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, “research on direct hydrogen production from seawater”, “Power-to-X technologies based on renewable energy sources”, and “high-energy density lithium metal batteries” represent energy and electrical science, technology, and engineering research fronts; “mechanism of high temperature superconductor (HTS) material in compact fusion reactor” , “research on hydrogen production process route and critical material by nuclear energy”, and “critical technology in geological disposal of high-level radioactive waste” represent nuclear science, technology, and engineering research fronts; “detecting method of remote sensing image change for energy resources”, “drilling speed prediction model based on artificial neural networks”, and “characteristics and effects of reservoir stimulation in hydraulic fracturing” represent geology resources science, technology, and engineering research fronts; and “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”, “theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations”, and “advancements in deep rock mechanics modeling for safe and efficient underground mining” represent research fronts of mining science, technology, and engineering.

The annual publication status of the core papers related to each frontier from 2017 to 2022 is shown in Table 1.1.2.

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	Research on direct hydrogen production from seawater	455	13 177	28.96	2020.8
2	Mechanism of high temperature superconductor (HTS) material in compact fusion reactor	468	4 595	9.82	2019.9
3	Detecting method of remote sensing image change for energy resources	36	2 342	65.06	2020.3
4	Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems	11	379	34.45	2021.5
5	Power-to-X technologies based on renewable energy sources	212	5 174	24.41	2020.4
6	High-energy density lithium metal batteries	282	75 243	266.82	2018.6
7	Research on hydrogen production process route and critical material by nuclear energy	174	15 263	87.72	2018.4
8	Critical technology in geological disposal of high-level radioactive waste	387	3 058	7.90	2020.0
9	Drilling speed prediction model based on artificial neural networks	42	686	16.33	2019.4
10	Characteristics and effects of reservoir stimulation in hydraulic fracturing	162	2 474	15.27	2019.9
11	Theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations	114	783	6.87	2019.7
12	Advancements in deep rock mechanics modeling for safe and efficient underground mining	30	1 309	43.63	2020.0

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	2017	2018	2019	2020	2021	2022
1	Research on direct hydrogen production from seawater	19	31	32	55	108	210
2	Mechanism of high temperature superconductor (HTS) material in compact fusion reactor	56	68	66	74	97	107
3	Detecting method of remote sensing image change for energy resources	1	0	7	11	14	3
4	Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems	0	0	0	0	6	5
5	Power-to-X technologies based on renewable energy sources	13	16	23	48	44	68
6	High-energy density lithium metal batteries	55	92	60	57	17	1
7	Research on hydrogen production process route and critical material by nuclear energy	52	46	44	21	7	4
8	Critical technology in geological disposal of high-level radioactive waste	55	42	51	58	71	110
9	Drilling speed prediction model based on artificial neural networks	1	5	8	4	9	10
10	Characteristics and effects of reservoir stimulation in hydraulic fracturing	12	28	29	32	24	37
11	Theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations	16	20	11	25	21	21
12	Advancements in deep rock mechanics modeling for safe and efficient underground mining	1	3	6	7	10	3

(1) Research on direct hydrogen production from seawater

Direct hydrogen production from seawater is a technology that directly decomposes seawater into hydrogen and oxygen without pretreatment processes like desalination. However, due to the extremely complex composition of seawater (up to 92 chemical elements), it faces many challenges such as chlorination, membrane clogging and corrosion. Since the concept of direct seawater electrolysis was proposed in 1975, the four major paths of direct seawater electrolysis for hydrogen production have still been the main focus internationally for half a century. One is direct seawater electrolysis by developing catalysts, through improving electrochemical activity, introducing selective site or constructing protective coatings to avoid the competition between chlorination and oxygen precipitation reactions. The second is direct seawater electrolysis based on asymmetric electrolyte, which is achieved by adding a pure electrolyte at the anode side and seawater at the cathode side. The third is to isolate the purity ions via the hydrophilic reverse osmosis membrane. The last is seawater electrolysis based on physical mechanics, through the construction of a gas-liquid phase interface between seawater and electrolyte, and the use of the difference in saturated vapor pressure between the two as the mass transfer driving force, inducing the seawater in the form of gaseous water migration across the membrane to the electrolyte, completely isolating seawater ions and at the same time realizing the seawater without desalination process, side reactions, additional energy consumption of the seawater for the purpose of direct hydrogen production. The development of direct seawater electrolysis technology for hydrogen production will help promote the global emerging strategic industry of “offshore wind power and other renewable energy utilization—seawater hydrogen production”.

(2) Mechanism of high temperature superconductor (HTS) material in compact fusion reactor

Controlled fusion energy is an ideal clean energy resource for the future, and the most likely method for realizing controlled thermonuclear fusion at present is magnetic confinement fusion. Tokamak are considered to be the most promising magnetic confinement devices for realizing controlled nuclear fusion, and superconducting magnets are one of the key components of tokamak devices. Conventional tokamak devices use low-temperature superconducting magnets. In order to obtain a high fusion energy gain and fusion power density, the devices are often built very large, which increases the cost of the device. With the development of superconducting material technology, second-generation high-temperature superconducting materials have higher temperature margins, current densities, and critical magnetic fields compared to low-temperature superconducting materials. These characteristics promote the birth of more compact, higher magnetic field of high-temperature superconducting magnets. The breakthrough in high-temperature superconducting magnet technology has formed a new compact fusion reactor technology route, which not only greatly reduces the cost, but also dramatically shortens the research and development cycle. MIT Technology Review named the compact fusion reactor as one of the top ten breakthrough technologies in 2022. Internationally representative are the SPARC device from Massachusetts Institute of Technology (MIT) in the USA and the STEP device from Karam Fusion Energy Center in the UK, both of which are currently in the conceptual design stage.

(3) Detecting method of remote sensing image change for energy resources

Remote sensing imaging change detection is the use of multi-source remote sensing images and related geographic spatial data covering the same surface area at different times, in combination with corresponding features and remote sensing imaging mechanisms, in order to determine and analyze the changes in the features of the region through the image and graphic processing theory and mathematical modeling methods, including changes in the location and scope of the features, as well as changes in their properties and states.

In the initial stage, medium and low resolution remote sensing images were used. With the improvement of spatial resolution of remote sensing images, the differences in spatial texture representations of the same ground objects become larger, and the features of the ground objects become more complex and diverse. Traditional change detection methods are no longer sufficient to meet the needs. Hyperspectral image change detection and high-resolution image change detection have become important fields of change detection.

Modern information technologies such as remote sensing big data, the Internet, artificial intelligence (AI), and cloud computing are thriving, driving the rapid transformation and upgrading of remote sensing monitoring technology models. Utilization of existing data and computing resources, surface normalization and intelligent monitoring, and timely and efficient acquisition of land feature change information has become one of the current research hotspots. Future research trends include application scene change detection, construction and application of a dedicated sample set for large-scale change detection, and information mining of multi-source data.

(4) Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems

Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems study refers to the investigation of the thermal, hydrological, and mechanical interactions of rocks within geothermal systems by integrating multiple spatial and temporal scales. This simulation-based research aims to gain a deeper understanding of the impacts of geothermal energy extraction and subsurface water flow on geological fault zones and rock properties, with the ultimate goal of enhancing efficient geothermal resource development and environmental management.

The primary research directions are as follows: ① micro-scale research focuses on the microscopic characteristics of rock, including pore structure, mineral composition, thermal conductivity, and interactions between rocks and fluids; ② at the mesoscale, the research involves simulating the thermal-hydro-mechanical behavior of small-scale rocks, revealing relationships between fluid seepage, heat transfer, and mechanical responses within geothermal systems; and ③ macro-scale investigations explore the thermo-hydro-mechanical coupling behavior of rocks across the entire geothermal system, considering the influence of geological structures and groundwater flow on geothermal resources. Cross-scale simulations integrate information from different scales to provide comprehensive guidance for geothermal energy development.

With the advancement of computational capabilities and interdisciplinary collaboration, multiscale fractured simulation of the thermo-hydro-mechanical coupling processes in geothermal system rocks are expected to progress further. This will be reflected in ① more refined and efficient simulation methods utilizing new numerical algorithms, artificial intelligence, and other technologies to achieve more accurate simulation results; ② increased importance of data-driven simulation methods, optimizing numerical models utilizing real monitoring data to improve predictive accuracy, placing more emphasis on coupling effects, considering the mutual influences of factors such as temperature, pressure, and fluid transport; and ③ enhanced interdisciplinary cooperation, incorporating expertise from fields such as geology, hydrology, and geophysics into simulation studies.

(5) Power-to-X technologies based on renewable energy sources

Power-to-X technology is the use of green electricity generated from renewable energies (solar, wind, hydro, etc.) to produce green hydrogen, green methanol, green ammonia, and other products. This emerging technology can realize the transformation of intermittent renewable energies into storable chemical energy, thus contributing to the large-scale storage of renewable electricity. Meanwhile, Power-to-X enables linking renewable energies to industry, transportation, energy and power sectors. Therefore, it provides a suitable solution for the global economy decarbonization and for the provision of non-fossil fuel products.

At present, water electrolysis toward hydrogen is the key field of Power-to-X technology. Meanwhile, coupling green hydrogen with CO_2 and/or N_2 can provide a wealth of products. The direct conversion of H_2O with CO_2 and/or N_2 toward green methanol, green ammonia, and other products is also an active field of Power-to-X technolog. Of note, co-electrolysis of H_2O/CO_2 toward syngas, in combination with distributed micro-Fischer-Tropsch process holds a grand promise for generating carbon-neutral fuels and chemicals. Biomass and bio-derived platform molecules are one family of abundant renewable resources on earth with diverse molecular framework, active functional groups, and flexible molecular tailorability compared with CO_2 and N_2. Thus, it is a suitable object for green electricity processing. Moreover, biomass-based products are perfectly compatible with the economic system. Therefore, the Power-to-X technology coupled with biomass conversion has a great potential in carbon-neutral economy.

Breaking the key scientific and technological bottlenecks of the whole chain of material-electrode-electrolyzer-system, improving the energy conversion efficiency and the economic value of the products, and optimizing the linking method between the Power-to-X technology and the industrial, transportation and energy and power sectors is at the core of this grand topic.

(6) High-energy density lithium metal batteries

As an anode in second batteries, lithium (Li) metal has a very high theoretical specific capacity of 3 860 mAh/g and the lowest redox potential. Thus, it is the ultimate choice of anode material for high energy second batteries. In the 1970s attempts were made to use metallic Li as the anode in rechargeable batteries. However, it was found that Li dendrites were easily formed during charging (i.e., electrochemical deposition of Li), which could pierce the separator film and cause internal short-circuit, leading to thermal runaway and combustion explosion. In addition, Li dendrites could fracture to result in Li pulverization that will enhance the reactivity and safety risk. These fatal flaws block the commercialization of Li metal second batteries. Then, more attention was paid to Li+ intercalation anode materials. Finally, lithium-ion batteries based on graphite anodes entered the market in 1991. With the rapid development of electric vehicles and energy storage in the recent 10 years, second batteries with a higher energy density are demanded, and Li metal second batteries have come into sight again. Li-S battery and other new systems with an energy density above 400 Wh/kg have been intensively investigated. Nevertheless, two major problems of Li dendrite growth and low cycling efficiency related to Li metal anode still need to be solved. Optimization of the current collector structure, modification of the anode surface and use of Li metal composites can effectively suppress Li dendrite growth. Moreover, the electrochemical performance of Li metal anode is strongly dependent on the paired electrolytes. The optimization of liquid electrolyte compositions can improve the property of solid-electrolyte interphase layer, and in turn, suppress Li dendrite growth and enhance the Coulombic efficiency. In particular, the use of organic/inorganic composite electrolytes or inorganic electrolytes is expected to fundamentally solve the problems of Li metal anode. With the continuous emergence of new materials and the optimization of cell structures and charging mode, the practical application of Li metal second batteries might be realized.

(7) Research on hydrogen production process route and critical material by nuclear energy

As a secondary energy, hydrogen is an energy carrier or energy flow. The combination of nuclear energy and hydrogen energy will basically clean the whole process of energy production and utilization. The use of nuclear power to provide electricity for hydrogen production by electrolysis of water is one of the ways of hydrogen production by nuclear energy. At present, the main problem of hydrogen production from water electrolysis is the high energy consumption and low efficiency. If hydrogen production by electrolytic water in nuclear power is conducted during the low power consumption, the power grid resources can be rationally utilized and the cost of hydrogen production can be reduced. The high temperature generated by the nuclear fission process in the reactor has been extensively studied for direct use in thermal-chemical hydrogen production. Compared with hydrogen production by electrolytic water, the thermochemical process has a higher efficiency and a lower cost.

The principle and typical process of thermal-chemical hydrogen production is based on the thermochemical cycling, which catalyzes the thermal decomposition of water at 800–1 000 ℃ to produce hydrogen and oxygen. More than 100 thermochemical cycles have been developed. One of the keys to this method is to provide low-cost high-temperature heat sources. In recent years, the high temperature generated by nuclear fission in the reactor is an active research topic in the international nuclear engineering field, which may become a new application field of nuclear energy in the future. Hydrogen production by thermochemical process includes biomass thermochemical hydrogen production, thermochemical iodine-sulfur cycle hydrogen production, high temperature solid oxide electrolytic hydrogen production, methane (high temperature) reforming hydrogen production, of which the iodine-sulfur thermochemical cycle process is considered to be a more promising process. Thermal hydrogen production first requires the reactor to provide a high temperature of 750–1 000 ℃ . The cross-contamination of the nuclear system and the hydrogen production system during heat exchange must be prevented. The international roadmap for the 4th generation nuclear energy system (Gen IV) fully considers the issue of nuclear energy hydrogen production. In the recommended six nuclear energy systems, in addition to the very high temperature gas cooled reactor (VHGR) which mainly produces hydrogen, gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), and molten-salt reactor (MSR) give consideration to both power generation and hydrogen production.

(8) Critical technology in geological disposal of high-level radioactive waste

High-level radioactive waste refers to the high-level waste liquid and its solidified body generated from the reprocessing of spent fuel in nuclear reactors. According to the classification of radioactive waste in China, high-level radioactive waste is divided into two categories: high-level liquid waste and high-level solid waste. High-level radioactive waste is a special waste that is highly radioactive, highly toxic, with long half-life nuclides and heat, which is extremely difficult to be safely dispose of, posing a series of scientific, technical, engineering, humanistic and sociological challenges. The internationally widely adopted feasible solution is deep geological disposal, that is, the high-level waste is buried in the geological body 500–1 000 m deep from the surface, so that it is permanently isolated from the human living environment. The underground works where high-level radioactive waste is buried are called “high-level radioactive waste disposal repositories”. Through the construction of an underground laboratory for high-level waste disposal, with the underground laboratory as a platform, many countries have determined the disposal site, developed a complete disposal theory and technical system, and entered the construction/preparation stage of the disposal repository. Finland received a permit for the construction of the repository in November 2015 and began construction in 2016; Sweden and France obtained permits for the construction of repositories; The USA allocated funds to restart the Yucca Mountain project in 2017. On May 6, 2019, with the consent of the State Council of the People’s Republic of China, the Bureau of Science, Technology and Industry for National Defense officially approved the underground laboratory construction project, which is a milestone for the geological disposal of high-level radioactive waste in China.

Major scientific issues to be addressed for the safe disposal of high-level waste include accurate prediction of the geological evolution of the disposal site, the characteristics of deep geological environment, the behavior of deep rock mass, groundwater and engineering materials under multi-field coupling conditions (medium-high temperature, ground stress, hydraulic action, chemical action and radiation action), the geochemical behavior of low-concentration transuranic radionuclides and their migration with groundwater, and the safety evaluation of disposal systems under ultra-long time scales, etc.

(9) Drilling speed prediction model based on artificial neural networks

The artificial intelligence-based drilling rate prediction model is a method that employs machine learning and data analysis techniques to forecast drilling rates in oil and gas drilling operations. This model analyzes various factors such as historical drilling data, geological information, drilling parameters, and applies artificial intelligence algorithms such as neural networks, decision trees, and support vector machines to construct a predictive model, providing decision-making support for drilling operation planning and optimization. Its research directions primarily encompass data collection, feature engineering, algorithm modeling, and model optimization. It requires the collection of a substantial amount of historical drilling data, extraction of features relevant to drilling rates, selection of appropriate algorithms for building predictive models, and iterative optimization to enhance accuracy and stability. With the continuous advancement of data technology and artificial intelligence, coupled with the increasing diversity and real-time nature of data, the gradual integration of information from other fields, and the application of automation technology, the model will become more accurate and reliable, offering real-time, comprehensive, and precise drilling rate prediction results.

(10) Characteristics and effects of reservoir stimulation in hydraulic fracturing

Hydraulic fracturing technology is the process of injecting fracturing fluid, which contains various additives, into the reservoir at a high pressure, utilizing the natural or induced fracture system of the reservoir. This process enlarges the fracture network of the reservoir and prevents the fractures from closing after the fracturing fluid is withdrawn, with the help of proppants such as sand or ceramic particles. As a result, the shale gas can continuously release and transport to the surface. China began studying the hydraulic fracturing technology in the 1950s. After years of exploration and reference, the first field test of hydraulic fracturing in shale gas wells was conducted in China from 2009 to 2011, marking the beginning of theoretical research and field application of shale gas fracturing. In 2012, Jiaoye 1 HF Well in Fuling Shale Gas Field achieved high production through hydraulic fracturing, indicating the localization of the fracturing technology in China. Since then, with the steady development of the fracturing technology, the total number of shale gas fracturing wells in China has reached 1 092 by 2020, and shale gas production has been increasing year by year. In 2020, the national shale gas production reached 200.4×10^{8} m^{3}.

From the point of view of the total degree of reservoir reconstruction, the early implementation of the fracturing technology in China mainly includes the conventional staged multi-cluster fracturing technology, the synchronous fracturing technology, the zipper fracturing technology, the repeated fracturing technology, and so on. The staged multi-cluster fracturing technology is the leading technology of shale gas fracturing. With the in-depth development of shale gas development, to improve the transformation effect, especially the transformation volume and fracture network complexity of deep shale gas, the dense cluster forced sand fracturing technology has been developed since 2018. In the process of implementing this technology, to control the equilibrium degree of fractures, the temporary plugging fracturing technology and the non-uniform perforation fracturing technology have been developed to achieve adequate control of fracture extension uniformity.

(11) Theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations

Generally, oil and gas resources in marine areas with a water depth exceeding 300 meters are generally classified as deepwater oil and gas. Deepwater oil and gas resources are abundant with significant potential, offering extensive prospects for exploration, development, and reservoir enhancement. Deepwater have emerged as a crucial replacement area for oil and gas reserves and production due to their substantial quantities. However, the lifespan of platforms limits deepwater oil and gas development, necessitating the achievement of stable and high production within a constrained timeframe. Quality enhancement and efficiency improvement of oil and gas development is urgently required. Over 70% of global oil and gas resources are located in the oceans, with 40% originating from deepwater sources. Of the 101 newly discovered large oil and gas fields in the past decade, 67% are deepwater fields accounting for 68% of the reserves. China’s current deepwater oil and gas production has reached tens of millions of tons, marking significant progresses. Nevertheless, China’s deepwater oil and gas exploration and development still remain in the preliminary stage. Complex reservoir origins, exploration, characterization, drilling and completion, and production challenges, coupled with heavy reliance on foreign materials and equipment, hinder further progress. Therefore, there is a pressing need to formulate theories for quality enhancement and efficiency improvement of oil and gas development in China's complex deepwater geological formations. Key research areas include geological exploration methods, refined characterization techniques, safe drilling and completion technologies, research for supportive materials and equipment, and efficient production methods. Active exploration of novel approaches, development of new technologies, materials, and equipment, establishment of theoretical frameworks for quality enhancement and efficiency improvement of complex deepwater oil and gas development, and the formulation of scientifically reasonable development models hold the potential to significantly contribute to national energy security.

(12) Advancements in deep rock mechanics modeling for safe and efficient underground mining

Advancements in deep rock mechanics modeling for safe and efficient underground mining refers to the application of advanced mechanical models and numerical simulation techniques to study the mechanical behaviors of rocks, such as deformation, fracturing, and stress distribution, in deep underground mining, in order to predict and assess geological hazards like rock instability and collapses that might occur. This research provides scientific guidance for safe and efficient mining practices.

In the domain of safe and efficient deep underground mining rock mechanics modeling, the main research directions encompass the following vital areas: ① constitutive modeling of rocks explores the deformation characteristics of different rock types under extreme conditions like high pressure and temperature, providing accurate numerical descriptions of rock deformation behaviors during mining; ② studies on mechanical behavior of porous rock masses concern the influence of groundwater flow on rock mechanics and the response of rock-water coupling within porous media during extraction; and ③ studies on multiscale modeling utilize cross-scale simulations to reveal rock mechanics responses from micro to macro scales.

With the rapid advancement of the computer technology, rock mechanics modeling for safe and efficient deep underground mining is becoming more refined and accurate. This will be reflected in: ① models considering nonlinearities, anisotropy, and damage characteristics of rocks in greater detail to enhance simulation accuracy; ② deeper investigations into coupling effects, encompassing factors such as groundwater flow, temperature, and stress in simulations, leading to more comprehensive predictions of rock mechanics responses; and ③ increased application of artificial intelligence and machine learning techniques for optimizing model parameters, accelerating simulation processes, and improving simulation efficiency. As the depth of deep mining operations increases, rock mechanics modeling will also focus on studying mechanical behaviors at even deeper underground levels.

1.2 Interpretations for four key engineering research fronts

1.2.1 Research on direct hydrogen production from seawater

Water electrolysis highly relies on freshwater resources, while the shortage of freshwater resources seriously restricts the development of hydrogen production. Ocean is the largest hydrogen source on earth, and obtaining sea water to produce "green hydrogen" is an important strategic direction for future scientific and industrial development. However, the composition of seawater is extremely complex, involving 92 chemical elements, many microorganisms, solid impurities, etc. Its lower conductivity and large fluctuations easily lead to side reactions, catalyst deactivation, and membrane clogging, and other issues in the electrolysis process, which poses a great challenge to the high performance, stability, high efficiency, and compatibility of the electrolysis system.

Desalination followed by hydrogen production is the most mature seawater hydrogen production technology path and has been conducted in China and abroad in large-scale demonstration projects. However, this type of technology relies heavily on large-scale desalination equipment, and the process is complex and occupies a large amount of land resources, which further pushes up the cost of hydrogen production and the difficulty of engineering construction. Since the concept of direct seawater hydrogen production was proposed in 1975, the four major paths of direct seawater electrolysis for hydrogen production have still been the main focus internationally for half a century. Of the four major paths, catalyst engineering is currently the most traditional and conventional way to solve the challenge of seawater hydrogen production, mainly through the improvement of electrochemical activity, the introduction of selective sites, and the construction of protective coatings to avoid the competition between chlorination and oxygen precipitation reactions. The second path is direct hydrogen production from seawater based on asymmetric electrolyte, which is achieved by adding a single, pure electrolyte at the anode side and seawater at the cathode side. The third path is based on membrane isolation, which excludes impurity ions in seawater by utilizing the in-situ membrane screening method of hydrophilic reverse osmosis. The last path is based on the phase change migration of physical mechanics, through the construction of a gas-liquid phase interface between seawater and electrolyte, and the use of the difference in saturated vapor pressure between the two as the mass transfer driving force, inducing the seawater in the form of gaseous water migration across the membrane to the electrolyte, completely isolating seawater ions and at the same time realizing direct hydrogen production without the desalination process, side reactions, additional energy consumption of seawater. This pathway has been validated in the world's first offshore wind power seawater direct electrolysis hydrogen production sea trial on May 27, 2023 in Xinghua Bay, Fujian Province in China.

In the engineering research front of "research on direct hydrogen production from seawater", the countries with the highest publication of core papers and the average citations per paper are China and the USA, respectively (Table 1.2.1), and there are lots of collaborations among China, the USA, and Australia (Figure 1.2.1). In the top ten institutions in terms of the number of papers published, Chinese Academy of Sciences and Qingdao University of Science and Technology rank top two, and the institutions with the highest citations per paper are University of Houston and Tianjin University (Table 1.2.2). There are many collaborations between China University of Petroleum (East China), Qingdao University of Science and Technology, Shenzhen University, and Zhengzhou University (Figure 1.2.2). Countries and institutions with the greatest output of citing papers are shown in Tables 1.2.3 and 1.2.4.

At present, the phase change migration of seawater direct electrolysis hydrogen production technology route has begun to take advantage, is expected to realize 100 Nm^3/h H_2 seawater hydrogen production system mass production by 2025, before 2028 to realize 1 000–3 000 Nm^3/h H_2 seawater hydrogen system mass production, before 2033 to realize the application scenario to the sewage, wastewater, and other non-pure water resources of the direct production of hydrogen on a large scale (Figure 1.2.3). Countries and institutions with the greatest output of citing papers are shown as Tables 1.2.3 and 1.2.4.

Table 1.2.1 Countries with the greatest output of core papers on "research on direct hydrogen production from seawater"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	249	54.73	7 803	31.34	2021.3
2	USA	79	17.36	3 432	43.44	2020.5
3	Republic of Korea	31	6.81	584	18.84	2021.0
4	Australia	25	5.49	1 162	46.48	2020.7
5	Japan	23	5.05	280	12.17	2020.2
6	UK	19	4.18	223	11.74	2020.7
7	Germany	15	3.30	939	62.60	2019.7
8	Canada	15	3.30	566	37.73	2020.5
9	India	15	3.30	262	17.47	2021.1
10	Netherlands	12	2.64	516	43.00	2020.3

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "research on direct hydrogen production from seawater"

Table 1.2.2 Institutions with the greatest output of core papers on "research on direct hydrogen production from seawater"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	28	6.15	632	22.57	2021.0
2	Qingdao University of Science and Technology	27	5.93	318	11.78	2021.8
3	Wuhan University of Technology	17	3.74	435	25.59	2021.5
4	University of Houston	12	2.64	1 703	141.92	2021.0
5	China University of Petroleum (East China)	11	2.42	244	22.18	2021.5
6	Nankai University	11	2.42	213	19.36	2021.5
7	Tianjin University	10	2.20	467	46.70	2020.9
8	Shenzhen University	10	2.20	198	19.80	2021.4
9	Zhengzhou University	9	1.98	155	17.22	2021.8
10	University of Shanghai for Science and Technology	9	1.98	60	6.67	2021.7

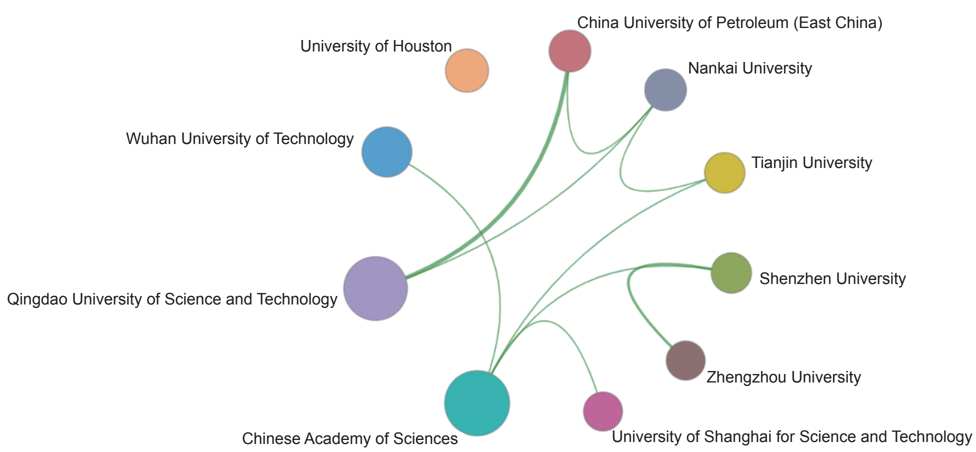

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "research on direct hydrogen production from seawater"

Table 1.2.3 Countries with the greatest output of citing papers on “research on direct hydrogen production from seawater”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	561	57.54	2020.4
2	USA	119	12.21	2020.0
3	Australia	56	5.74	2020.3
4	Republic of Korea	54	5.54	2020.3
5	Germany	35	3.59	2020.3
6	UK	33	3.38	2020.4
7	Singapore	28	2.87	2020.2
8	Japan	25	2.56	2020.3
9	Iran	23	2.36	2019.8
10	Canada	22	2.26	2020.4

Table 1.2.4 Institutions with the greatest output of citing papers on “research on direct hydrogen production from seawater”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	77	26.55	2020.1
2	Soochow University	27	9.31	2020.0
3	Tsinghua University	24	8.28	2020.5
4	Hunan University	24	8.28	2020.4
5	Zhengzhou University	23	7.93	2020.6
6	Tianjin University	21	7.24	2020.3
7	Wuhan University of Technology	21	7.24	2020.4
8	Beijing University of Chemical Technology	19	6.55	2020.3
9	University of Science and Technology of China	18	6.21	2020.4
10	Qingdao University of Science and Technology	18	6.21	2020.4

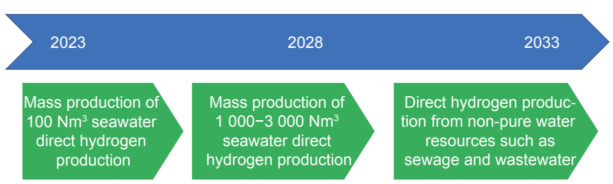

Figure 1.2.3 Roadmap of the engineering research front of “research on direct hydrogen production from seawater”

1.2.2 Mechanism of high temperature superconductor (HTS) material in compact fusion reactor

Fusion energy is clean, safe, and relatively abundant, which is the ideal energy source that is most likely to fundamentally solve the future energy crisis. Tokamak devices are considered to be the most promising magnetic confinement devices for the realization of controlled nuclear fusion. A superconducting magnet is one of the key components of a tokamak device, providing the poleward and ringward magnetic fields that generate and confine the plasma to realize fusion. In tokamak devices, the fusion energy gain and fusion power density have a scalar relationship with the toroidal magnetic field, and the central toroidal magnetic field of magnets utilizing traditional low-temperature superconducting materials can only reach about 7 T, such as the EAST of China, the JT-60SA of Japan, the JET of the UK, and the International Thermonuclear Experimental Reactor (ITER) of international cooperation. With the development of superconducting material technology, the second generation high-temperature superconducting materials have higher temperature margins, current densities, and critical magnetic fields compared to low-temperature superconducting materials. These properties have led to the creation of more compact high-temperature superconducting magnets with higher magnetic fields. Since the cost of a tokamak device is approximately cubic to the large radius of the device, the high-temperature superconducting magnet technology can effectively reduce the overall cost of the fusion device, which plays an important role in further promoting the application of fusion energy in the future. At present, British Tokamak Energy has completed the preparation of the ST25-HTS device, which confirms the feasibility of combining tokamak and high-temperature superconducting materials. In the next five years, MIT plans to use high-temperature superconducting materials to complete a SPARC demonstration device with a center ring magnetic field greater than 12 T, a power gain coefficient Q greater than 2, and a fusion energy greater than 50 MW. Compact high-temperature superconducting tokamak utilizing high-temperature superconducting magnets has become an important research direction for future controlled fusion technology.

In the research front of "mechanism of high temperature superconductor (HTS) material in compact fusion reactor", the top three countries in terms of the number of core papers published are China, the USA, and Japan. The top three countries in terms of the citations per paper are the USA, Republic of Korea, Switzerland, and Russia (Table 1.2.5). In the top ten countries, China has more cooperation with the USA, and Germany has more cooperation with Switzerland (Figure 1.2.4). In the top ten institutions in terms of the number core paper published, Chinese Academy of Sciences, University of Science and Technology of China, and MIT are the top three, and the top three institutions with the highest citations per paper are MIT, University of Colorado, and Princeton Plasma Physics Laboratory (Table 1.2.6). In the top ten institutions, there are more collaborations between Chinese Academy of Sciences and University of Science and Technology of China (USTC), and more collaborations between the National Institute for Fusion Science (NIFS) and Tohoku University (Tohoku, Japan) (Figure 1.2.5). The main output

Table 1.2.5 Countries with the greatest output of core papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	130	27.78	959	7.38	2020.0
2	USA	116	24.79	2 238	19.29	2019.9
3	Japan	72	15.38	994	13.81	2019.6
4	Germany	44	9.40	565	12.84	2019.7
5	Italy	41	8.76	379	9.24	2020.0
6	Switzerland	40	8.55	677	16.93	2020.0
7	UK	30	6.41	350	11.67	2020.2
8	Republic of Korea	25	5.34	456	18.24	2019.5
9	France	22	4.70	271	12.32	2019.5
10	Russia	18	3.85	301	16.72	2019.8

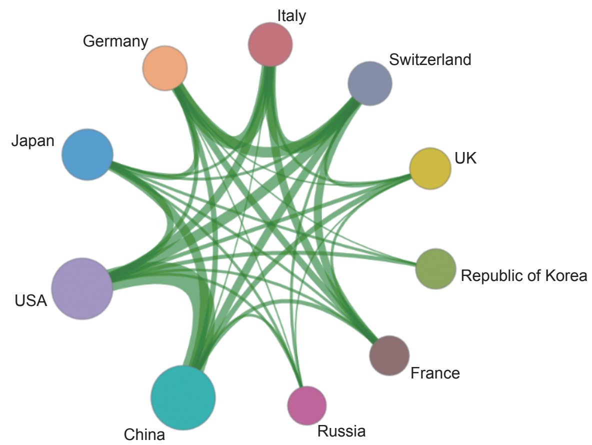

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

Table 1.2.6 Institutions with the greatest output of core papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	87	18.59	517	5.94	2020.0
2	University of Science and Technology of China	42	8.97	234	5.57	2020.2
3	Massachusetts Institute of Technology	29	6.20	1003	34.59	2019.6
4	National Institute for Fusion Science	27	5.77	173	6.41	2019.9
5	Tohoku University	22	4.70	204	9.27	2019.3
6	Politecnico di Torino	20	4.27	195	9.75	2020.1
7	Karlsruhe Institute of Technology	20	4.27	178	8.90	2019.7
8	Princeton Plasma Physics Laboratory	19	4.06	249	13.11	2020.0
9	Lawrence Berkeley National Laboratory	17	3.63	75	4.41	2020.8
10	University of Colorado	15	3.21	265	17.67	2020.9

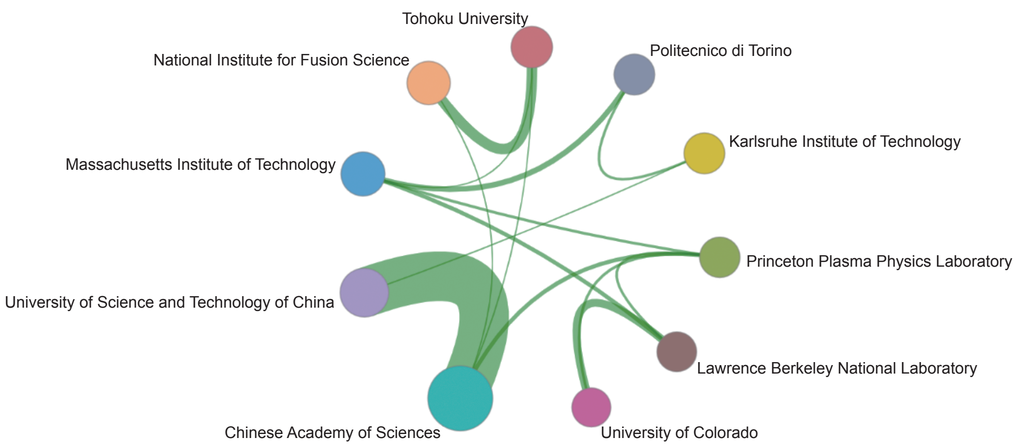

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

countries of citing papers are China and the USA (Table 1.2.7), and the main output institutions of citing papers are Chinese Academy of Sciences, the USTC, and MIT (Table 1.2.8).

In the next ten years, compact fusion reactors built on an international scale utilizing high-temperature superconducting magnets include the SPARC device of MIT, a small-scale version of the planned fusion power plant. The successful operation of SPARC will prove that a full-scale commercially operated fusion power plant is feasible, and can be expected to be a zero-emission, unlimited energy source, clearing the way for the rapid design and construction of commercially available, controllable fusion power stations, clearing the way for the rapid design and construction of a commercial controllable fusion power plant, making fusion power the centerpiece of future clean energy and changing the future energy landscape of the world. After completing the feasibility study on the application of high-temperature superconducting fusion reactors, the construction of high-temperature superconducting fusion power stations will be conducted to realize fusion power generation (Figure 1.2.6).

Table 1.2.7 Countries with the greatest output of citing papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 120	29.11	2021.0
2	USA	828	21.52	2020.8
3	Japan	372	9.67	2020.7
4	Germany	332	8.63	2020.7
5	UK	246	6.39	2021.0
6	Italy	224	5.82	2020.9
7	Republic of Korea	166	4.32	2021.0
8	France	161	4.19	2020.8
9	Switzerland	150	3.90	2020.9
10	Russia	145	3.77	2021.1

Table 1.2.8 Institutions with the greatest output of citing papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	385	32.06	2021.1
2	University of Science and Technology of China	153	12.74	2021.0
3	Massachusetts Institute of Technology	129	10.74	2020.6
4	Shanghai Jiao Tong University	86	7.16	2021.0
5	Oak Ridge National Laboratory	82	6.83	2020.8
6	National Institute for Fusion Science	68	5.66	2020.4
7	Lanzhou University	64	5.33	2021.3
8	Karlsruhe Institute of Technology	61	5.08	2020.4
9	Tsinghua University	61	5.08	2020.6
10	Seoul National University	57	4.75	2021.0

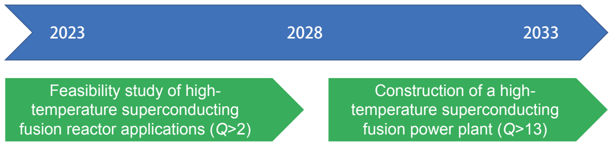

Figure 1.2.6 Roadmap of the engineering research front of “mechanism of high temperature superconductor (HTS) material in compact fusion reactor”

1.2.3 Detecting method of remote sensing image change for energy resources

Change detection is an important direction in the research of remote sensing image processing and analysis methods. The core is to use remote sensing images from different periods at the same region to analyze the change status and correlation of land features. The utilization of remote sensing spectral information has undergone a process from black and white panchromatic images to multispectral, hyperspectral, and time series, while the change detection methods have also evolved from pixel based algebraic calculations to machine learning algorithms and multi method joint algorithms. For example, the traditional methods are to use time series for change detection, including classification, threshold, image transformation, model, etc. In recent years, with the continuous launch of remote sensing satellites equipped with high spatial resolution optical cameras and the widespread application of mobile and flexible drone remote sensing, the number, detection accuracy, and information integrity of remote sensing images have continuously improved. The frequency of obtaining data for the same area has also gradually increased, providing an important foundation for remote sensing image change detection. In this context, the “artificial intelligence plus remote sensing big data” model has become a common consensus in the construction of industry application systems in recent years. The main research directions include the effective extraction of joint features of “time space spectrum” in multi temporal hyperspectral images, high-precision change detection and calculation methods based on deep learning, and so on. High-precision and automated change detection methods have important practical and strategic significance for mineral resource exploration, national ecological environment protection, and marine environmental monitoring.

The International Society of Photogrammetry and Remote Sensing has established a separate working group for change detection for remote sensing imagery research for many years, dedicated to promoting the development of multi-field change detection utilizing the remote sensing technology. The U.S. National Geospatial-Intelligence Agency has also incorporated change detection for remote sensing imagery detection and analysis into strategic planning. China has also attached great importance to the application of the remote sensing change detection technology in the detection of geographical conditions. Since 2010, the Ministry of Land and Resources has been conducting national remote sensing detection work every year, utilizing change detection for multi-temporal remote sensing imagery technology to continuously update national land survey results.

In the engineering research front of “detecting method of remote sensing image change for energy resources”, the main producing country of core papers is China (35), accounting for 97.22% of the total, while other countries account for less than 10%. Italy (3) ranks second, accounting for 8.33% (Table 1.2.9). In terms of the main producing institutions of core papers (Table 1.2.10), China accounts for 8 of the Top 10 institutions. Among them, Wuhan University (13), Chinese Academy of Sciences (6), and Beihang University (4) rank top three. China (777) is also the main producer of citing papers, accounting for 67.80% of the total. The USA (82) ranks second, only accounting for 7.16% (Table 1.2.11). The top three major producing institutions for citing core papers are Wuhan University (125), Chinese Academy of Sciences (116), and Xi’an University (39) (Table 1.2.12). Cooperation in this field is dominated by China, with Italy, the USA, the Netherlands and other countries cooperating around China (Figure 1.2.7). Collaborative research between institutions is concentrated at Wuhan University, Chinese Academy of Sciences, Beihang University, Nanjing University of Information Science and Technology, and Central South University (Figure 1.2.8).

In the next 5–10 years, the detecting methods of remote sensing imaging change for energy resources will usher in a series of important development (Figure 1.2.9). The fusion of high-resolution and multi-spectral data will provide more accurate detection capabilities for resource change, including the application of the multi-source data fusion and hyperspectral technology. In addition, the popularization of machine learning and deep learning technologies will automate the analysis of remote sensing data and reduce the degree of manual intervention. Moreover, time-series data analysis will help better understand the trend and periodicity of resource change, and improve detection accuracy. The use of cloud computing and distributed computing resources will also increase the efficiency of data processing and analysis. These methods will play a key role not only in environmental monitoring, resource management, and climate change research, but also in areas such as smart city planning, sustainable development, precision agriculture, and forest resource management. With continuous development, the application of these detection methods for energy resources will become more extensive, providing more powerful tools for decision-making support and resource management.

Table 1.2.9 Countries with the greatest output of core papers on "detecting method of remote sensing image change for energy resources"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	35	97.22	2 330	66.57	2020.3
2	Italy	3	8.33	193	64.33	2020.7
3	Netherlands	2	5.56	398	199.00	2019.5
4	Germany	2	5.56	54	27.00	2020.0
5	Australia	2	5.56	47	23.50	2020.5
6	USA	1	2.78	20	20.00	2020.0
7	UK	1	2.78	15	15.00	2021.0

Table 1.2.10 Institutions with the greatest output of core papers on "detecting method of remote sensing image change for energy resources"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Wuhan University	13	36.11	1 153	88.69	2020.1
2	Chinese Academy of Sciences	6	16.67	432	72.00	2019.2
3	Beihang University	4	11.11	312	78.00	2020.8
4	Nanjing University of Information Science and Technology	3	8.33	256	85.33	2020.3
5	Central South University	3	8.33	179	59.67	2021.0
6	Utrecht University	2	5.56	398	199.00	2019.5
7	China University of Mining and Technology	2	5.56	138	69.00	2020.0
8	Southwest Jiaotong University	2	5.56	75	37.50	2021.0
9	University of Trento	2	5.56	63	31.50	2021.0
10	Beijing Normal University	2	5.56	28	14.00	2021.0

Table 1.2.11 Countries with the greatest output of citing papers on "detecting method of remote sensing image change for energy resources"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	777	67.80	2021.3
2	USA	82	7.16	2021.1
3	Italy	42	3.66	2021.3
4	Germany	41	3.58	2021.1
5	Republic of Korea	38	3.32	2021.0
6	Canada	35	3.05	2021.3
7	UK	34	2.97	2021.3
8	Netherlands	27	2.36	2020.7
9	India	26	2.27	2021.5
10	France	25	2.18	2020.7

Table 1.2.12 Institutions with the greatest output of citing papers on "detecting method of remote sensing image change for energy resources"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Wuhan University	125	26.54	2021.1
2	Chinese Academy of Sciences	116	24.63	2021.2
3	Xidian University	39	8.28	2021.1
4	China University of Geosciences	31	6.58	2021.4
5	Nanjing University of Information Science and Technology	30	6.37	2021.1
6	Sun Yat-sen University	27	5.73	2021.2
7	Northwestern Polytechnical University	23	4.88	2021.1
8	University Trento	23	4.88	2021.1
9	Beihang University	20	4.25	2021.2
10	German Aerospace Center (DLR)	19	4.03	2021.2

Figure 1.2.7 Collaboration network among major countries in the engineering research front of "detecting method of remote sensing image change for energy resources"

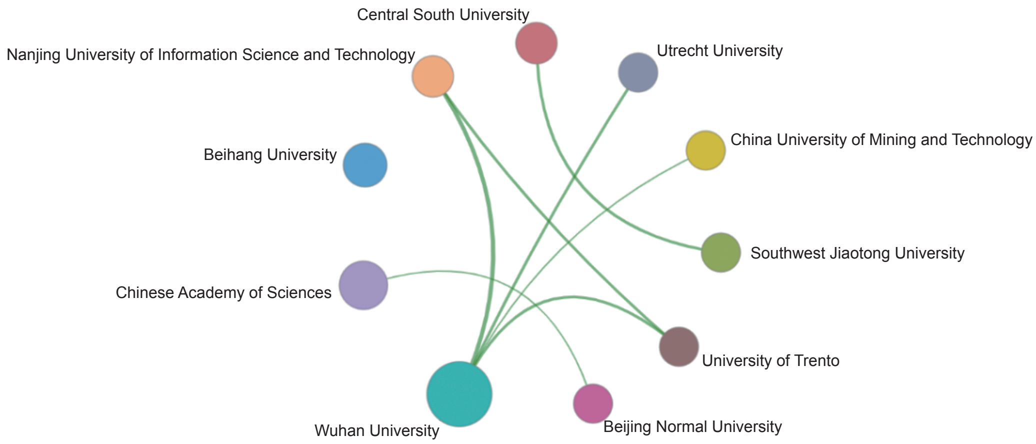

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "detecting method of remote sensing image change for energy resources"

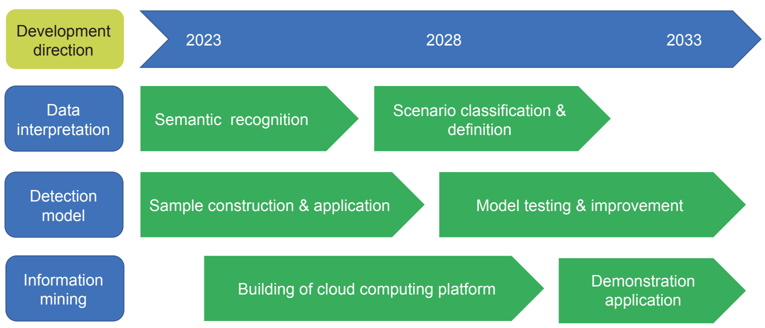

Figure 1.2.9 Roadmap of the engineering research front of "detecting method of remote sensing image change for energy resources"

1.2.4 Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems

Multiscale fractured modeling and simulation of coupled thermo-hydro mechanical processes in rocks for geothermal systems is a pivotal forefront in the interaction between geothermal energy utilization and geological environment. The research in this field aims to deeply understand the thermal, hydrological, and mechanical coupling behaviors of rocks within geothermal systems, providing a scientific foundation for geothermal resource development and management. Over the past few decades, significant progress has been made in this field due to advancements in numerical simulation, computational capabilities, and data monitoring technologies.

The history of research into the thermal-hydro mechanical coupled processes in fracture rocks for geothermal system can be traced back to the 1980s. Initially, the research mainly focused on single-scale experiments and theoretical models, exploring relationships between elements such as temperature, pressure, and water flow within geothermal systems. With the development of experimental equipment and computer technology, multiscale fractured experiments and simulation methods gradually came into play, enabling researchers to more comprehensively unveil the complex coupling behaviors of geothermal systems. In recent years, with the growing attention paid to deep geothermal resources, multiscale fractured simulation research has gained more significance in predicting and addressing challenges in geothermal energy development.

The thermal-hydro mechanical coupled behavior in geothermal systems profoundly impacts the efficiency and sustainability of geothermal energy utilization. Understanding the physical and chemical responses of rocks aids in optimizing geothermal energy production processes and reducing resource waste. Additionally, the fractured behavior of rocks in geothermal systems is closely related to underground water flow and geological hazards, bearing importance for groundwater resource management and geological disaster prevention.

Multiscale fractured simulation research encompasses several aspects: ① cross-scale simulations from micro to macro scales to deeply understand the thermal, hydrological, and mechanical interactions within rocks in geothermal systems; ② coupling experimental research and numerical simulations to validate the accuracy of simulation results; ③ development of efficient algorithms and simulation tools to enhance computational efficiency of multiscale simulations; and ④ application of real-time monitoring and data acquisition techniques to improve the accuracy of simulation models.

In the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”, the main contributing countries are China, the USA, and Australia (Table 1.2.13 and Figure 1.2.10). The primary contributing institutions are Xi’an University of Technology, China University of Mining and Technology, Chengdu University of Technology, and Purdue University (Table 1.2.14). These four institutions have substantial collaboration (Figure 1.2.11). The top three countries in terms of citing papers are China, the USA, and Australia (Table 1.2.15). The main output institutions of citing core papers are China University of Mining and Technology, Xi’an University of and Technology, Henan Polytechnic University, Anhui University of Science and Technology, and Purdue University (Table 1.2.16).

The roadmap of the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems” is presented in Figure 1.2.12. The future development direction will center on following aspects. ① High-precision model construction, coupling effects study, and data-driven simulation. Future research on high-precision model construction will focus on more refined model construction, including inputting more accurate rock physical parameters, pore structures, and geological fracture characteristics. This will contribute to more realistic simulations of the complex thermal-hydro-mechanical coupling behaviors within geothermal systems. ② Coupled effects study will focus on the coupling effects between different scales and different physical processes, exploring the impact of rock thermal, hydrological, and mechanical interactions on geothermal system behaviors. ③ Data-driven simulation will integrate more actual monitoring data to validate model accuracy, optimize parameters, and enhance the reliability of simulation results.

The future development trend in “multiscale fractured modeling and simulation of coupled thermo-hydro mechanical processes in rocks for geothermal systems” will center on followings. ① Multi-physics field coupling: Beyond thermal-hydro mechanical coupling, future research will consider interactions between multiple physical fields such as chemistry and fluid flow, achieving more comprehensive geothermal system simulations. ② High-performance computing application: As computing capabilities improve, future simulation research will increasingly rely on high-performance computing to enable finer and more complex simulations for accurately predicting geothermal system behaviors.

Geothermal energy, as a sustainable form of clean energy, has tremendous potential. Multiscale simulation research contributes to a better understanding of geothermal resource distribution, variations, and sustainable utilization methods. This is crucial for improving development efficiency and reducing environmental risks associated with geothermal energy.

Multiscale fractured simulation research has broad applications in geothermal resource exploration, development, and

Table 1.2.13 Countries with the greatest output of core papers on “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	11	100.00	379	34.45	2021.5
2	USA	4	36.36	118	29.50	2021.2
3	Australia	1	9.09	65	65.00	2022.0

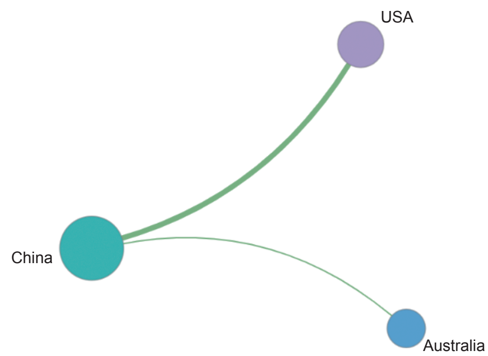

Figure 1.2.10 Collaboration network among major countries in the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

Table 1.2.14 Institutions with the greatest output of core papers on “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Xi’an University of Technology	8	72.73	348	43.50	2021.4
2	China University of Mining and Technology	5	45.45	221	44.20	2021.4
3	Chengdu University of Technology	4	36.36	156	39.00	2021.2
4	Purdue University	4	36.36	118	29.50	2021.2
5	Henan Polytechnic University	4	36.36	42	10.50	2021.5
6	Monash University	1	9.09	65	65.00	2022.0
7	Beijing Research Institute of Uranium Geology (ALBRIUG)	1	9.09	49	49.00	2021.0
8	Hohai University	1	9.09	49	49.00	2021.0
9	Xi’an University of Science and Technology	1	9.09	43	43.00	2021.0
10	Xuzhou University of Technology	1	9.09	23	23.00	2021.0

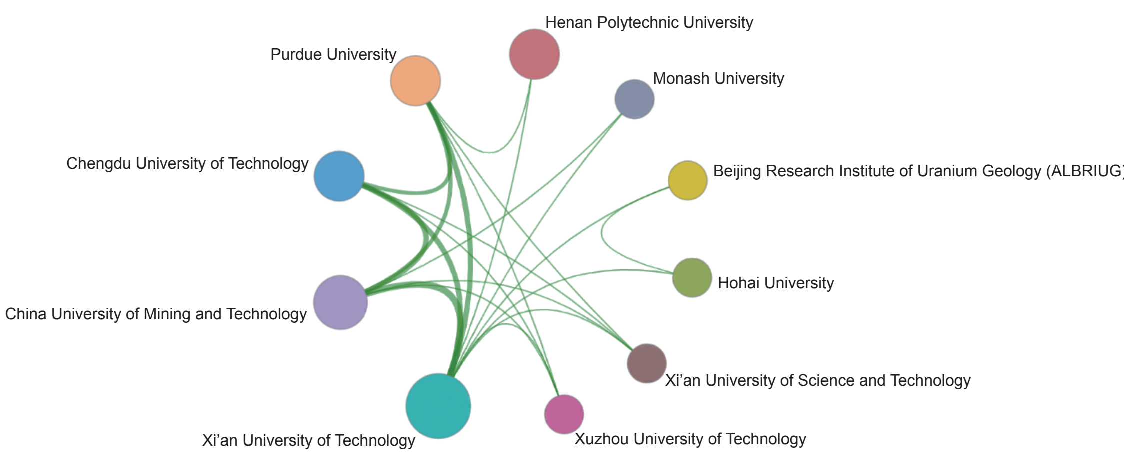

Figure 1.2.11 Collaboration network among major institutions in the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

Table 1.2.15 Countries with the greatest output of citing papers on "multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	190	84.07	2021.9
2	USA	16	7.08	2021.8
3	Australia	8	3.54	2021.8
4	Poland	3	1.33	2022.0
5	UK	2	0.88	2022.0
6	Japan	2	0.88	2022.0
7	Iran	1	0.44	2021.0
8	Russia	1	0.44	2021.0
9	India	1	0.44	2021.0
10	Portugal	1	0.44	2022.0

Table 1.2.16 Institutions with the greatest output of citing papers on "multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Mining and Technology	55	28.21	2021.8
2	Xi'an University of Technology	30	15.38	2021.8
3	Henan Polytechnic University	22	11.28	2021.7
4	Anhui University of Science and Technology	15	7.69	2021.9
5	Purdue University	14	7.18	2021.7
6	Xi'an University of Science and Technology	12	6.15	2021.9
7	Chongqing University	11	5.64	2021.9
8	Xuzhou University of Technology	11	5.64	2021.6
9	Shandong University of Science and Technology	11	5.64	2021.9
10	Guizhou University	8	4.10	2022.0

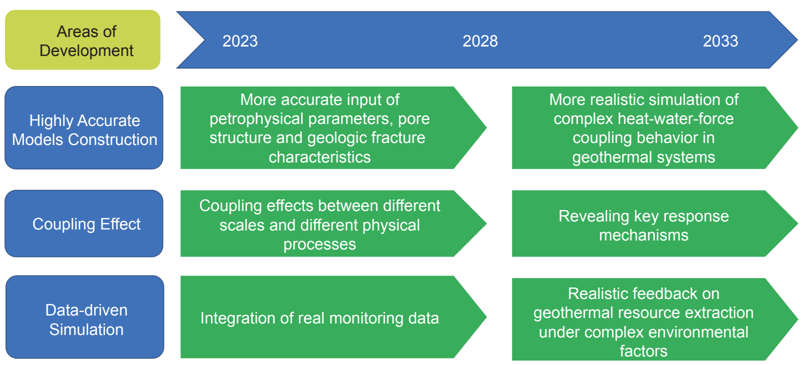

Figure 1.2.12 Roadmap of the engineering research front of "multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems"

management. In geothermal energy extraction processes, it can aid in predicting geothermal system behaviors, optimizing production plans, and reducing production risks. Furthermore, it can be applied to the study of interactions between geothermal energy, groundwater, and geological environments, as well as in designing integrated utilization schemes of geothermal energy and other energy forms.

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. In these 12 engineering development fronts, "fast charging and management technology for batteries", "long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies", and "data-driven technology for security operation and monitoring system of intelligent power distribution networks" represent the engineering development front of energy and electrical science; "fast reactor metal fuels, nitride & carbide fuel and fuel cycles", "deuterium tritium operation experiment of device Tokamak", and "nuclear energy hydrogen production-industrial application coupling technology" represent the engineering development front of nuclear science, technology, and engineering; "exploration method for mineral deposits utilizing high-precision ground gravity measurement", "seismic data interpretation and utilization based on deep learning", and "research and development of portable geological exploration and sampling device" represent the engineering development front of geology resources science, technology, and engineering; "research on intelligent collaborative platform for oil and gas exploration and development", "optimal and rapid drilling technology of long horizontal well on large platform in shale reservoir", and "research and development of intelligent perception drilling detection equipment for coal mines under complex conditions" represent the engineering development front of mining science, technology, and engineering.

The disclosure of core patents involved in each development front from 2017 to 2022 is presented in Table 2.1.2.

(1) Fast charging and management technology for batteries

The capability of Li-ion/Na-ion batteries determines the competitiveness and performance of electric vehicles. The full charging time of the existing power battery is about 60 minutes, which is 20 times of the refueling time of the car. As a result, achieving fast-charging can enhance the market share and broaden applications of electric vehicles. The United States Advanced Battery Consortium has proposed specific indicators for power battery charging, requiring 80% of the total battery power to be charged within 15 min. However, due to the polarization from sluggish ion transport, fast-charging often causes metal plating at the anode side, leading to capacity decay and safety issues. Management technologies and battery material modification are two major strategies towards fast-charging. These strategies enhance the fast-charging capability of batteries by lowering the energy barrier of the rate-limiting step for the entire charging process. The aforementioned management technologies include battery intelligent temperature control system and algorithm optimized charging protocol, while material modification mainly focuses on electrode design, anode material, binder, electrolyte, and solid electrolyte interphase (SEI). Nevertheless, rate-limiting step of the entire charging process is hard to identify, and may varies with external conditions or cycling parameters, which makes strategies aiming at a single step less effective. Under this circumstance, it is necessary to switch from suppressing Li or Na plating to regulating Li or Na plating. Through a series of metal plating regulation methods such as SEI engineering, a uniformly-distributed, less-dendritic, and highly-reversible Li or Na plating at the anode side in fast-charging operations can be realized. This not only intrinsically solves safety problems from Li or Na dendrite plating, restoring the cycling life, but also increases the state of charge under fast-charging. Therefore, this Li or Na plating regulation as well as morphology control is one of the most important tendencies in future development of fast-charging, which is an important trend in the development of fast charging technology in the future.

Table 2.1.1 Top12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Fast charging and management technology for batteries	464	15 925	34.32	2018.5
2	Fast reactor metal fuels, nitride & carbide fuel and fuel cycles	312	507	1.62	2019.9
3	Exploration method for mineral deposits utilizing high-precision ground gravity measurement	342	5 472	16.00	2018.5
4	Research on intelligent collaborative platform for oil and gas exploration and development	275	618	2.25	2020.4
5	Long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies	1 616	2 558	1.58	2020.1
6	Data-driven technology for security operation and monitoring system of intelligent power distribution networks	109	3 137	28.78	2019.0
7	Deuterium tritium operation experiment of device Tokamak	143	216	1.51	2020.0
8	Nuclear energy hydrogen production-industrial application coupling technology	142	181	1.27	2019.8
9	Seismic data interpretation and utilization based on deep learning	336	4 714	14.03	2019.1
10	Research and development of portable geological exploration and sampling device	872	497	0.57	2020.3
11	Optimal and rapid drilling technology of long horizontal well on large platform in shale reservoir	392	8 076	20.60	2018.6
12	Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions	178	1 930	10.84	2019.8

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	2017	2018	2019	2020	2021	2022
1	Fast charging and management technology for batteries	136	119	96	73	39	1
2	Fast reactor metal fuels, nitride & carbide fuel and fuel cycles	43	32	54	49	65	69
3	Exploration method for mineral deposits utilizing high-precision ground gravity measurement	92	94	70	56	26	4
4	Research on intelligent collaborative platform for oil and gas exploration and development	9	31	40	36	71	88
5	Long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies	178	210	219	225	319	465
6	Data-driven technology for security operation and monitoring system of intelligent power distribution networks	22	21	24	21	18	3
7	Deuterium tritium operation experiment of device Tokamak	14	18	25	21	27	38
8	Nuclear energy hydrogen production-industrial application coupling technology	24	21	17	15	26	39
9	Seismic data interpretation and utilization based on deep learning	51	68	86	70	56	5
10	Research and development of portable geological exploration and sampling device	51	101	82	176	237	225
11	Optimal and rapid drilling technology of long horizontal well on large platform in shale reservoir	104	84	103	52	47	2
12	Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions	18	15	22	58	64	1

(2) Fast reactor metal fuels, nitride & carbide fuel and fuel cycles

There are two types of fast reactor fuel that have been used internationally, ceramic fuel and metal fuel. Fast reactor metal fuel, nitride and carbide fuel are being developed internationally. Such fuels have a higher breeding ratio than oxide fuels.

Metal fuel has the characteristics of high thermal conductivity, low fuel temperature, and high safety margin. The swelling can be inhibited by the improvement of material technology. Fast reactor metal fuel is recognized as one of the main types of fast reactor fuel in the future. The metal fuel manufacturing process is more simplified, and the metal fuel and dry reprocessing (separated metals are U and Pu) can better directly cooperate with the production of new fuels, forming an integrated fuel cycle system.

The research and development of metal fuel mainly focuses on U-Zr alloy and U-Pu-Zr alloy. The metal fuel usually consists of a binary alloy of U-10Zr alloys or a ternary alloy of U-Pu-10Zr. MAs is added to oxide fuel and metal fuel to become transmutation fuel.

Mixed plutonium-uranium nitride fuel and carbide fuel are new fuel forms under development. The plutonium uranium density of UPuN and UPuC is higher than that of oxide fuel, which can obtain a higher breeding ratio, a shorter breeding time, a better thermal conductivity, and an excellent compatibility with sodium coolant and stainless-steel cladding.

Many countries in the world have conducted the research and development and application of carbide and carbide fuel. The USA, France, Russia, India, and other countries have conducted research and development of a variety of carbides and carbide fuels. Russian Fast Reactor (in addition to MOX) fuel selected mixed nitride fuel (MNUP) as one of the future fast reactor fuel options. The experimental fast reactor FBTR in India uses carbide (Pu, U)C fuel.

(3) Exploration method for mineral deposits utilizing high-precision ground gravity measurement

Ground gravity measurement refers to the method of utilizing the gravimeter to measure the gravity at a certain point on the ground, and utilizing the change of underground density reflected by the gravity for mineral exploration. It is one of the important geophysical prospecting methods to conduct regional geological research, mineral exploration and resource investigation by analyzing the characteristics of relative gravity and absolute gravity.

The technology of ground gravity measurement has been greatly developed in China and abroad. Based on the idea of zero-length spring, the USA and Canada have designed and produced a quartz spring gravimeter which has a measurement accuracy of 5 μGal. China has reached 30 μGal. A quartz spring gravimeter has played a significant role in mineral exploration, and is still the main technical equipment in the world. However, the traditional spring gravimeter has been developed to the extreme level, with little margin for improving measurement accuracy.

At present, based on the principle of atomic interference, a number of ground absolute gravimeters and gravity gradiometers have been developed in China and abroad. The absolute gravimeter measurement sensitivity reaches 4.2–44.0 $\mu Gal/Hz^{1/2}$, the gravity gradiometer can measure the gravity gradient signal to 170 E, and the probe volume is significantly reduced. As a new generation of quantum gravity sensor, the atomic gravimeter is expected to have a measurement sensitivity of 10^{-4} μGal. However, it faces with challenges such as miniaturization and improved measurement accuracy. Atomic gravimeter also faces problems such as insufficient scaling factor and low phase extraction efficiency. The atomic gravimeter also faces enormous challenges in practical application.

The main research direction is the development of miniaturized and high-precision atomic absolute gravimeter/gravity gradiometer, fine data processing and interpretation, etc., providing more accurate and technologically more advantageous exploration technologies, which has important practical and strategic significance for building the security of China's mineral resources.

(4) Research on intelligent collaborative platform for oil and gas exploration and development

The intelligent collaborative platform for oil and gas exploration and development refers to the provision of an integrated environment that encompasses information sharing, technological innovation, production and operation integration, and intelligent collaboration, facilitating multidisciplinary interaction and integrated exploration and development. In the current wave of oil and gas technological and digital revolutions, the integration of new technologies such as big data and artificial intelligence with the oil and gas industry has become a significant avenue for innovation. Foreign oil and gas companies, such as Shell, Schlumberger, Halliburton, BP, Chevron, and Eni, have made initial progress in constructing intelligent platform solutions for exploration and development. However, the global informatization level of the oil and gas industry remains relatively low, far below the industry average. Presently, China is still in the transitional phase from digitization to intelligence. China National Petroleum Corporation (CNPC) has made phased progress in establishing the "Exploration and Development Dream Cloud" platform. Sinopec has built the "Petrochemical Intelligence Cloud" platform, and China National Offshore Oil Corporation (CNOOC) has constructed collaborative working environments and systems for onshore and offshore exploration and development. Yet, the overall development still lags behind international counterparts.

The key research directions include artificial intelligence technology, intelligent oil and gas exploration, integrated geological engineering, intelligent equipment research and development, cloud computing platform construction, and data sharing, etc. The developmental trend involves the organic integration of hardware facilities, software development, digital technology, and oil and gas expertise, culminating in a fully digitized, automated, and intelligent professional application environment for exploration and development. It is expected to change the mode of exploration and development work, enhance efficiency, maximize comprehensive benefits, propel the digital transformation and intelligent development of the oil and gas industry, and safeguard national energy security.

(5) Long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies

Thermal energy storage (TES) and thermo-mechanical energy storage (TMES) technologies are energy storage techniques based on heat and mass transfer, and reversible heat-work conversion. They make large-scale energy storage possible from both technical and economic perspectives and realize long-term and seasonal energy storage. With advantages such as high energy density, flexible utilization, high overall efficiency and controllable costs, they are crucial for promoting the green transformation of energy and building zero-carbon power systems based on renewable energy sources. TES technologies include sensible heat storage, latent heat storage, and thermochemical heat storage. TMES technologies encompass compressed-air/CO_2 energy storage, liquid-air/CO_2 energy storage, and Carnot battery (also known as pumped-thermal electricity/energy storage).

The main technical directions for long-term and large-scale TES and TME technologies include the construction of multiscale coupling mechanisms between heat storage and heat/mass transfer, active control strategies for the physical and chemical properties of heat storage materials, the development and preparation of safe and effecient encapsulation and insulation materials, structural optimization techniques for heat storage units based on the topology optimization theory and AI algorithms, high entropy efficiency compression and expansion techniques under extreme temperature and pressure conditions, thermodynamic and economic analyses of TES and TMES systems, and intelligent operation and control techniques for multi-scenario operation of TES and TMES systems.

The development trend in this field at the material level is that novel composite heat storage materials can be designed and prepared actively based on comprehensive considerations of their thermo-physical properties, corrosiveness, and stability. At the component level, combined with additive manufacturing technologies such as 3D printing, heat storage units and compressors/turbines with a high degree of freedom for specific targets can be explored and developed. At the system level, TES and TMES systems can be integrated with the zero-carbon power and fuel systems, and extend to smart energy systems that provide flexible energy solutions.

(6) Data-driven technology for security operation and monitoring system of intelligent power distribution networks

As informatization and automation of intelligent power distribution networks continues to improve, the amount of data collected from the operation of power distribution networks has increased dramatically. At the same time, the deep integration of power distribution networks and the Internet of Things has also promoted data interaction within and outside power companies. There gradually forms a big data environment for the secure operation and monitoring of intelligent power distribution networks. However, the types of data obtained from power distribution networks are diverse and the granularity of data is high. In addition, the correlation between online and offline data is extremely complex. Existing model-based analysis, calculation, and optimization control methods for power distribution networks cannot be adapted for practical application. It is urgent to explore data-driven analysis and decision-making, operation optimization, monitoring and control technologies for intelligent power distribution networks to achieve comprehensive intelligent improvement in monitoring, dispatching, protection, control of power distribution systems empowered by big data. The main research directions of data-driven secure operation and monitoring technology for intelligent power distribution networks include development of multi-parameter sensors and edge computing devices for intelligent power distribution networks; security and privacy protection mechanisms for distribution network data communication networks; operation situation awareness and digital twin AI modeling technology for intelligent power distribution networks; multiscale, refined data mining and data fusion technology for intelligent power distribution networks; data-driven aggregation control and interactive support technology for massive demand-side resources in power distribution systems; data-driven source-network-load-storage optimization scheduling method for intelligent power distribution networks; and protection and control technology for smart distribution networks based on fault data mining.

(7) Deuterium tritium operation experiment of device Tokamak

Magnetic confinement deuterium-tritium fusion based on tokamak is by far the most promising way for the development of controlled fusion energy. In the context of “carbon neutrality” and the increasing demand for energy in the long-term development, developing fusion energy is the ultimate way to solve energy problems. Tritium is a rare radioactive isotope that, when fused with the isotope deuterium, produces more neutrons and energy output compared to reactions between deuterium-deuterium particles. Deuterium-tritium reaction reaches fusion conditions at lower temperatures compared to other elements. However, due to the short half-life of tritium and difficulties in preparation, its price is extremely high. Only deuterium is used in most of the experiment in devices at present. Therefore, in order to verify the physical and engineering challenges involved in deuterium-tritium fusion reactions, the International Thermonuclear Experimental Reactor (ITER) is scheduled to conduct deuterium-tritium plasma experiments starting from 2035. By conducting deuterium-tritium fusion experiments, fusion performance can be directly verified, tritium related behavior in tokamak can be analyzed, and deuterium-tritium plasma behavior, alpha particle behavior, and their impact on plasma can be studied. The key issues in tokamak deuterium- tritium experiments include alpha particle heating related physics, plasma energy confinement, isotope effect, particle transport, magnetohydrodynamic (MHD) stability, fusion power production, demonstration of safe handling of tritium, tritium breeding system, safe remote maintenance of tokamak, etc.

(8) Nuclear energy hydrogen production-industrial application coupling technology

Compared with traditional hydrogen production technologies, nuclear energy hydrogen production has advantages such as cleanliness, high efficiency, and economy. Therefore, the scientific research and industrial application of nuclear energy hydrogen production have gradually become a hot spot. Electrolytic water hydrogen production —the direct application of hydrogen or the form of energy storage for power generation is expected to become another commercial application of large-capacity long-term energy storage technology besides pumped storage. At the same time, the industrial application of nuclear energy hydrogen production includes the supply of diversified products of water, electricity, and hydrogen from nuclear energy to petrochemical parks, to supply water thermoelectric hydrogen diversified products, and the application in the fields such as fuel synthesis and metallurgy.

Applications in hydrogen and synthetic fuel production include the production of hydrogen by Cu-Cl thermochemical mixing cycle utilizing the heavy water reactor ACR-700 in Canada. Germany has utilized the prototype reactor to produce process heat and produce mixed gas through coal gasification. Japan has proposed the concept of utilizing GTHTR300C for hydrogen production. South Africa has proposed the concept of PBMR with steam improvement and thermochemical sulfur mixing cycle. The USA has proposed a plan for hydrogen production by high-temperature steam electrolysis utilizing H_2-MHR. Japan proposed the concept of utilizing GTHTR300C to make steel. There are also hydrogen-based green fuel synthesis technology, the hydrogen metallurgy technology, the coal ammonia mixed combustion technology, and the hydrogen doped/hydrogen burning turbine technology. The coupling technology of hydrogen energy industrial applications mainly include process simulation and optimization, high-efficiency reactor, corrosion resistance test of engineering materials, measurement and control technology of engineering materials.

(9) Seismic data interpretation and utilization based on deep learning

The fields of Earth science and energy are undergoing unprecedented changes by deep learning. The seismic interpretation technology based on deep learning simulates the neural structure of the human brain to achieve automatic learning and analysis of seismic data, which brings great potential for geological exploration, reservoir prediction and oil and gas development. Foreign companies such as Schlumberger, CGG, and Halliburton have made significant progress in the seismic interpretation technology based on deep learning. They have successively launched intelligent fault identification, layer pickup, and seismic analysis, and other products, achieving efficient and accurate structural interpretation and reservoir analysis function, providing important technical support for energy exploration and development. At present, China is faced with challenges such as deep ultra-deep exploration, unconventional heterogeneous reservoir, engineering dessert prediction, and improving oil recovery in abandoned oil and gas fields. New and higher requirements are proposed for high-precision seismic interpretation technology. The seismic data interpretation technology based on deep learning is expected to become the key to improving the efficiency of oil exploration and oil and gas development. China has made phased progress. Although individual technologies have ranked in the forefront of the world, the overall level still needs to be improved. The research direction of the seismic interpretation technology based on deep learning includes the intelligent logging analysis technology, intelligent structure interpretation, reservoir prediction and reservoir development, etc. The future development will cover multi-physical field data fusion, the construction of an automated interpretation platform, intelligent description of reservoirs, and real-time seismic monitoring. The integration of seismic data with other geological and geophysical data will further improve the accuracy and reliability of interpretation. At the same time, an intelligent interpretation platform should be established to realize the integrated process from data pre-processing to result visualization. In addition, deep learning techniques will be combined with geological simulation to achieve intelligent description of reservoir properties to assist in oil reservoir evaluation and optimization. These technologies will bring new breakthroughs to geoscience and energy.

(10) Research and development of portable geological exploration and sampling device

The portable geological exploration and sampling device consists of portable drilling rig, sampling tools, flushing fluid circulation system and other apparatus. It is based on a lightweight and modular design, easy to disassemble and transport, and suitable for geological exploration sampling in areas with inconvenient transportation and limited construction sites. A relatively complete technology and equipment system has been established abroad. The equipment in China has similar drilling capabilities to foreign countries, However, there are still gaps in sampling technology system construction, and equipment automation, and other aspects. At present, the key investigation areas for the new round of strategic breakthrough in mineral exploration in China have shifted to areas like coverage areas, mid to high mountains, and deep cutting areas. Portable geological exploration and sampling devices are key technical equipment for coordinating mineral exploration and development, ecological protection, and practicing green exploration. The main research directions for the development of portable geological exploration and sampling devices include light weighting of drilling rigs, high-efficiency drilling process, electrification and automation upgrading, and integration of comprehensive technology for green exploration. The development trend of portable geological exploration and sampling devices include the optimization of structure, materials, and automation upgrade of drilling process, to improve the portability of drilling rigs and reducing personnel labor intensity; realization of green exploration through the research and application of technologies such as clean energy driven, environmentally friendly flushing fluids, and mud non-landing system; the study of sampling technology system, which meets the requirements of different geological conditions and geological needs for efficient in-situ pollution-free sampling; the integration of multiple processes and carriers of one drilling rig, to achieve multiple functions and improve problem-solving capabilities; and the research of supporting parameter monitoring system, in combination with the artificial intelligence technology, to achieve diagnosis of working conditions, lithology identification and so on.

(11) Optimal and rapid drilling technology of long horizontal well on large platforms in shale reservoir

Shale reservoirs have the characteristics of “low porosity and low permeability”, whose production relies on horizontal drilling and hydraulic fracturing technologies. The optimal and rapid drilling technology of long horizontal well on large platform refers to the simultaneous arrangement of multiple long horizontal wells on a single platform to reduce the occupied area of the well site, increase the control volume of the underground oil and gas reservoir, achieve high-quality and rapid drilling in shale reservoirs, shorten drilling cycles, and lower operational costs. The USA and Canada were pioneers in commercial shale oil and gas production, while China is accelerating its entry into the phase of industrialized commercial production. The Southwest oil and gas field drilled China’s first shale gas horizontal well and the first commercially valuable shale gas well. Changqing Oilfield has established the largest onshore shale oil long horizontal well platform in Asia, the Hua H100 platform. The horizontal section of well H90-3 measures 5 060 meters, marking the longest onshore horizontal section length in Asia. However, compared to the primarily marine shale reservoir conditions in North America, the predominantly terrestrial shale reservoirs in China are buried deeper, have complex topography, poor stratigraphic continuity, intense fragmentation, high technical requirements and development costs, posing significant drilling and production challenges. The main research directions include factory-like operation techniques, optimized horizontal well trajectory, accelerated horizontal well supporting technologies, wellbore structure optimization, enhanced drilling parameters, drilling fluid system optimization, speed-enhancing equipment development, efficient directional drilling patterns, and comprehensive friction reduction and sliding guidance technology research. Undertaking large-scale operations based on long horizontal wells as a foundation, researching efficient drilling and completion techniques, holds the potential to facilitate the efficient development of shale oil and gas in China.

(12) Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions

Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions is an advanced technological apparatus designed to address the complex conditions and high risks of deep coal mining environments. Its core concept involves integrating artificial intelligence, the sensor technology, data analysis, and related fields to make the drilling process more intelligent, automated, and capable of perceiving real-time underground mining conditions in real-time, ensuring the safety of miners and enhancing the efficiency of mining.

In terms of primary technological directions, the development of intelligent perceptive drilling equipment for coal mines covers several key areas. The first is the development of high-precision sensor technology, including geological exploration sensors, temperature-humidity sensors, gas detection sensors, etc. which can monitor the physical parameters and environmental conditions of underground coal seams in real time. The second is the development of data collection and processing technology which is the foundation for intelligent perception. By utilizing big data analysis and machine learning algorithms, data collected by sensors is transformed into useful information, predicting potential risks and making corresponding decisions. The last is the development of the automation control technology, the utilization of which can automate the drilling processes, reduce manual intervention, thereby minimizing accident risks.

With ongoing technological advancements, the development trends of intelligent perceptive drilling equipment for coal mines are becoming increasingly apparent. On the one hand, more emphasis will be placed on multi-modal data fusion, incorporating data from various types of sensors to achieve comprehensive underground information gathering. On the other hand, more emphasis will be placed on intelligent decision-making support, utilizing advanced algorithms and models to achieve automated risk prediction and emergency response. Additionally, breakthroughs in communication technology are anticipated, enabling real-time data transmission between the underground environment and surface command centers, thereby enhancing the efficiency of overall emergency response.

2.2 Interpretations for four key engineering development fronts

2.2.1 Fast charging and management technology for batteries

Realizing fast charging of batteries can enhance the market share and broaden the application of electric vehicles. When charging a battery, Li or Na ions leave from layered cathodes and get solvated with electrolyte solvents, all the way heading for the anode side through electrolyte and are finally inserted into layered anodes. The precise understanding of the rate-limiting step of the above charging process remains controversial, but it is widely believed that ion de-solvation, transport in SEI, and diffusion in anode are possible rate-limiting steps. The inferior kinetics of the rate-limiting step increase the internal resistance of the battery during fast-charging, thus causing Li or Na plating on anode surface, which eventually leads to safety problems and capacity decay.

The battery management technology and material modification can effectively enhance the fast-charging performance. The management technology includes battery intelligent temperature control system and algorithm optimized charging protocol. The former can heat the cell to an elevated temperature to boost the ion conduction, thus reducing the resistance of the rate-limiting step. However, the control of the temperature with surgical precision is challenging. The latter can balance and optimize multiple signals and parameters inside a cell, though there is still lack of data supporting.

Battery material modification include the research in electrode design, anode material, binder, electrolyte and SEI. Electrode with three-dimensional and gradient design can enhance active reacting interfaces, thereby accelerating ion diffusion. However, due to cost, fabrication, and energy density limitations, this solution is currently difficult to popularize. Advanced anode materials such as silicon, red/black phosphorus have excellent fast-charging capabilities. However, their electrical conductivity and volume expansion still need extensive research efforts. Mixed ion-electron conducting binders are also designed for fast-charging applications. However, it is difficult for mass production. Electrolyte with weak solvation structure can be used in fast-charging operations, but the difficulty is how to improve the oxidative stability and voltage window of such electrolytes. SEI engineering, by constructing a inorganic-rich SEI, has been confirmed to be effective in enhancing fast-charging capability. In addition, this strategy can also regulate Li or Na plating and tuning its morphology, ensuring a uniform, dendrite-free, and high-reversible plating behavior, which not only can solve the intrinsic problems caused by dendrites plating, but also can achieve a 100% state of charge for fast-charging.

In the engineering research front of “fast charging and management technology for batteries”, China ranks first in the world with 217 published patents, accounting for 46.77%, followed by the USA, Japan, and Republic of Korea (Table 2.2.1). Of all the parties, the USA and Republic of Korea have extensive cooperation, while China has cooperation with the USA and Canada (Figure 2.2.1). Institutions with large number of published patents are Nanotek Instruments Incorporated, Samsung Electronics Company Limited, Tsinghua University, and Ningde Contemporary Amperex Technology Limited (Table 2.2.2). Nanotek Instruments Incorporated has very close cooperation with Global Graphene Group Incorporated. United Technologies Corporation has extensive cooperation with Raytheon Corporation. Tsinghua University and Ningde Contemporary Amperex Technology Limited have close cooperation (Figure 2.2.2).

Realizing fast-charging procedure for Li-ion and Na-ion batteries depends on the synergistic development of battery material modification and management technology. For battery management technology, it is necessary to further develop the temperature control system and charge protocol, in order to achieve precise tuning of cell temperature, reduced system volume and cost. It is also important to complete algorithm network and realize real-time feedback for battery status. A more effective charge protocol with large output power and accurate monitoring of Li or Na plating at anode side is also highly desired. In the area of battery material modification, it is essential to design three-dimensional electrode, functional binder, weak-solvation electrolyte, and inorganic component-based SEI that significantly reduces internal resistance and inhibits Li or Na plating. In addition, the anode material should be switched gradually from carbon-based to silicon-based and eventually phosphorus-based materials. Moreover, based on the previous research, SEI engineering is still needed to regulate Li or Na plating during fast-charging operations, towards a uniformly-distributed, non-dendritic and highly-reversible Li or Na plating at anode side. Finally, this advanced battery with multiple technologies integrated is expected to realize a 3-minute fast- and full-charging performance on electric vehicles. The roadmap of the engineering development front of “fast charging and management technology for batteries” is presented as Figure 2.2.3.

Table 2.2.1 Countries with the greatest output of core patents on “fast charging and management technology for batteries”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	217	46.77	5 840	36.67	26.91
2	USA	144	31.03	6 002	37.69	41.68
3	Japan	37	7.97	1 481	9.30	40.03
4	Republic of Korea	34	7.33	1 448	9.09	42.59
5	Canada	9	1.94	329	2.07	36.56
6	Germany	9	1.94	321	2.02	35.67
7	UK	6	1.29	194	1.22	32.33
8	Israel	5	1.08	270	1.70	54.00
9	Denmark	4	0.86	118	0.74	29.50
10	France	2	0.43	61	0.38	30.50

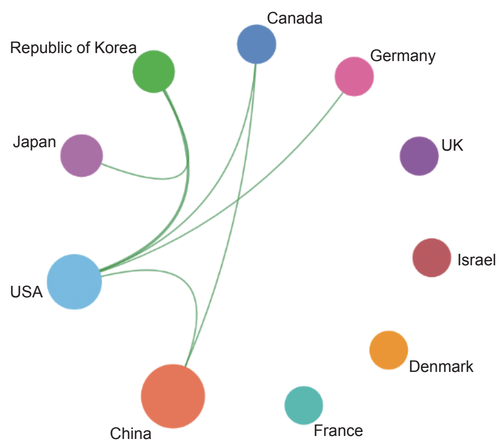

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “fast charging and management technology for batteries”

Table 2.2.2 Institutions with the greatest output of core patents on “fast charging and management technology for batteries”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nanotek Instruments Incorporated	37	7.97	1 738	10.91	46.97
2	Samsung Electronics Company Limited	21	4.53	912	5.73	43.43
3	Global Graphene Group Incorporated	19	4.09	850	5.34	44.74
4	United Technologies Corporation	19	4.09	658	4.13	34.63
5	General Electric Company	18	3.88	693	4.35	38.50
6	LG Chemistry Limited	10	2.16	425	2.67	42.50
7	Tsinghua University	10	2.16	356	2.24	35.60
8	Kabushiki Kaisha Toshiba	8	1.72	361	2.27	45.12
9	Ningde Contemporary Amperex Technology Limited	8	1.72	235	1.48	29.38
10	Raytheon Corporation	8	1.72	227	1.43	28.38

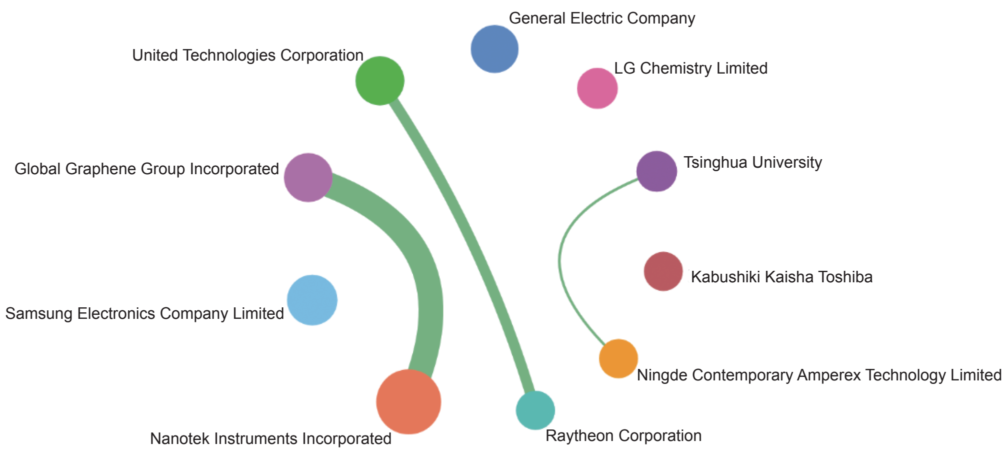

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "fast charging and management technology for batteries"

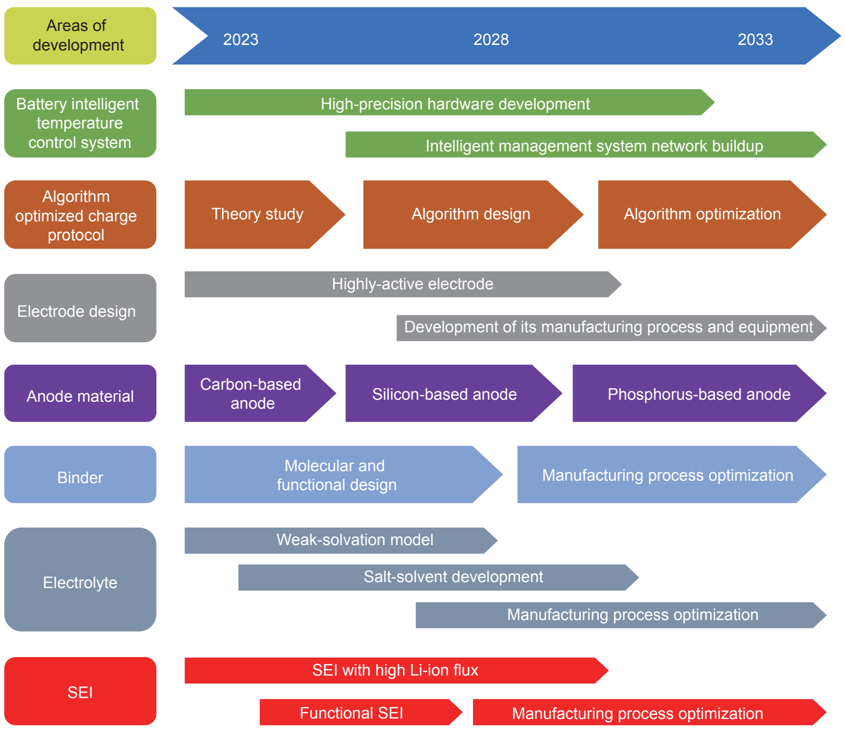

Figure 2.2.3 Roadmap of the engineering development front of "fast charging and management technology for batteries"

2.2.2 Fast reactor metal fuels, nitride & carbide fuel and fuel cycles

The fast reactor nuclear energy system can realize closed nuclear fuel cycle through nuclear fuel reprocessing, ensuring the sustainable development of nuclear energy. Utilizing fast reactor technology can effectively utilize ^{238}U (accounting for 99.3% of natural uranium), which can meet the needs of nuclear energy development based on domestic uranium resources. It can effectively incinerate long-life radioactive waste and solve the problem of environmental friendliness. High temperature and radiation resistance are the most important characteristics of fast reactor fuels, which means that the extended reactor life reduces the requirements for the outer part of the fuel cycle. Generating high power while maintaining a relatively low fuel temperature is also an important feature. Fast reactors can achieve fuel proliferation and MA transmutation, and recycle all elements, including uranium, plutonium and MA, through simplified and efficient dry reprocessing.

The nuclear fuel suitable for fast reactors should have a long in-reactor residence time, be able to withstand repeated power transients, be able to provide high power density, have a large margin to cope with overpower, good ability to cope with cladding failure, simple manufacturing, simple and economical post-processing technology and other characteristics. The advantages of metal fuel are good nuclear characteristics, hard energy spectrum, and close to the theoretical upper limit of proliferation. Nitride and fluoride nuclear fuels, still classified as ceramic fuels, have the advantage of a better proliferation capacity and a shorter fast reactor doubling time compared to oxide fuels. Another advantage of metallic fuel in sodium-cooled fast reactors is that the reactor can continue to operate without contaminating the coolant in the event of damage to the cladding and exposed fuel. In addition, the metal fuel greatly reduces the requirements of the fuel cycle outside the reactor. The manufacture is simple, easy, and cost-effective, with fewer post-treatment processes, and compact and economical recycling facilities. Deep burnup reduces the flow of fissile materials, thus, metallic fuels lay the foundation for a more economical fuel cycle.

Argonne National Laboratory in the USA developed the integrated fast reactor based on metal fuel from 1984 to 1994. TerraPower in the USA proposed the concept of traveling wave reactor around 2006 and conducted engineering design research. The traveling wave reactor has the characteristics of deep burnup, which can realize in-situ proliferation and incineration of ^{238}U in the reactor, so as to effectively improve the utilization rate of natural uranium resources through one pass. In 2012, Russia’s national strategic plan for the peaceful use of nuclear energy “Breakthrough” program was officially launched, planning to build a fast reactor, closed fuel cycle technology, reprocessing, advanced nuclear fuel and new structural materials and other fields of engineering construction and related scientific research, to achieve the same site closed nuclear fuel cycle.

In terms of fast reactor technology, China has built a 65 MWt China Experimental Fast Reactor (CEFR) and is building a 600 MWe Demonstration Fast Reactor. Research on integrated fast reactor system is being conducted, which consists of a reactor and supporting fuel regeneration facilities. The reactor adopts a metal fuel fast reactor, and simultaneously realizes three functions of power generation, proliferation, and transmutation. The fuel regeneration facility integrates dry reprocessing and fuel manufacturing processes. The reactor and fuel recycling facilities are designed at the same site to realize the integration of closed fuel cycle processes.

Table 2.2.3 lists the main countries with the greatest output of core patents on “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”. It can be observed that the main output countries are China, Japan, and the USA, among which the amount of patent disclosure and the proportion of patent citations in China is much higher than that in other countries. There is no cooperation among major producing countries. As can be seen from Table 2.2.4, Nuclear Power Institute of China has disclosed a large number of patents. In terms of cooperation among major institutions, TerraPower Limited Liability Company has cooperated with General Electric Company, Nuclear Power Institute of China, and China Nuclear Power Technology Research Institute (Figure 2.2.4).

The roadmap of the engineering development front of “fast reactor metal fuels, nitride & carbide fuel and fuel cycles” is shown in Figure 2.2.5. The development goal of metal fuel is to master the manufacturing technology and process of U-Zr alloy, and it is expected to complete the irradiation test of U-Zr alloy metal fuel assemblies by 2030, with a burnup consumption of 150 GWd/tHM. The development path for the fast reactor and other advanced reactor fuels is to conduct research and development of nitride, carbide, U-Pu-Zr, U-Pu-Am-Zr alloy and other advanced fuels, and break through the manufacturing process and key technologies by 2033 to provide higher-performance fuel for advanced reactor.

Table 2.2.3 Countries with the greatest output of core patents on “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	162	51.92	237	46.75	1.46
2	Japan	47	15.06	28	5.52	0.60
3	USA	39	12.50	196	38.66	5.03
4	Republic of Korea	26	8.33	10	1.97	0.38
5	Russia	23	7.37	9	1.78	0.39
6	Sweden	4	1.28	16	3.16	4.00
7	France	3	0.96	4	0.79	1.33
8	Canada	1	0.32	3	0.59	3.00
9	Italy	1	0.32	2	0.39	2.00
10	Germany	1	0.32	1	0.20	1.00

Table 2.2.4 Institutions with the greatest output of core patents on “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nuclear Power Institute of China	68	21.79	36	7.10	0.53
2	China Nuclear Power Technology Research Institute	19	6.09	30	5.92	1.58
3	General Electric Company	18	5.77	13	2.56	0.72
4	Korea Atomic Energy Research Institute	18	5.77	7	1.38	0.39
5	Mitsubishi Heavy Industries Limited	18	5.77	6	1.18	0.33
6	Xi’an Jiaotong University	17	5.45	49	9.66	2.88
7	TerraPower Limited Liability Company	16	5.13	119	23.47	7.44
8	Westinghouse Electric Company	14	4.49	42	8.28	3.00
9	Shanghai Institute of Applied Physics, Chinese Academy of Sciences	8	2.56	16	3.16	2.00
10	Kabushiki Kaisha Toshiba	8	2.56	5	0.99	0.62

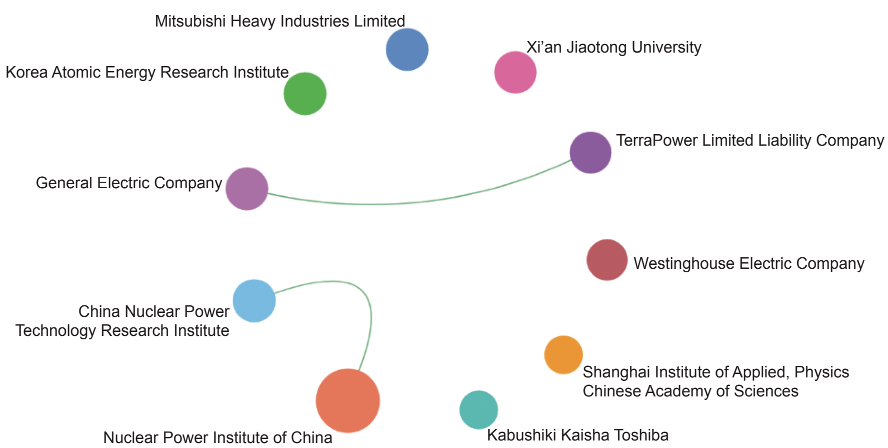

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”

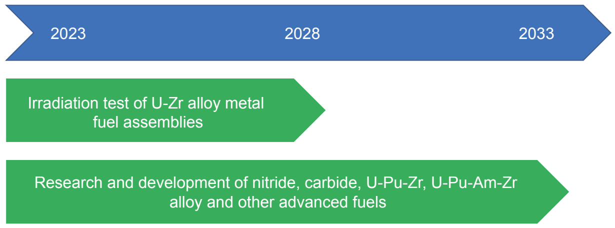

Figure 2.2.5 Roadmap of the engineering development front of “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”

2.2.3 Exploration method for mineral deposits utilizing high-precision ground gravity measurement

The technology of ground gravity measurement has been greatly developed in China and abroad. Based on the idea of zero-length spring, a quartz spring gravimeter has been designed and produced by LaCoste Romberg in the USA and Scientrex in Canada. Scientrex has developed to the 6th generation CG-6 gravimeter, with a measurement accuracy better than 5 μGal, which has played a major role in mineral prospecting and is still the main technical equipment in countries around the world. The first gravimeter based on the cold atom interference principle was proposed by Stanford University in the 1990s, and the recent measurement sensitivity of the gravimeter based on this principle has reached 8 $\mu Gal/Hz^{1/2}$. The University of Birmingham in the UK developed an atomic gravity gradiometer, which observed the gravity gradient signal of 170 E. A French company, iXblue, has developed the first mobile atomic gravity gradiometer in the world with an accuracy of less than 1 E, with a measuring resolution of 0.15 E.

China has also made progress, but the overall technology still lags behind foreign countries. In the 1990s, Beijing Geological Instrument Factory produced ZSM quartz spring gravimeter with a measuring accuracy of 30 μGal. Eight institutions, including Zhejiang University of Technology and Huazhong University of Science and Technology, have conducted research on ground atomic absolute gravimeter, and the measuring sensitivity has reached 4.2–44.0 $\mu Gal/Hz^{1/2}$. The Institute of Precision Measurement of the Chinese Academy of Sciences has reported a highly integrated atomic absolute gravity gradiometer with an accuracy of less than 1 E and a probe size as small as 92 L. However, both of them are in the prototype development stage, not yet practical.

In the engineering development front of “exploration method for mineral deposits utilizing high-precision ground gravity measurement”, the top two countries in the number of core patents are the USA and China, with a number of 120 and 87, accounting for 35.09% and 25.44% of the total, respectively, and the proportion of patents in other countries is less than 12.00%. In addition, the total number of patents cited in the USA is the highest (2 419), accounting for 44.21% of the total number of citations, while the total number of citations in China and Germany are 17.40% and 11.90%, respectively, and the total number of patents cited in other countries for related technologies is less than 10.00%. The UK has the highest citations per patent (20.25) (Table 2.2.5). In terms of the main institutions of core patents (Table 2.2.6), Infineon Technologies AG (12), TDK Corporation (9), and Robert Bosch Manufacturing Solutions GMBH (9) have more patents. In addition, Hyperfine Research Incorporated has the highest percentage of citations (5.39%) and the highest citations per patent (73.75) (Table 2.2.6). Countries such as Germany, the USA, France, and Switzerland focus on cooperations (Figure 2.2.6). There is no cooperation among major producing institutions.

The traditional spring gravimeter has been developed to the extreme, with little margin for improving the measurement accuracy. As a new generation of quantum gravity sensor, the atomic gravimeter is expected to have a measurement sensitivity of 10^{-4} μGal. However, it is faced with key problems such as miniaturization of atomic gravimeter and improvement of measurement accuracy. In addition, the atomic gravimeter is also faced with problems such as insufficient scale factor and low phase extraction efficiency, which pose enormous challenges to practical application.

The main research fields are the development of miniaturized and high-precision atomic absolute gravimeter/gravity gradiometer, data fine processing, and interpretation, etc., providing higher precision and technologically more advantageous prospecting technology, which has an important practical and strategic significance for building the security of mineral resources of China.

Table 2.2.5 Countries with the greatest output of core patents on "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	120	35.09	2 419	44.21	20.16
2	China	87	25.44	952	17.40	10.94
3	Germany	40	11.70	651	11.90	16.27
4	Japan	32	9.36	520	9.50	16.25
5	Republic of Korea	12	3.51	156	2.85	13.00
6	Canada	11	3.22	212	3.87	19.27
7	Switzerland	9	2.63	142	2.60	15.78
8	France	8	2.34	126	2.30	15.75
9	Netherlands	6	1.75	69	1.26	11.50
10	UK	4	1.17	81	1.48	20.25

Table 2.2.6 Institutions with the greatest output of core patents on "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Infineon Technologies AG	12	3.51	245	4.48	20.42
2	TDK Corporation	9	2.63	152	2.78	16.89
3	Robert Bosch Manufacturing Solutions GMBH	9	2.63	132	2.41	14.67
4	Melexis Bulgaria Limited	8	2.34	94	1.72	11.75
5	Allegro MicroSystems	7	2.05	138	2.52	19.71
6	Halliburton Energy Services Incorporation	5	1.46	59	1.08	11.80
7	CNH Industrial Capital Canada Limited	5	1.46	44	0.80	8.80
8	Hyperfine Research Incorporated	4	1.17	295	5.39	73.75
9	Facebook Technologies	4	1.17	91	1.66	22.75
10	United Technologies Corporation	4	1.17	45	0.82	11.25

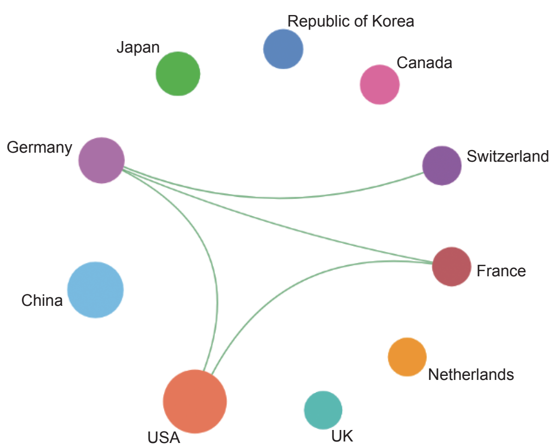

Figure 2.2.6 Collaboration network among major countries in the engineering development front of "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

High precision ground gravity survey technology has broad development prospects in mineral exploration, basic geological research, and other fields (Figure 2.2.7). In the next 5 to 10 years, the key development trend of this technology is the development of practical high-precision atomic absolute gravimeter/gravity gradiometer, accurate terrain correction methods, 3D forward and inversion and geological modeling technology for direct prospecting, and the formation of a rapid and fine measurement of gravity exploration methods and prospecting technology system. At the same time, it is necessary to realize the independent development, miniaturization and practical application of the surface gravimeter, and study the surface gravity and multi-type and multi-source data fusion, well-ground multi-parameter joint constrained inversion, three-dimensional imaging and other gravity processing and interpretation methods to meet the needs of deep mineral resources exploration, better serve the fields of earthquake prevention and national defense construction, which is expected to greatly improve the success rate of prospecting and increase reserves, and enhance social and economic benefits.

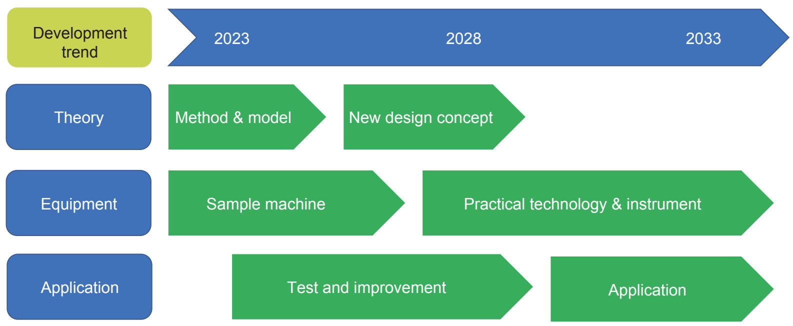

Figure 2.2.7 Roadmap of the engineering development front of "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

2.2.4 Research on intelligent collaborative platform for oil and gas exploration and development

The intelligent collaborative platform for oil and gas exploration and development refers to the provision of an integrated environment that encompasses information sharing, technological innovation, production and operation integration, and intelligent collaboration, facilitating multidisciplinary interaction and integrated exploration and development. In the current wave of oil and gas technological and digital revolutions, the integration of new technologies such as big data and artificial intelligence with the oil and gas industry has become a significant avenue for innovation.

Foreign countries have made initial strides in constructing intelligent collaborative platforms for oil and gas exploration and development. For instance, Akselos deployed digital twins for Shell's Bonga FPSO, Schlumberger collaborated with Google on the DELFI cloud platform, Total Energies established an integrated oil and gas production collaborative research platform, and Halliburton signed strategic agreements with Accenture and Microsoft. BP and Microsoft also entered into a strategic partnership, while companies like Chevron, Eni, and Abu Dhabi National Oil Company have undertaken intelligent platform research. China's intelligent collaborative platform development started relatively later and is currently in the transition from digitization to intelligence. China National Petroleum Corporation (CNPC) has developed the "Exploration and Development Dream Cloud" platform, Sinopec has established the "Petrochemical Intelligence Cloud" platform for the energy and chemical industry, and China National Offshore Oil Corporation (CNOOC) is dedicated to creating collaborative working environments and onshore-offshore coordination systems for exploration and development. Although China has achieved preliminary advancements in domestic intelligent collaborative platform construction, overall technology still lags behind foreign counterparts. Currently, the global level of informatization in the oil and gas industry remains relatively low, well below the industry average. In the future, key research directions include the artificial intelligence technology, intelligent oil and gas exploration, integrated geological engineering, intelligent equipment research and development, cloud computing platform construction, and data sharing, etc.

Regarding the engineering development front of “research on intelligent collaborative platform for oil and gas exploration and development”, the major patent-producing countries are China and the USA, with respective publication numbers of 240 and 21, accounting for 87.27% and 7.64%, respectively. The patent publications of other countries related to relevant technologies all account for less than 2.00%. China has the highest citations (441), accounting for 71.36%, while the USA accounts for 26.54%, and other countries all account for less than 5.00%. The USA has the highest citations per patent (7.81), as shown in Table 2.2.7. In terms of patent-producing institutions (Table 2.2.8), major contributors include China Petroleum and Chemical Corporation (12), Southwest Petroleum University (9), China University of Petroleum (Beijing) (8), PetroChina Company Limited (8), China Railway Tunnel Group Company Limited (7), and Central South University (7). Among them, institutions with a percentage

Table 2.2.7 Countries with the greatest output of core patents on “research on intelligent collaborative platform for oil and gas exploration and development”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	240	87.27	441	71.36	1.84
2	USA	21	7.64	164	26.54	7.81
3	Canada	5	1.82	27	4.37	5.40
4	France	5	1.82	27	4.37	5.40
5	Netherlands	5	1.82	27	4.37	5.40
6	Saudi Arabia	5	1.82	5	0.81	1.00
7	India	5	1.82	0	0.00	0.00
8	Russia	2	0.73	4	0.65	2.00
9	Norway	2	0.73	3	0.49	1.50
10	Republic of Korea	1	0.36	6	0.97	6.00

Table 2.2.8 Institutions with the greatest output of core patents on “research on intelligent collaborative platform for oil and gas exploration and development”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Petroleum and Chemical Corporation	12	4.36	34	5.50	2.83
2	Southwest Petroleum University	9	3.27	12	1.94	1.33
3	China University of Petroleum (Beijing)	8	2.91	16	2.59	2.00
4	PetroChina Company Limited	8	2.91	8	1.29	1.00
5	China Railway Tunnel Group Company Limited	7	2.55	36	5.83	5.14
6	Central South University	7	2.55	20	3.24	2.86
7	Schlumberger Technology Corporation	6	2.18	27	4.37	4.50
8	China National Offshore Oil Corporation	5	1.82	4	0.65	0.80
9	Dalian University of Technology	4	1.45	9	1.46	2.25
10	Shandong University of Science and Technology	4	1.45	5	0.81	1.25

of citations exceeding 5.00% include China Petroleum and Chemical Corporation (5.50%) and China Railway Tunnel Group Company Limited (5.83%). Countries emphasizing cooperation include the USA, the Netherlands, Canada, and France (Figure 2.2.8), with collaborative research between institutions focused on PetroChina Company Limited and Southwest Petroleum University (Figure 2.2.9).

The intelligent collaborative platform for oil and gas exploration and development holds significant prospects in achieving data interconnection, technological exchange, and collaborative research. It is applicable to upstream oil and gas operations such as exploration, drilling, and production. In the next 5 to 10 years, its key development directions include interdisciplinary integration, enhanced data sharing, top-level design, and refined technological architecture.

By organically integrating hardware facilities, software development, digital technology, and oil and gas expertise, a fully digitized, automated, and intelligent professional application environment is expected to be built for the exploration and development process, achieving collaboration in multi-domain in oil and gas exploration and development (Figure 2.2.10). This transformation aims to alter the exploration and development work model, enhance efficiency, maximize comprehensive benefits, and drive the digital transformation and intelligent development of the oil and gas industry.

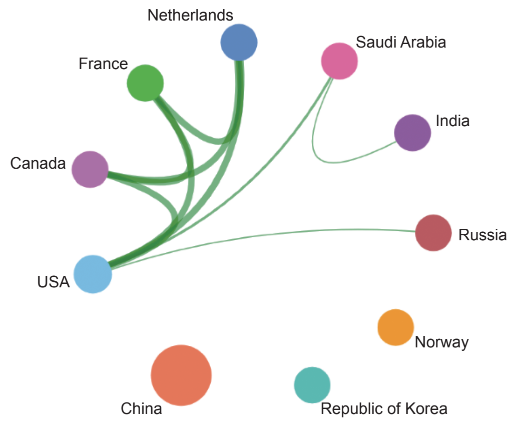

Figure 2.2.8 Collaboration network among major countries in the engineering development front of “research on intelligent collaborative platform for oil and gas exploration and development”

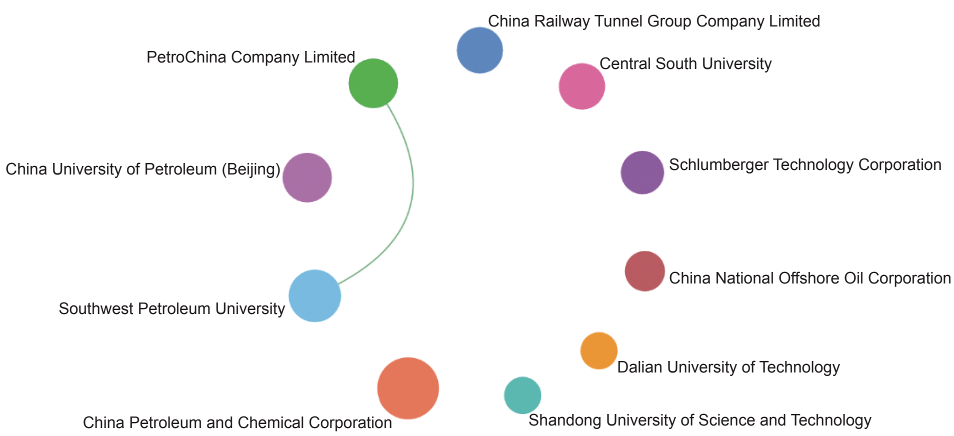

Figure 2.2.9 Collaboration network among major institutions in the engineering development front of “research on intelligent collaborative platform for oil and gas exploration and development”

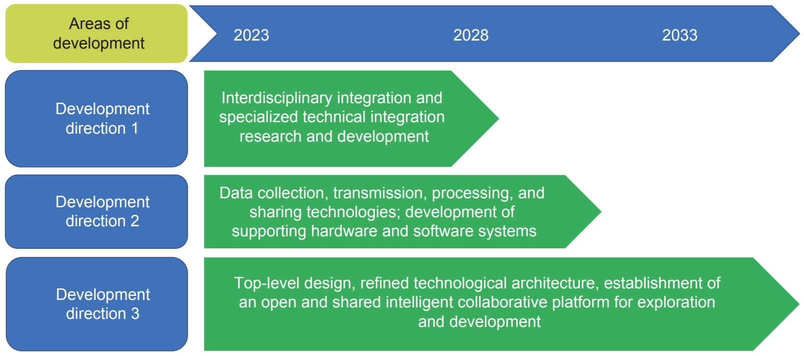

Figure 2.2.10 Roadmap of the engineering development front of "research on intelligent collaborative platform for oil and gas exploration and development"

Participants of the Field Group

Leaders

WENG Shilie, NI Weidou, ZHOU Shouwei, PENG Suping, HUANG Zhen

Office of the Ministry of Energy and Mining Engineering

ZONG Yusheng, XIE Guanghui

Editorial Office of *Frontiers in Energy*

LIU Riuqin, YIN Liang, FU Lingxiao

Library and Information Personnel

CHEN Tiantian, CHEN Meng

Members

Energy and Electrical Science, Technology and Engineering Section:

Director of Section: WENG Shilie, YUE Guangxi

Secretary-general of Section: JU Yonglin, ZHOU Tuo

Participants: XIE Heping, LIU Tao, YANG Jun, ZHOU Baowen, LIANG Zheng, YAN Zheng, ZHAO Yao, YANG Li, TAI Nengling, XU Xiaoyuan, ZHOU Tuo, JU Yonglin

Report Writers: LIU Tao, YANG Jun, ZHOU Baowen, LIANG Zheng, YAN Zheng, ZHAO Yao

Nuclear Science, Technology and Engineering Section:

Director of Section: YE Qizhen, LI Jiangang

Secretary-general of Section: SU Gang, GAO Xiang

Participants: GAO Xiang, GUO Yinghua, SU Gang, ZHOU Hongbo

Report Writers: LI Gongshun, GUO Qing, YANG Yong, SU Gang, ZHOU Hongbo, SUN Xiaolong

Geology Resources Science, Technology and Engineering Section:

Director of Section: ZHAO Wenzhi, MAO Jingwen

Secretary-general of Section: LIU Min, WANG Kun

Participants: XIONG Shengqing, JIAN Wei, LIU Min, WANG Kun, LIU Xielu, ZHU Lei, LI Yongxin

Report Writers: WANG Kun, XIONG Shengqing, ZHOU Xihua, QIAN Rongyi, GAO Xiuhe, LI Yongxin, DONG Jin, GUAN Ming, LIU Min, TAN Chunliang, YUE Yongdong, LI Zhixin

Mining Science, Technology and Engineering Section:

Director of Section: YUAN Liang, LI Gensheng

Secretary-general of Section: ZHOU Fubao, WU Aixiang, ZHANG Nong, SONG Xianzhi

Participants: JIANG Bingyou, SHI Guoqing, LIANG Dongxu, HUANG Zhongwei, RUAN Zhuen, WANG Haizhu, XU Fuqiang, RONG Haoyu

Report Writers: JIANG Bingyou, SONG Xianzhi, LIANG Dongxu, XU Fuqiang, SHI Guoqing, WANG Gaosheng, LI Shuang