection Acoustic Imaging Logger, which can make reservoir predictions. At present, China has made progress in different stages, but overall, the technology is still lagging behind foreign countries. The main research directions of the technology are development of downhole test instruments, test process improvement, data transmission and storage, data analysis and interpretation, etc.

The top two countries with most published core patents for looking-around and looking-ahead while-drilling technology are the USA (63) and China (56), with proportions of 49.22% and 43.75%, respectively. The proportion of core patents of other countries is below 6.00%. The USA has the highest number of citations (206) and highest percentage of citations (59.88%) for published core patents. The percentage of citations in China and Canada are 35.47% and 11.92%, respectively, and the percentage of citations for related technologies in other countries are less than 10%. The top country with the highest citations per patent is Canada (5.86) (Table 2.2.7). Institutions with most published core patents include Halliburton Energy Services Incorporation (32), Schlumberger Technology Corporation (18), PetroChina Co., Ltd. (10), China Petroleum & Chemical Corporation (9), Institute of Geology and Geophysics Chinese Academy of Sciences (7). The top institution in terms of citation percentage is Halliburton Energy Services Incorporation (27.62%) and in terms of highest number of citations per patent is Institute of Geology and Geophysics, Chinese Academy of Sciences (8.29) (Table 2.2.8). Countries that focus on cooperation include the USA, Netherlands, Canada, and France (Figure 2.2.7), and cooperative research between institutions is concentrated in China National Offshore Oil Corporation and Hangzhou Xunmei Technology Co., Ltd. (Figure 2.2.8).

Look-ahead-while-drilling and look-around-while-drilling technologies have broad development prospects in the fields of geosteering and complex oil and gas evaluation. In the next 5–10 years, the key development directions of the technology are to reduce costs, increase efficiency, and improve the intelligence level. Combining look-ahead-while-drilling and look-around-while-drilling technologies with "one-trip logging" and "one-trip drilling" technology can simplify the operation process and reduce the cost. Research and development of new instruments and processes can efficiently produce logging information and realize fluid and core sampling, which is expected to greatly improve the

Table 2.2.7 Countries with the greatest output of core patents on "research and development of looking-around and looking-ahead while-drilling technology"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	63	49.22	206	59.88	3.27
2	China	56	43.75	122	35.47	2.18
3	Canada	7	5.47	41	11.92	5.86
4	France	7	5.47	31	9.01	4.43
5	Netherlands	7	5.47	31	9.01	4.43
6	Russia	2	1.56	1	0.29	0.50
7	Norway	2	1.56	0	0.00	0.00
8	Germany	1	0.78	3	0.87	3.00
9	Saudi Arabia	1	0.78	2	0.58	2.00

Table 2.2.8 Institutions with the greatest output of core patents on "research and development of looking-around and looking-ahead while-drilling technology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Halliburton Energy Services Incorporation	32	25.00	95	27.62	2.97
2	Schlumberger Technology Corporation	18	14.06	78	22.67	4.33
3	PetroChina Co., Ltd.	10	7.81	16	4.65	1.60
4	China Petroleum & Chemical Corporation	9	7.03	9	2.62	1.00
5	Institute of Geology and Geophysics, Chinese Academy of Sciences	7	5.47	58	16.86	8.29
6	China National Offshore Oil Corporation	5	3.91	6	1.74	1.20
7	Baker Hughes Incorporated	4	3.12	20	5.81	5.00
8	Hangzhou Xunmei Technology Co.,Ltd.	3	2.34	5	1.45	1.67
9	Institute of Acoustics, Chinese Academy of Sciences	3	2.34	4	1.16	1.33
10	University of Electronic Science and Technology of China	2	1.56	9	2.62	4.50

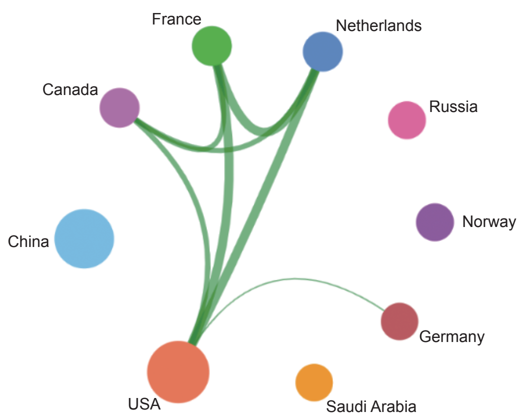

Figure 2.2.7 Collaboration network among major countries in the engineering development front of "research and development of looking-around and looking-ahead while-drilling technology"

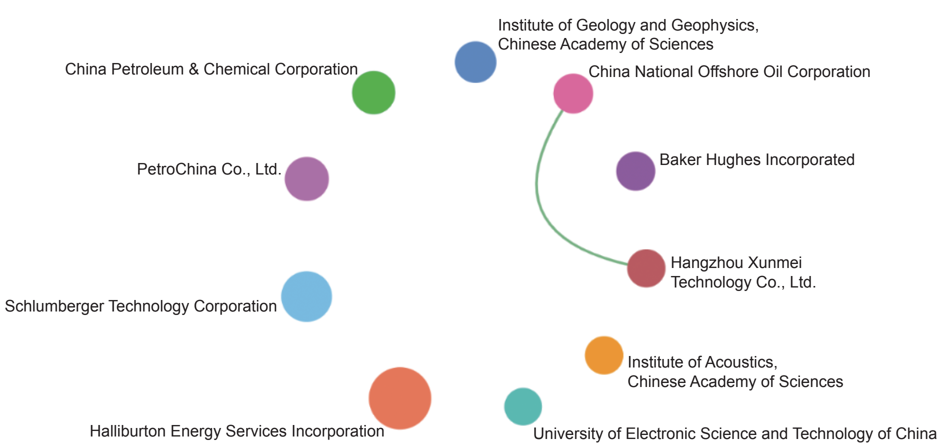

Figure 2.2.8 Collaboration network among major institutions in the engineering development front of "research and development of looking-around and looking-ahead while-drilling technology"

drilling-encounter ratio and oil and gas production. Combined with big data and cloud computing, improving the level of intelligence and strengthening the research and development of relevant software such as data measurement and information interpretation can lead to achieve efficient and high-precision data acquisition and analysis. This is expected to become an important part of intelligent drilling and smart oilfield. Figure 2.2.9 shows the roadmap of the engineering development front of "research and development of looking-around and looking-ahead while-drilling technology".

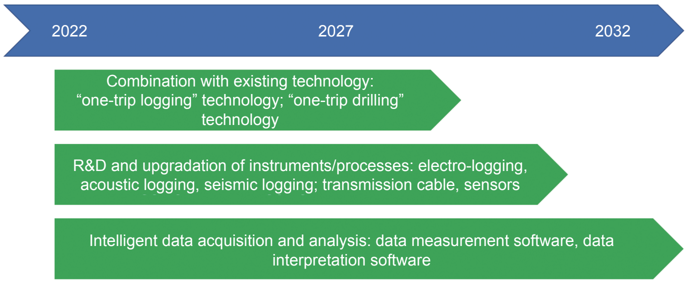

Figure 2.2.9 Roadmap of the engineering development front of "research and development of looking-around and looking-ahead while-drilling technology"

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