IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in top 12 engineering research fronts

The top 12 engineering research fronts 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, emerging research fronts include "renewable synthetic fuel," "on-site conversion and efficient utilization of petroleum resources," and "digital nuclear reactor and power plant intelligent simulation systems." "Advanced nuclear spent fuel reprocessing and nuclear fuel recycling," "fracture diagnosis and evaluation methods," "study of mantle plume-related ore deposits of critical metals," and "theory and technology for safe direct combustion of low-concentration gas" represent further developments in existing research fields. The research front of "fluidized mining of deep solid mineral resources and its process control mechanism" is revolutionizing the mining industry. The fronts of interdisciplinary integration include "basic theory and method for intelligent drilling," "solar photovoltaic thermal (PV/T) coupling system based on nano phase change materials (nano-PCMs)," "security of intelligent grid cyber-physical systems," and "Z-pinch driven inertial fusion mechanism based on pulse power technology."

The number of core papers published annually from 2014 to 2019 for each of the top 12 engineering research fronts is listed in Table 1.1.2.

(1) Renewable synthetic fuel

Increasing concerns regarding energy security and CO_2 emission require a widespread use and development of renewable energy, which is also the key to address issues of energy storage, climate change and to achieve sustainable development worldwide. Although the installed renewable power capacity, from sources such as solar and wind power,

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	Renewable synthetic fuel	87	14 388	165.38	2016.4
2	Advanced nuclear spent fuel reprocessing and nuclear fuel recycling	21	333	15.86	2016.0
3	On-site conversion and efficient utilization of petroleum resources	10	579	57.90	2016.6
4	Basic theory and method for intelligent drilling	44	257	5.84	2018.5
5	Solar PV/T coupling system based on nano-PCMs	44	1 753	39.84	2016.8
6	Security of intelligent grid cyber-physical systems	28	1 182	42.21	2016.8
7	Digital nuclear reactor and power plant intelligent simulation systems	4	43	10.75	2016.2
8	Z-pinch driven inertial fusion mechanism based on pulse power technology	45	1 433	31.84	2016.1
9	Fracture diagnosis and evaluation methods	98	3 238	33.04	2016.0
10	Study of mantle plume-related ore deposits of critical metals	8	442	55.25	2015.4
11	Theory and technology for safe direct combustion of low-concentration gas	122	951	7.80	2017.5
12	Fluidized mining of deep solid mineral resources and its process control mechanism	28	961	34.32	2016.2

Table 1.1.2 Annual number of core papers published for the top12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2014	2015	2016	2017	2018	2019
1	Renewable synthetic fuel	0	26	23	20	14	4
2	Advanced nuclear spent fuel reprocessing and nuclear fuel recycling	0	9	5	5	2	0
3	On-site conversion and efficient utilization of petroleum resources	0	2	2	4	2	0
4	Basic theory and method for intelligent drilling	0	1	3	4	12	15
5	Solar PV/T coupling system based on nano-PCMs	1	5	11	13	12	2
6	Security of intelligent grid cyber-physical systems	3	4	4	9	2	6
7	Digital nuclear reactor and power plant intelligent simulation systems	0	1	1	2	0	0
8	Z-pinch driven inertial fusion mechanism based on pulse power technology	0	17	14	8	5	1
9	Fracture diagnosis and evaluation methods	0	38	30	21	7	2
10	Study of mantle plume-related ore deposits of critical metals	2	3	1	2	0	0
11	Theory and technology for safe direct combustion of low-concentration gas	0	15	21	30	19	19
12	Fluidized mining of deep solid mineral resources and its process control mechanism	0	9	8	9	0	2

is increasing dramatically, their seasonal and intermittent features limit the direct integration of renewable energy into power grids. One strategy to overcome this is to develop renewable synthetic fuels, which converts CO_2 into stable, storable, and high-energy-density liquid fuels such as alcohols, ethers, and hydrocarbons using renewable energy sources. Renewable synthetic fuels can be utilized in power plants, internal combustion engines, aero engines, gas turbines, etc. The CO_2 released by using these fuels can be captured from the environment and reduced into renewable synthetic fuels again, thus forming a carbon-neutral energy cycle. In the field of renewable synthetic fuels, major technological approaches include electrocatalytic, photocatalytic, photoelectrocatalytic, and chemical reductions of CO_2 to fuel. This research front is focused on determining methods to improve product selectivity, conversion efficiency, and production rate.

(2) Advanced nuclear spent fuel reprocessing and nuclear fuel recycling

The world is facing a major challenge in the coordinated development of energy and environmental protection, and the situation regarding energy conservation and emission reduction is serious. As a clean, efficient, and large-scale means of energy production, nuclear energy has received considerable attention from international communities. The development and utilization of nuclear energy must be supported by nuclear fuel. The sustainable development of nuclear energy requires the continuous recycling of nuclear fuel through reprocessing, so that unburned fuel can be fully utilized, and the newly generated nuclear fuel can be used effectively. Furthermore, this recycling ensures that other valuable nuclides can be used. The nuclear fuel cycle represents the entire process that involves the preparation of nuclear fuel before it is injected into the reactor, combustion of the fuel in the reactor, and post-processing of the nuclear fuel. The various processing procedures after nuclear fuel is discharged from the reactor comprise the post-nuclear fuel cycle. These procedures include intermediate storage of spent fuel, nuclear fuel reprocessing, preparation and recycling of recovered fuel, radioactive waste treatment, and final disposal. Among these, nuclear fuel reprocessing is the most critical step. The main task of nuclear fuel reprocessing is to separate the fission products from spent fuel using chemical treatment methods; recover and purify valuable fissionable substances, such as ^{235}U and ^{239}Pu, and turn them into fuel elements; and return these elements to nuclear power plants (thermal reactors or fast reactors) for use, which can increase the utilization rate of nuclear fuel and save a considerable amount of uranium resources. This process can also help extract transuranium elements and fission products to advance the application of isotopes in the medical and aerospace industries. The reprocessing of spent fuel significantly reduces the toxicity and volume of radioactive waste that requires final geological disposal and promotes safe disposal. Therefore, reprocessing is of great significance to the sustainable development of nuclear energy. At the same time, nuclear fuel reprocessing technology is a typical dual-use sensitive technology that is strictly restricted by the international Nuclear Non-Proliferation Treaty. Development of the reprocessing technology is an important indicator of the overall national strength and international status of a country.

(3) On-site conversion and efficient utilization of petroleum resources

Research on on-site conversion and efficient utilization of petroleum resources comprises the integration of thermophysics, thermochemistry, materials science, and other multi-disciplinary areas; the transformation of low-grade resources into high-grade energy underground; and advanced research on the upgrade of high-viscosity crude oil and oil shale using *in-situ* conversion technology, which is expected to greatly increase the recovery rate or energy conversion rate and provide cutting-edge technology to deal with future structural changes in petroleum resources. The technology for *in-situ* upgrading of heavy oil has advanced from steam stimulation to steam flooding, steam assisted gravity drainage (SAGD), and fire flooding. In recent years, multi-media steam flooding technology has been developed. This technology is being further developed to include the application of highly active and universally applicable catalyst systems that allow the modification and viscosity reduction reactions of heavy oil to occur at a lower temperature, while simultaneously achieving ideal modification and viscosity reduction effects for different heavy oils. The shale oil underground *in-situ* conversion technology involves a physical and chemical process that uses horizontal well electric heating lightening technology to continuously heat the organic-rich shale interval to lighten multiple types of organic matter. Such a breakthrough in shale oil underground *in-situ* conversion technology would aid the development and utilization of shale oil resources and ensure long-term stability and an even higher production of crude oil. Promoting the *in-situ* conversion and efficient utilization of petroleum resources and realizing breakthroughs in commercialization are of great significance in the future development of the world petroleum industry.

(4) Basic theory and method for intelligent drilling

Drilling is a key aspect of the discovery, exploration, and exploitation of oil and gas resources. However, existing drilling technology cannot meet the development requirements of complex oil and gas resources in terms of economy, safety, efficiency, and environmental protection. The application of smart technology in the field of oil and gas exploration and development has become the development trend of the petroleum industry. Major international oil companies are actively implementing various intelligent oil and gas exploration and development strategies. Therefore, a new generation of drilling technology must be developed. Intelligent drilling is a transformative technology that integrates big data, artificial intelligence, information engineering, downhole control engineering, and other theories and technologies. Advanced drilling, closed-loop control, precise guidance, and intelligent decision-making are realized through the application of surface automatic drilling rigs, downhole intelligent actuators, intelligent monitoring, decision-making technologies, etc. This is expected to greatly improve the drilling efficiency and reservoir encountering rate. In addition, this will help reduce drilling costs and significantly increase the single-well production and recovery efficiency of complex oil and gas reservoirs.

The basic theories and methods of intelligent drilling mainly involve intelligent characterization of the drilling environment, intelligent perception of drilling conditions, intelligent decision-making of drilling schemes, and intelligent control of drilling parameters. The intelligent characterization of the drilling environment can realize fine characterization of the drilling environment and the physical properties of the reservoir, which is the basis for the realization of intelligent drilling monitoring, diagnosis, decision-making, and regulation. Intelligent perception of drilling conditions uses intelligent monitoring and data transmission technologies to realize real-time analysis and acquisition of geological and engineering parameters and provide dynamic data support for intelligent drilling engineering. The intelligent decision-making of the drilling plan is based on the integration and processing of geological engineering data, revealing the cooperative response mechanism between the geological engineering parameters and objective functions such as drilling rate, cost, and risk. In addition, it helps optimize and determine engineering parameters and construction plans. Intelligent control of drilling parameters is based on an integrated coordination mechanism between drilling parameters. It utilizes the intelligent control theory to achieve intelligent control of drilling parameters such as well trajectory, wellbore pressure, and fluid performance.

(5) Solar PV/T coupling system based on nano-PCMs

Based on the temperature characteristics of solar PV cells, the solar PV/T coupling system can consider both solar PV power generation and thermal energy conversion. While increasing electrical power generation, it can produce a certain amount of thermal energy. Currently, it is one of the most efficient methods for solar energy conversion and utilization. The use of nano-PCMs in PV/T systems can effectively control the operating temperature of the PV cells, with a high energy storage density and a fast heat storage and release speed, which is important for the efficient large-scale application of solar energy.

The main research topics include the micro-mechanisms of electricity and heat cogeneration for solar cells and optimization of the energy conversion process, new solar PV/T modules and their temperature characteristics, PV/T packaging with nano-PCMs, novel heat transfer mechanisms in nano-PCM energy storage and heat dissipation, the thermal characteristics of the PV/T coupling system using nano-PCMs, and the characteristics of electricity and heat cogeneration.

The combination of nano-PCMs and PV/T systems is important for realizing systematic solar thermoelectric conversion and improving energy efficiency. Research on and development of high-efficiency solar PV/T components and systems that integrate electricity and heat generation to meet the electricity, heating, and cooling loads of buildings and neighborhoods are receiving attention in the field of high-efficiency solar energy conversion and applications. Solar PV/T coupling systems are also an important energy source for future low-carbon cities, green buildings, and zero-energy buildings. Combined with nano-PCMs, PV/T technology can realize effective regulation and a stable energy supply for building energy systems.

(6) Security of intelligent grid cyber–physical systems

A smart grid cyber–physical system includes a power network, an information network, and a power grid cyber–physical network. It facilitates the real-time perception, dynamic control, and information service of smart grids based on distributed intelligent sensors and communication networks. The security of smart grid cyber–physical systems focuses on the security of the information network and physical network as well as the risk of coupling the two networks. Power grids can be attacked by injecting false information through sensing devices. Therefore, the security problem of cyber–physical systems can limit the power grid security. Various cyber–physical system attack strategies and corresponding risk and vulnerability evaluation methods have been investigated previously. In addition, a test platform has been established for security assessment. Considering the dynamic propagation of the risk in cyber–physical systems, it is vital to conduct in-depth research on the risk propagation and evolution mechanism. Moreover, advanced network security technologies should be developed to strengthen the defenses of the information network, reduce risk, and resist cyber-attacks. Furthermore, future research should focus on the establishment of cyber-security situational awareness platforms, which will be used to identify risk events and simulate risk propagation processes. Big data and situational prediction techniques can be combined to predict cyber-physical system security and guarantee the safe and reliable operation of cyber-physical systems in an actual environment.

(7) Digital nuclear reactor and power plant intelligent simulation systems

The development of a numerical reactor system refers to the entire process of providing a high-confidence expert reference database for the modeling of reactor operating conditions, the development of high-confidence numerical simulation software systems, and the establishment of virtual reactors for reactor engineering design, performance optimization, operating economy, safety, and reliability, based on the rapid development of high-performance computer systems. Using high-fidelity numerical methods and high-precision models, direct multi-physics simulations of the core design can be achieved, and more accurate calculation results can be obtained, improving the design margins from professional models and interprofessional interfaces, improving the safety and economy of design schemes and promoting reactor operation flexibility. In addition, the test project and scale can be optimized, thereby shortening the research and development cycle and reducing research and development costs. If high-fidelity numerical methods and high-precision models were used for the optimization of reactor operation, the competitiveness of nuclear power in the energy supply system can be enhanced.

Digitization/intelligence refers to the development of a digital design system integrating model research and development, engineering design, and comprehensive verification. Based on design data and new-generation intelligent technologies such as the Internet of Things, big data, and virtual reality, it realizes automated engineering design, intelligent computational analysis, and visualization of results and projects. In addition, it supports a multi-specialty, multi-project, fully collaborative, standardized digital construction system. Focusing on business scenarios such as nuclear power plant operation, maintenance, overhaul, decommissioning, and training, research is being conducted on key applications, such as production management, configuration management, intelligent monitoring and diagnosis, and intelligent robots in nuclear power plant operations. Other avenues of research include building digital twin power plants based on 3D simulation and virtual reality technologies, realizing the one-to-one mapping between the panoramic space of nuclear power plants and the real environment, and forming a digital twin with perception, analysis, decision-making, and execution capabilities. A database regarding the full life cycle of nuclear power plants should also be constructed. The integration of smart nuclear energy systems is being studied to realize nuclear power generation, nuclear energy supply at the site, and intelligent scheduling and management of various aspects of nuclear energy utilization, such as heat, nuclear energy, sea water desalination, and nuclear energy hydrogen production.

(8) Z-pinch driven inertial fusion mechanism based on pulse power technology

Controllable fusion energy is the ideal clean energy of the future. The main techniques to realize this energy are magnetic and inertial confinement. For the inertial confinement, the fusion energy is obtained by supplying the heating energy directly or indirectly onto the fusion target, compressing the target, and then realizing thermonuclear ignition and combustion under the inertial constraint of internal explosive motion. Key technologies related to this front include driving sources with high heating power, repetition rate, and stability; the structural design of the implosion chamber and the fusion target; optimization of the design of the ignition method; high-efficiency energy conversion; and Tritium cycle and extraction. The fast Z-pinch technology is based on pulse power technology. Therefore, it can realize high-efficiency energy conversion from the electric energy storage of the driver to kinetic energy or X-ray radiation energy of the Z-pinch load. It is expected to help realize the repetitive operation of the driver, which will provide a powerful energy source for driving inertial confinement fusion and inertial fusion energy. The inertial confinement driven by the Z-pinch is a complex multi-scale and multi-physical process. Current experimental techniques are not capable of directly achieving fusion ignition. Numerical simulation is an important means to study the physical problems of Z-pinch driven inertial confinement fusion. In the future, numerical simulation tools will be further developed and improved to conduct research on the physics of the whole process and associated key problems.

(9) Fracture diagnosis and evaluation methods

Fractures are the main spaces for the storage and circulation of oil and gas. Hydraulic fracturing occupies a high proportion of the production stimulation measures of low-permeability oil and gas reservoirs, and it is the main method for improving oil and gas recovery. Therefore, it is necessary to conduct research on fracturing diagnosis and evaluation methods to clarify the actual shape and parameters of fractures under current reservoir conditions. According to test results, and to compensate for the differences between theory and practical applications, the principles of hydraulic fracturing design are adjusted to ensure that the fracture parameters calculated by the fracturing model are in good agreement with the actual ones, which will further improve the applicability of the fracturing design plan. At the same time, this reduces fracturing investment and improves the effect of fracturing reconstruction. Although fracturing pressure fitting, tracers, production logging tools, micro-seismic fracture monitoring, micro-deformation fracture monitoring, and other methods have been used to diagnose and evaluate fractures for decades, little is known about them today and there are knowledge gaps pertaining to the complex shape, length, width, height, and distribution of diversion capacity. Owing to the characteristics of storage and hydraulic fracturing parameters, it is particularly important to accurately understand the fracture length and fracture orientation to optimize the overall development of low-permeability oilfields. In the future, research on fracture diagnosis and evaluation technology should be strengthened, as it is an important basis for deepening our understanding of fractures, correcting fracture prediction models, optimizing fracturing design and well pattern deployment, and ultimately helping oilfield developers optimize oilfield and single-well development plans to enhance the economic benefits.

(10) Study of mantle plume-related ore deposits of critical metals

A mantle plume links the mass and energy exchange between the core, mantle, and crust, thus providing a long-term and steady material base for various critical metal mineralizations. Plume-related magmatic sequences are found to host some specific types of mineralization, such as mafic-ultramafic layered intrusions and Fe-Ti-V oxide (Co and Sc), Ni-Cu-PGE (platinum group element) sulfides and Cr-Ti-Fe oxides deposits, komatiite and related Cu-Ni sulfides deposits, peralkaline complex-carbonatites and Nb-Ta-Zr-REE deposits. In contrast, metals in the crust are transported and further concentrated by hydrothermal convection, which is activated by thermal anomalies induced by a mantle plume. This leads to the formation of hydrothermal ore deposits that are indirectly related to mantle plumes, such as Mn-Co ores, Carlin-style gold deposits, and tellurium ore deposits associated with the Emeishan large igneous provinces (LIPs). Previous research has identified the following key controlling factors in plume-related critical metal mineralization: structure of the plume, magma source, crystal fractionation, crustal contamination and liquid immiscibility, magma replenishment, mingling/mixing, and intrusion processes. Although the key metal mineralization related to mantle plumes is gaining an increasing amount of attention, its theoretical framework has not been established yet, and the understanding of the key controlling factors still needs to be improved. Notably, there are two Permian LIPs in China, which host various types of critical metal deposits and thus provide rare opportunities for us to reveal the genetic links between mantle plumes and critical metal mineralization and establish a systematic theory of critical metal metallogeny. Therefore, in addition to previous case studies on individual deposits, emphasis should be placed on research on the metallogenic sequence of key metals in mantle plumes, which will contribute to building an integrated theoretical system for critical metal mineralization associated with mantle plumes.

(11) Theory and technology for safe direct combustion of low-concentration gas

Methane is the second largest greenhouse gas after CO_2, accounting for approximately 20% of global greenhouse gas emissions. The concentration of methane in the atmosphere is much lower than that of CO_2, but the global warming potential (GWP) of methane is 25 times that of the same amount of CO_2. According to the GWP, the methane emissions of the coal and oil energy industries are equivalent to more than 10 billion tons of CO_2, and the reduction of methane emissions in the energy industry is of great significance to environmental protection. As of 2018, the utilization rate of low-concentration coal mine gas with a concentration between 6% and 30% is only approximately 28%, and the utilization rate of ultra-low-concentration gas (including ventilation gas) with a concentration less than 6% is only 2%. Exploring the utilization technology of low-concentration gas, especially ultra-low-concentration gas, is the key to solving the problem of low gas utilization rate. For the combustion (oxidation) utilization of ultra-low-concentration gas and ventilation gas, research groups from various countries have proposed different thermal storage oxidation technologies, such as the thermal flow reversal reactor technology in the United States, the catalytic flow-reversal reactor technology in Canada, the catalytic gas turbine technology in Australia, the thermal regeneration oxidation technology in Germany, and the monolithic honeycomb catalytic oxidation technology in Germany. Some progress has been made, but the proportion of ultra-low-concentration gas in coal mines is large (more than 70% of the total gas emissions), and the gas concentration is low (< 6%). Furthermore, the concentration fluctuates greatly and crosses the explosion boundary range, and the content of impurities is high (dust, water vapor, and impurity gas). Therefore, the realization of safe transportation of explosive gas, efficient removal of impurity components, and efficient direct combustion (oxidation) of ultra-low-concentration gas is crucial for industrial application.

(12) Fluidized mining of deep solid mineral resources and its process control mechanism

The exploitation of deep solid resources faces high stress, high well temperature, and high well depth. Fluidized mining of deep solid mineral resources involves injecting a leaching solution into a deep ore deposit via injection wells to allow the leaching solution and targeted minerals to react. Then, the leaching solution containing soluble metallic ions is lifted to the surface. Finally, metallic products are obtained via solvent extraction electrowinning. Studies in this research area aim to develop an innovative green mining method and a regulation mechanism of deep solid mineral resources, promote mining reform, and eventually provide a reference for safe and efficient mining of deep solid resources.

There are several research topics in this area such as exploring the inlay interaction between the *in-situ* pore structure and valuable minerals of deep solid resources to realize a clear representation of deep mining environments and studying the law of multi-scale seepage of solution under high-temperature and high-pressure conditions deep underground. Other research avenues include detecting the leaching reaction mechanism of metallic minerals under multi-physics effects and building a model to describe the response of *in-situ* mineral dissolution and precipitation to pore structure evolution. Furthermore, a mathematical model of leachable evaluation and prediction of deep solid mineral resources has been developed, and an ameliorated technology system for deep-ground solution seepage and leaching reaction has been built.

The future development of this research front will include non-disturbed detection of multi-scale pore structures during the deep fluidized leaching process, coupling of deep pore structure, solution seepage, and leaching reaction, well-net setups and seepage intelligent controls of deep fluidized leaching, and other future research interests, to eventually achieve a breakthrough in the theory of fluidized mining of deep solid resources and the equipment for this technology.

1.2 Interpretations for four key engineering research fronts

1.2.1 Renewable synthetic fuel

There is an urgent need to develop zero-carbon and carbon-neutral energy technologies to sustainably develop the world’s infrastructure. George Andrew Olah, the Nobel Prize winner in Chemistry, discussed the concept and drawbacks of hydrogen economy in his book *Beyond Oil and Gas: The Methanol Economy* in 2006, and further proposed a promising idea, namely to create a renewable energy resource by converting CO_2 from both nature and industry into carbon-neutral alcohol and ether fuels. In 2018, four academicians of the Chinese Academy of Sciences, published a perspective in *Joule* (Joule, 2018, 2, 1925–1949), where they pointed out that the key to utilizing solar energy is to convert it into stable, storable, and high-energy-density chemical fuels, which is also the concept of renewable synthetic fuel.

Owing to the potential to address the energy and environmental challenges, renewable synthetic fuels have attracted increasing attention in recent years. Major economies, including China, the United States, Europe, Japan, and South Korea are all pursuing researches in this field. The Department of Energy of the United States established 46 Energy Frontier Research Centers, which support the study of solar power generation and solar-to-fuel conversion technology. In 2010, it established the Joint Center for Artificial Photosynthesis (JCAP) with Caltech, University of California campuses in Irvine and San Diego, the Lawrence Berkeley National Laboratory, and the SLAC National Accelerator Laboratory, which is the largest research program dedicated to the advancement of solar fuel generation science and technology. In 2020, the JCAP started to investigate the solar-fuel reactor system in order to convert CO_2 into liquid fuel driven by solar energy at a large scale. The European Union and South Korea also established the Energy-X and KCAP programs, aiming to achieve the cyclic utilization of carbon energy on a CO_2 basis. According to a report by BOSCH, renewable synthetic fuels will be widely used in Europe by 2050, which could reduce CO_2 emissions by 2.8 billion tons (approximately three times the annual CO_2 emissions in Germany).

In June 2019, the China Association for Science and Technology announced a list of the top 20 scientific and engineering technical problems of 2019 which play a guiding role in scientific and technological innovation, of which the development of renewable synthetic fuel is one of the foremost scientific problems. Domestic scientific research institutions represented by Tsinghua University, the University of Science and Technology of China, the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences, and Shanghai Jiao Tong University have also been committed to this field for a long time. Currently, the major technological paths include electrocatalytic, photocatalytic, photoelectrocatalytic, and chemical reductions of CO_2 to fuel. However, each of these remains at the experimental exploration stage, and a number of technical bottlenecks need to be overcome before industrial application is possible. Significant further work on the reaction mechanism, catalytic materials, and reactor systems is required to greatly improve the product selectivity, conversion efficiency, and production rate in order to promote the practical application of this technology.

The top three countries with the greatest output of core papers on “renewable synthetic fuel” are the United States (37), China (31), and Canada (10), and the corresponding citations per paper reach 185, 222, and 123, respectively, as listed in Table 1.2.1. Among the major countries with publications on this research front, there is a large amount of cooperation among the United States, China, and Canada, as shown in Figure 1.2.1. The top two institutions with the greatest output of core papers are Stanford University (8) and the Chinese Academy of Sciences (6), as given in Table 1.2.2. Out of the top 10 institutions by publication volume, there is a large amount of cooperation among Stanford University, SLAC National Accelerator Laboratory, the University of Toronto, the University of Science and Technology of China, and Chinese Academy of Sciences, as demonstrated in Figure 1.2.2. The top three countries with the greatest output of citing papers are China (4 818), the United States (1 580), and Japan (523), as presented in Table 1.2.3. The top three institutions with the greatest output of citing papers are the Chinese Academy of Sciences (860), the University of Chinese Academy of Sciences (351), and the University of Science and Technology of China (239), as shown in Table 1.2.4.

Table 1.2.1 Countries with the greatest output of core papers on “renewable synthetic fuel”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	37	42.53%	6 863	185.49	2016.7
2	China	31	35.63%	6 896	222.45	2016.6
3	Canada	10	11.49%	1 238	123.80	2017.3
4	Japan	8	9.20%	1 642	205.25	2015.1
5	South Korea	7	8.05%	1 044	149.14	2016.1
6	France	6	6.90%	721	120.17	2015.8
7	Netherlands	5	5.75%	1 054	210.80	2015.2
8	Saudi Arabia	4	4.60%	2 011	502.75	2016.2
9	Spain	3	3.45%	391	130.33	2015.7
10	Germany	3	3.45%	277	92.33	2016.7

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “renewable synthetic fuel”

Table 1.2.2 Institutions with the greatest output of core papers on “renewable synthetic fuel”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Stanford University	8	9.20%	1 070	133.75	2017.4
2	Chinese Academy of Sciences	6	6.90%	1 314	219.00	2016.8
3	Leiden University	5	5.75%	1 054	210.80	2015.2
4	Tokyo Institute of Technology	5	5.75%	837	167.40	2015.2
5	SLAC National Accelerator Laboratory	5	5.75%	604	120.80	2018.0
6	University of Toronto	5	5.75%	563	112.60	2017.6
7	University of Science and Technology of China	4	4.60%	1 396	349.00	2015.8
8	Brookhaven National Laboratory	4	4.60%	1 040	260.00	2016.0
9	University of Delaware	4	4.60%	643	160.75	2016.2
10	University of California, Berkeley	4	4.60%	394	98.50	2017.2

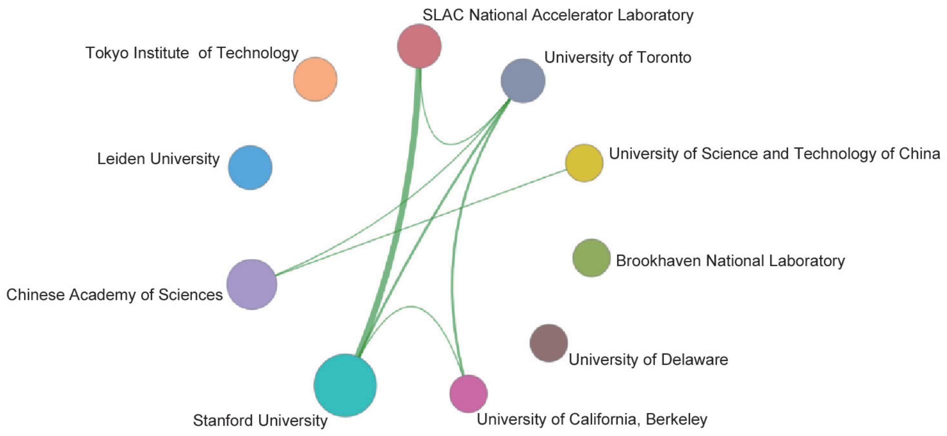

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “renewable synthetic fuel”

Table 1.2.3 Countries with the greatest output of citing papers on “renewable synthetic fuel”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	4 818	49.96%	2018.4
2	USA	1 580	16.38%	2018.3
3	Japan	523	5.42%	2018.1
4	Germany	501	5.19%	2018.3
5	South Korea	415	4.30%	2018.4
6	Australia	392	4.06%	2018.5
7	Canada	335	3.47%	2018.5
8	India	326	3.38%	2018.4
9	UK	266	2.76%	2018.3
10	France	253	2.62%	2018.3

Table 1.2.4 Institutions with the greatest output of citing papers on “renewable synthetic fuel”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	860	33.17%	2018.4
2	University of Chinese Academy of Sciences	351	13.54%	2018.5
3	University of Science and Technology of China	239	9.22%	2018.4
4	Tianjin University	186	7.17%	2018.4
5	Jiangsu University	146	5.63%	2018.0
6	Tsinghua University	140	5.40%	2018.4
7	Beijing University of Chemical Technology	140	5.40%	2018.7
8	Fuzhou University	138	5.32%	2018.0
9	Nanyang Technological University	137	5.28%	2018.4
10	Wuhan University of Technology	132	5.09%	2017.9

1.2.2 Advanced nuclear spent fuel reprocessing and nuclear fuel recycling

Nuclear fuel reprocessing is divided into two categories depending on whether it is conducted in an aqueous medium: water reprocessing and dry reprocessing. Water reprocessing comprises the chemical separation and purification processes in aqueous solutions such as precipitation, solvent extraction, and ion exchange, while dry reprocessing consists of processes, such as the fluorination volatilization process, high-temperature metallurgical treatment, high-temperature chemical treatment, the liquid metal process, the molten salt electrolysis process, and other chemical separation methods in an anhydrous state. Dry reprocessing has advantages in terms of processing high burnup spent fuel, especially fast reactor spent fuel, but is relatively difficult to implement and is still an important research direction at present.

Traditional spent fuel water reprocessing, e.g., the Plutonium uranium recovery by extraction (Purex) process, is currently used for the reprocessing of spent fuel in nuclear power plants. However, owing to its deep burnup, higher radioactivity, and high fission product content, spent fuel reprocessing in nuclear power plants is more focused on separating key elements such as neptunium and technetium more reliably and efficiently, and, through the separation of high radioactive nuclei and transmutation, to shorten the volume and storage duration for better environmental compatibility. In order to adapt to future requirements, thermal reactor spent fuel reprocessing plants will be reliable, safe, and economical. For this reason, research on and development of reprocessing technology, equipment, control, etc. are still under way. Further research on the post-treatment process includes improvements to the Purex process, such as simplifying the process flow, reducing investment costs, and using salt-free reagents to reduce waste generation.

In France, Areva developed the COEX process. In accordance with so-called non-proliferation considerations, the process does not produce pure Pu products, but produces U-Pu mixed products. It is said that this product is beneficial to the manufacture of mixed oxide fuel, but this is a controversial topic. The United States developed the UREX+ process, which separates U, Tc, and I, and the remaining products (including Pu) in the high-level radioactive waste liquid undergo further separation. Separation–transmutation is a strategic measure to minimize nuclear waste. In this method, the minor actinides (MAs) and long-lived fission products (LLFPs) are first separated from the high-level radioactive waste generated by the reprocessing of spent fuel. Then, the MAs and LLFPs are made into targets and transmuted in a transmuter (fast reactor or accelerator driven sub-critical system) to transform the long-lived MAs and LLFPs into short-lived or stable nuclides, in order to reduce the volume and long-term toxicity of high-level radioactive waste that requires geological disposal. Russia has rebuilt RT-1 and continues to reprocess the spent fuel. Meanwhile, the RT-2 plant can also reprocess the spent fuel.

In terms of the research and development of advanced main processes, based on the newly-built experimental platform of Nuclear Fuel Reprocessing Radiochemical Experimental

Facility, in 2015, the China Institute of Atomic Energy successfully completed a 100-hour thermal experiment of continuous operation of the advanced process, and comprehensively obtained the key process indicators such as process flow fragment purification, uranium-plutonium yield, and uranium-plutonium separation. Furthermore, it highlighted the trend in the data of key elements, such as neptunium and technetium in the process, and investigated the stability and reliability of the process.

Regarding the separation process of high-level radioactive waste liquid, Tsinghua University developed the trialkylphosphine oxide process in the 1970s. After 160 hours of radioactive verification, the conditions for a pilot-scale test were prepared. The next step is to conduct research on the separation of high-level radioactive waste liquids in the reprocessing of power reactor fuel.

In recent years, several domestic research institutions and universities have successfully conducted basic and applied research on different separation technologies, such as the chemical processes of actinides, the separation and extraction processes of neptunium, the separation of new actinium and lanthanum, and the separation of strontium and cesium. These institutions have also aimed to develop thorium-based molten salt reactors and conducted preliminary research on dry post-processing technology. Furthermore, they have researched electrolytic refining and the separation of uranium and rare earths, ionic liquid separation of rare earths, and supercritical CO_2 extraction and separation of uranium.

In addition to the water separation process, another direction of research abroad is the research and development of the dry separation process as a candidate for advanced reprocessing. As nuclear fuel burnup further increases, spent fuel will become more radioactive, which may make it difficult for organic solvent-based water reprocessing. As a result, dry post-processing, which was studied by various countries in the 1960s and the 1970s, has become an active research field after approximately 20 years. Countries that are currently actively developing dry reprocessing techniques include the United States, Russia, Japan, France, India, and South Korea.

Dry reprocessing is a high-temperature chemical process, and the most promising method is the molten salt electrolytic refining method for metal fuel and oxide fuel. Compared with water reprocessing, the advantages of dry reprocessing are as follows: The inorganic reagents used have good high-temperature resistance and radiation resistance. In addition, the process flow is simple, and the equipment structure is compact. Furthermore, the equipment has good economic efficiency, and the recycling of reagents reduces waste generation. Moreover, Pu and MAs are recycled together, which helps prevent nuclear proliferation. However, dry reprocessing technology is difficult to implement. The strong irradiation of the components requires the entire process to be operated remotely, and the atmosphere needs to be strictly controlled to prevent hydrolysis and precipitation. Furthermore, the structural materials must have good high-temperature resistance, radiation resistance, and corrosion resistance.

As shown in Table 1.2.5, 30 core papers have been published in this direction, and the countries with the largest number of core papers are the United States, the United Kingdom, France, Germany, and China. It can be seen from Table 1.2.6 that the organizations that have published the largest number of core papers on this research topic are the French Alternative Energies and Atomic Energy Commission, the Joint Research Center of the European Commission, and the Korea Atomic Energy Research Institute. From the cooperation network among the top 10 core paper publishing countries (Figure 1.2.3), it can be seen that France, Germany, and the United Kingdom have frequent cooperation, and China and the United States have some cooperation. As demonstrated in Figure 1.2.4, out of the top 10 institutions by publication volume, there is a large amount of cooperation among French Alternative Energies and Atomic Energy Commission, Joint Research Center of the European Commission, Central Laboratory, Forschungszentrum Juelich, and Karlsruhe Institute of Technology; Korea Atomic Energy Research Institute, South Korea University of Science and Technology, and Ulsan National Institute of Science and Technology also have close cooperation on this front. The top five countries with the greatest output of citing papers are the United States, China, India, France, and Germany, as presented in Table 1.2.7. The top institutions with the greatest output of citing papers are the Chinese Academy of Sciences, French Alternative Energies and Atomic Energy Commission, University of Chinese Academy of Sciences, University of Tokyo, and Idaho National Laboratory, as shown in Table 1.2.8.

Table 1.2.5 Countries with the greatest output of core papers on “advanced nuclear spent fuel reprocessing and nuclear fuel recycling”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	5	23.81%	92	18.40	2016.0
2	UK	4	19.05%	94	23.50	2016.2
3	France	4	19.05%	78	19.50	2015.2
4	Germany	4	19.05%	75	18.75	2016.5
5	China	3	14.29%	67	22.33	2016.7
6	South Korea	3	14.29%	39	13.00	2015.7
7	India	3	14.29%	34	11.33	2016.7
8	Japan	2	9.52%	29	14.50	2016.0
9	Spain	1	4.76%	11	11.00	2016.0
10	Russia	1	4.76%	11	11.00	2015.0

Table 1.2.6 Institutions with the greatest output of core papers on “advanced nuclear spent fuel reprocessing and nuclear fuel recycling”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	French Alternative Energies and Atomic Energy Commission	4	19.05%	78	19.50	2015.2
2	Joint Research Center of the European Commission	3	14.29%	61	20.33	2016.0
3	Korea Atomic Energy Research Institute	3	14.29%	39	13.00	2015.7
4	Central Laboratory	2	9.52%	52	26.00	2015.5
5	Forschungszentrum Juelich	2	9.52%	52	26.00	2015.5
6	Karlsruhe Institute of Technology	2	9.52%	52	26.00	2015.5
7	Government of India Department of Atomic Energy	2	9.52%	24	12.00	2017.0
8	University of Utah	2	9.52%	24	12.00	2015.5
9	South Korea University of Science and Technology	2	9.52%	23	11.50	2016.0
10	Ulsan National Institute of Science and Technology	2	9.52%	23	11.50	2016.0

Figure 1.2.3 Collaboration network among major countries in the engineering research front of “advanced nuclear spent fuel reprocessing and nuclear fuel recycling”

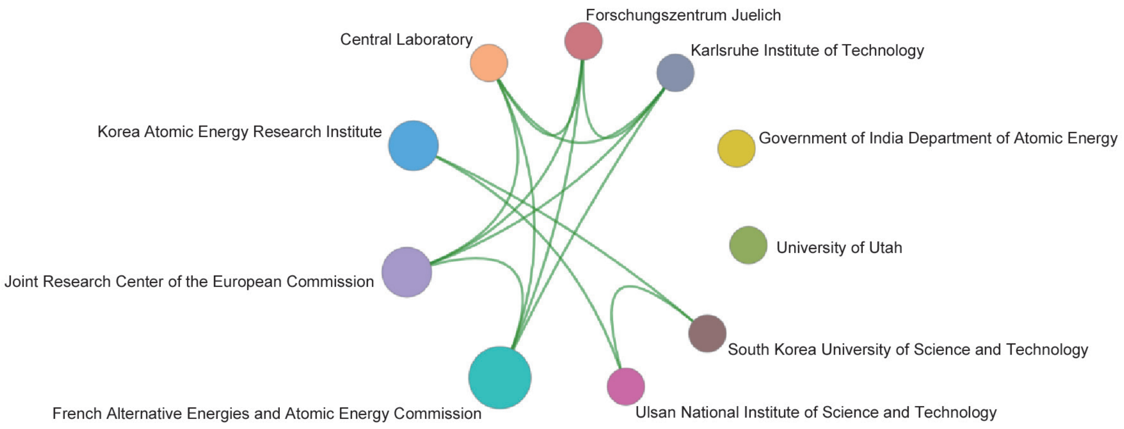

Figure 1.2.4 Collaboration network among major institutions in the engineering research front of "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

Table 1.2.7 Countries with the greatest output of citing papers on "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	78	21.91%	2018.5
2	China	70	19.66%	2018.4
3	India	38	10.67%	2018.4
4	France	35	9.83%	2017.6
5	Germany	31	8.71%	2017.9
6	Japan	22	6.18%	2018.2
7	UK	22	6.18%	2017.9
8	Russia	21	5.90%	2017.9
9	South Korea	17	4.78%	2018.1
10	Spain	15	4.21%	2018.1

Table 1.2.8 Institutions with the greatest output of citing papers on "advanced nuclear spent fuel reprocessing and nuclear fuel recycling"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	29	18.12%	2018.7
2	French Alternative Energies and Atomic Energy Commission	17	10.62%	2017.0
3	University of Chinese Academy of Sciences	17	10.62%	2018.7
4	University of Tokyo	15	9.38%	2018.2
5	Idaho National Laboratory	15	9.38%	2018.2
6	Bhabha Atom Research Center	15	9.38%	2018.3
7	Homi Bhabha National Institute	14	8.75%	2018.5
8	Indira Gandhi Center for Atomic Research	13	8.12%	2018.2
9	North China Electric Power University	9	5.62%	2017.7
10	Forschungszentrum Juelich	9	5.62%	2017.6

1.2.3 On-site conversion and efficient utilization of petroleum resources

As the degree of exploration and development increases, the quality of petroleum resources is deteriorating. The remaining oil in old oilfields is extremely dispersed, and the development of crude oil is approaching the limit of profitability. A large amount of shale oil is difficult to flow and produce and faces common problems of efficient resource utilization. Flow and extraction are common challenges in the efficient use of these resources. Research on on-site conversion and efficient utilization of petroleum resources refers to the integration of thermophysics, thermochemistry, materials science, and other multi-disciplines to transform low-grade resources into high-grade energy underground. It also refers to advanced research on *in-situ* upgrading of high-viscosity crude oil and oil shale *in-situ* conversion technology, which is expected to greatly increase the recovery rate or energy conversion rate and provide cutting-edge technology to deal with future structural changes in petroleum resources.

The technology for *in-situ* upgrading of heavy oil has advanced from steam stimulation to steam flooding, SAGD, and fire flooding. In recent years, multi-media steam flooding technology has been developed, and this technology is being furthered by developing highly active and universally applicable catalysts. The system enables the modification and viscosity reduction reactions of heavy oil to occur at a lower temperature and, at the same time, achieve the ideal modification and viscosity reduction effects for different heavy oils.

Shale oil underground *in-situ* conversion involves a physical and chemical process that uses horizontal well electric heating lightening technology to continuously heat the organic-rich shale interval to lighten multiple types of organic matter. This advancement in shale oil underground *in-situ* conversion technology would help in the development and utilization of shale oil resources and ensure the long-term stability and even higher production of domestic crude oil. Promoting the *in-situ* conversion and efficient utilization of petroleum resources and realizing commercial breakthroughs are of great significance to improving China's crude oil self-sufficiency and the future development of the world's petroleum industry.

Relevant papers in this area are published primarily by China, the United States, India, and other countries, as given in Table 1.2.9. The foremost institutions include the Chinese Academy of Sciences, the University of Chinese Academy of Sciences, and Anna University, as listed in Table 1.2.10. In terms of international cooperation, Malaysia has cooperated with India, Canada with Turkey, and China with the United States (Figure 1.2.5). Close collaberation exists between Ann University and the University of Malaya; Gachon University, the Korea Advanced Institute of Science and Teahnology, and the Korea Institute of Energy Research; the Chinese Academy of Sciences and the University of Chinese Academy of Sciences (Figure 1.2.6). Moreover, the papers are cited primarily by countries such as China, the United States, and India, and by institutions such as the Chinese Academy of Sciences, the University of Chinese Academy of Sciences, and the University of Toronto (Tables 1.2.11 and 1.2.12).

Table 1.2.9 Countries with the greatest output of core papers on "on-site conversion and efficient utilization of petroleum resources"

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	3	30%	105	35	2017.0
2	USA	2	20%	68	34	2016.5
3	India	1	10%	201	201	2016.0
4	Malaysia	1	10%	201	201	2016.0
5	South Korea	1	10%	90	90	2015.0
6	Germany	1	10%	49	49	2018.0
7	Canada	1	10%	47	47	2017.0
8	Turkey	1	10%	47	47	2017.0
9	Iran	1	10%	32	32	2015.0
10	Spain	1	10%	28	28	2018.0

Table 1.2.10 Institutions with the greatest output of core papers on "on-site conversion and efficient utilization of petroleum resources"

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	2	20%	64	32	2017
2	University of Chinese Academy of Sciences	2	20%	64	32	2017
3	Anna University	1	10%	201	201	2016
4	University of Malaya	1	10%	201	201	2016
5	Gachon University	1	10%	90	90	2015
6	Korea Advanced Institute of Science and Technology	1	10%	90	90	2015
7	Korea Institute of Energy Research	1	10%	90	90	2015
8	Max Planck Society	1	10%	49	49	2018
9	Ruhr University of Bochum	1	10%	49	49	2018
10	Istanbul Technical University	1	10%	47	47	2017

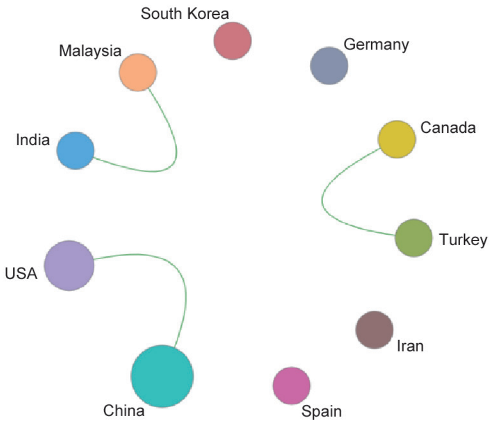

Figure 1.2.5 Collaboration network among major countries in the engineering research front of "on-site conversion and efficient utilization of petroleum resources"

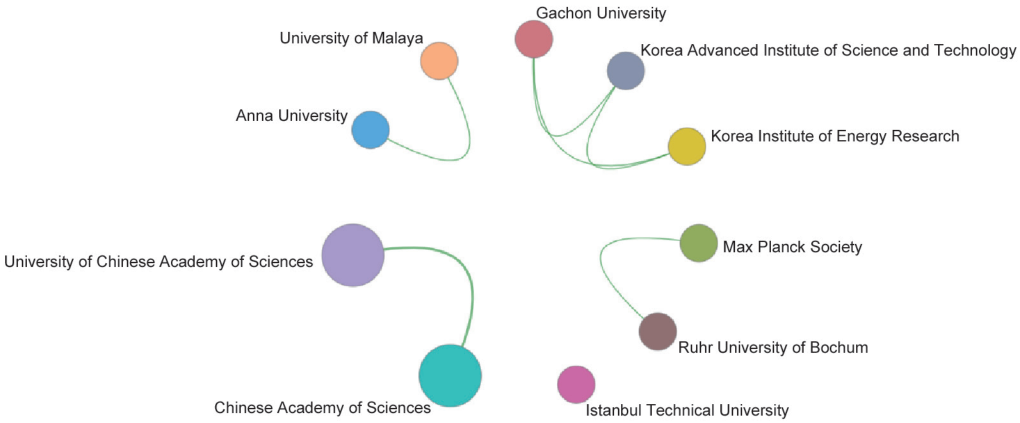

Figure 1.2.6 Collaboration network among major institutions in the engineering research front of "on-site conversion and efficient utilization of petroleum resources"

Table 1.2.11 Countries with the greatest output of citing papers on “on-site conversion and efficient utilization of petroleum resources”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	199	38.72%	2018.8
2	USA	75	14.59%	2018.1
3	India	37	7.20%	2018.5
4	South Korea	35	6.81%	2017.8
5	Canada	34	6.61%	2018.4
6	Iran	29	5.64%	2018.1
7	Spain	22	4.28%	2018.5
8	Brazil	22	4.28%	2018.6
9	UK	21	4.09%	2017.9
10	Japan	18	3.53%	2018.5

Table 1.2.12 Institutions with the greatest output of citing papers on “on-site conversion and efficient utilization of petroleum resources”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	59	32.24%	2018.8
2	University of Chinese Academy of Sciences	39	21.31%	2018.7
3	University of Toronto	11	6.01%	2018.7
4	Korea Advanced Institute for Science and Technology	10	5.46%	2016.9
5	Xiamen University	10	5.46%	2018.9
6	Zhengzhou University	9	4.92%	2019.4
7	Dalian University of Technology	8	4.37%	2018.9
8	University of North Carolina	8	4.37%	2016.9
9	Texas A&M University	8	4.37%	2017.6
10	Harbin Institute of Technology	7	3.83%	2019.4

1.2.4 Basic theory and method for intelligent drilling

As the core driving force of today’s technological revolution and industrial innovation, intelligent technology has become crucial. The application of smart technology in the field of oil and gas exploration and development has become an important trend in the development of the petroleum industry. Major international oil companies such as Schlumberger and Halliburton are actively implementing the strategic layout of intelligent oil and gas exploration and development. Drilling is a key part of the discovery, exploration, and exploitation of oil and gas resources. Intelligent drilling technology is a transformative technology that integrates big data, artificial intelligence, information engineering, downhole control engineering, and other theories and technologies. This is expected to greatly improve the drilling efficiency and reservoir drilling encountering rate. Furthermore, this technology can reduce drilling costs and significantly increase the single-well production and recovery efficiency of complex oil and gas reservoirs.

The intelligent characterization of the drilling environment can provide a precise description of the drilling environment working conditions and the physical properties of the reservoir, which is the basis for the realization of intelligent drilling monitoring, diagnosis, decision-making, and regulation. The eDrilling Company has established a virtual wellbore to provide early warnings of gas invasion and well kick. Sinopec realized the direct characterization of rock physical properties using the amplitude variation with offset inversion method. The focus of research in this area is 3D geological modeling, drilling process visualization, and digital twin simulation.

Intelligent perception of drilling conditions is based on intelligent monitoring and data transmission technologies. It combines artificial intelligence algorithms, realizes real-time analysis and collection of geological and engineering data, and provides dynamic data support for the realization of intelligent drilling engineering. At present, King Fahd University of Petroleum and Minerals in Saudi Arabia has achieved a high-precision prediction of the rate of penetration (ROP) using neural network technology. Northeast Petroleum University in China used the improved back-propagation algorithm to predict the friction factor of the drill string to overcome individual differences in the friction factor. The main research trends in this area are the response mechanism of downhole monitoring devices, automatic diagnosis of risks in wells, and early warning theory.

The intelligent decision-making of the drilling plan is based on the integration and processing of geological engineering data, revealing the cooperative response mechanism between the geological engineering parameters and objective functions such as drilling rate, cost, and risk. Moreover, it helps optimize and determine engineering parameters and construction schemes. Drilling efficiency, construction cost, and drilling risk are the most important objective functions of intelligent decision-making. At present, Saudi Aramco analyzes the response of drilling parameters to changes in lithology in real time and obtains optimal control parameters through algorithms such as gradient search. The China Petroleum Engineering Institute proposed a bit selection database, which realized bit selection based on formation information. Research on multi-source data fusion, geological engineering model reconstruction, and intelligent coordinated control strategies for all drilling conditions will effectively promote the development of intelligent decision-making technology for drilling. The main research trend of intelligent decision-making is the two-way efficient real-time transmission of massive data, and the closed-loop optimization theory of downhole control parameters.

Intelligent control of drilling parameters is based on an integrated coordination mechanism between drilling parameters. It utilizes the intelligent control theory to achieve intelligent control of drilling parameters such as well trajectory, wellbore pressure, and fluid performance. The Halliburton fracturing parameter intelligent control system uses real-time measurement and an adaptive rate control algorithm to intelligently adjust the pump speed to achieve uniform fracturing. Intelligent control of drilling engineering parameters is a key component to realize intelligent drilling. The closed-loop control of ROP, intelligent steering drilling, and wellbore stability will become the focus of future research.

According to Table 1.2.13, the countries with the largest number of core papers on this research topic are China, Iran, and Australia. The percentage of core papers on this topic in each country other than China, Iran, and Australia is less than 10%. The percentage of Chinese core papers is 38.64%. The each country with the most citations of core papers in this direction is Iran, and the one with the most citations per core paper is Malaysia. Table 1.2.14 shows that Amirkabir University of Technology in Iran and Southwest Petroleum University in China have the largest number of core papers on this research topic, each with a fraction of more than 10%, while each of the other institutions has published less than 10% of the total papers. The core papers from the Amirkabir University of Technology are cited most frequently, and the core papers University of Technology Malaysia have the most citations per paper.

From Figure 1.2.7, it can be seen that China, Iran, the United States, and Australia cooperate more with other countries in this field. According to Figure 1.2.8, collaborative research among institutions is mainly carried out by Amirkabir University of Technology, University of Tehran, Iran Petroleum University of Technology, Islamic Azad University, and Sharif University of Technology, each of which has cooperative relations with three other institutions.

According to Table 1.2.15, the countries with the largest number of citing papers on this research topic are China, Iran, and Vietnam. The percentage of citing papers in China exceeds 30%. It can be seen from Table 1.2.16 that the institutions with the largest number of papers on this research topic are Duy Tan University, Amirkabir University of Technology, University of Technology Malaysia, and Ton Duc Thang University, with the percentage of citing papers written by each university exceeding 10%.

Table 1.2.13 Countries with the greatest output of core papers on “basic theory and method for intelligent drilling”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	17	38.64%	66	3.88	2018.7
2	Iran	15	34.09%	155	10.33	2018.1
3	Australia	5	11.36%	31	6.20	2018.8
4	Malaysia	3	6.82%	45	15.00	2018.7
5	USA	3	6.82%	37	12.33	2019.3
6	Saudi Arabia	2	4.55%	20	10.00	2018.5
7	France	2	4.55%	18	9.00	2019.0
8	South Africa	2	4.55%	12	6.00	2018.5
9	UK	2	4.55%	11	5.50	2018.0
10	Canada	2	4.55%	9	4.50	2019.5

Table 1.2.14 Institutions with the greatest output of core papers on “basic theory and method for intelligent drilling”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Amirkabir University of Technology	5	11.36%	79	15.80	2019.0
2	Southwest Petroleum University	5	11.36%	21	4.20	2018.8
3	University of Tehran	4	9.09%	23	5.75	2017.5
4	Iran Petroleum University of Technology	3	6.82%	43	14.33	2016.7
5	Islamic Azad University	3	6.82%	26	8.67	2016.7
6	Sharif University of Technology	3	6.82%	21	7.00	2019.3
7	University of Technology Malaysia	2	4.55%	38	19.00	2019.0
8	King Fahd University of Petroleum and Minerals	2	4.55%	20	10.00	2018.5
9	Chiba University	2	4.55%	2	1.00	2019.0
10	China University of Geoscience	2	4.55%	2	1.00	2019.0

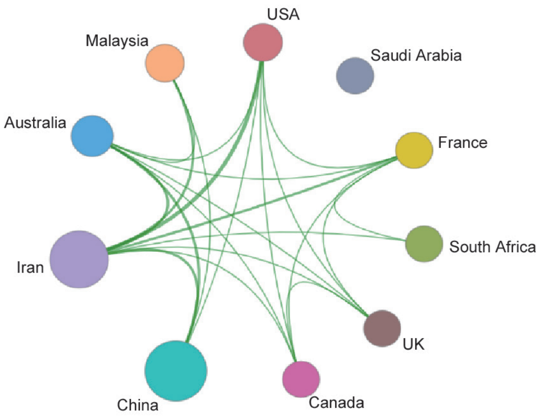

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “basic theory and method for intelligent drilling”

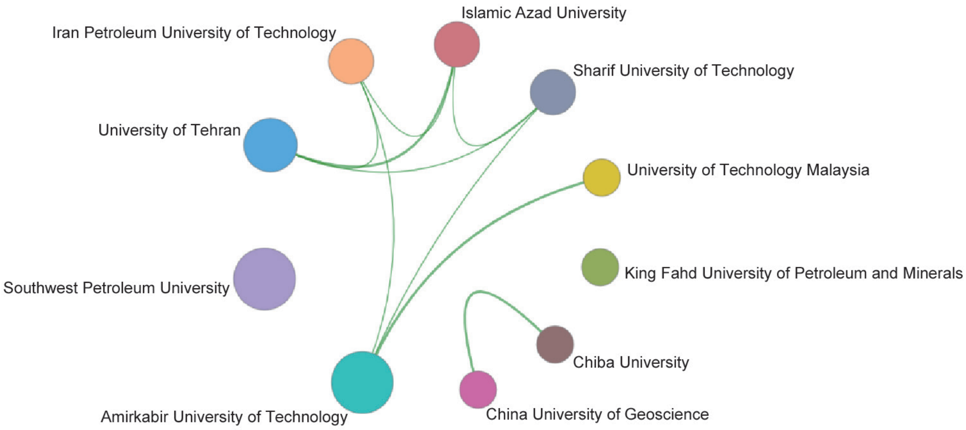

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "basic theory and method for intelligent drilling"

Table 1.2.15 Countries with the greatest output of citing papers on "basic theory and method for intelligent drilling"

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	158	31.29%	2018.9
2	Iran	98	19.41%	2018.8
3	Vietnam	70	13.86%	2018.9
4	Malaysia	48	9.50%	2019.0
5	USA	36	7.13%	2019.2
6	Saudi Arabia	32	6.34%	2019.3
7	UK	17	3.37%	2018.9
8	Australia	16	3.17%	2018.9
9	Canada	11	2.18%	2018.3
10	Greece	10	1.98%	2019.1

Table 1.2.16 Institutions with the greatest output of citing papers on "basic theory and method for intelligent drilling"

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Duy Tan University	55	17.57%	2018.8
2	Amirkabir University of Technology	47	15.02%	2018.8
3	University of Technology Malaysia	42	13.42%	2019.0
4	Ton Duc Thang University	36	11.50%	2019.2
5	Central South University	31	9.90%	2019.0
6	Islamic Azad University	25	7.99%	2018.8
7	King Fahd University of Petroleum and Minerals	24	7.67%	2019.4
8	Southwest Petroleum University	17	5.43%	2018.9
9	China University of Petroleum	16	5.11%	2018.7
10	Shahrood University of Technology	10	3.19%	2018.8

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 tabulated 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.

Of these top 12 development fronts, "development of a three-dimensional imaging system for Earth observation" and "key technologies for future electric grids with a high proportion of renewable energy" are emerging fronts. Further developments in existing research fields include "key technologies for controlled nuclear fusion engineering testing reactor," "nuclear spent fuel reprocessing and nuclear fuel recycling," "nuclear battery technology and applications," "seismic data acquisition and processing technology based on compressed sensing," and "system for undisturbed detection of multi-scale pore structures in deep mining processes." "All-solid-state lithium battery with high energy density, long life, and controllable interface" is a revolutionary front. The fronts of interdisciplinary integration include "key technologies for coupling electric vehicles and the smart grid," "intelligent monitoring and early-warning information collection system for coal mine disasters," "research and development of three-dimensional prospecting technology for solid mineral resources," and "research on oil and gas intelligent drilling system and tools."

The numbers of core papers published each year from 2014 to 2019 for the top 12 engineering development fronts are listed in Table 2.1.2.

(1) Key technologies for coupling electric vehicles and the smart grid

Electric vehicles use batteries and electric motors to replace the power system of conventional oil engine vehicles. Their application can effectively reduce dependence on oil resources and reduce urban environmental pollution. At the same time, the charging load of electric vehicles can be adjusted in a certain margin in time and location. Then, the charged electric vehicles can be used as mobile energy

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

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Key technologies for coupling electric vehicles and the smart grid	59	4 228	71.66	2014.7
2	Key technologies for controlled nuclear fusion engineering testing reactor	29	113	3.90	2016.7
3	Development of a three-dimensional imaging system for Earth observation	35	400	11.43	2016.0
4	Intelligent monitoring and early-warning information collection system for coal mine disasters	271	5 438	20.07	2015.7
5	Key technologies for future electric girds with a high proportion of renewable energy	473	1 933	4.09	2016.6
6	All-solid-state lithium battery with high energy density, long life, and controllable interface	65	357	5.49	2016.8
7	Nuclear spent fuel reprocessing and nuclear fuel recycling	56	118	2.11	2015.8
8	Nuclear battery technology and applications	139	1 008	7.25	2015.9
9	Research and development of three-dimensional prospecting technology for solid mineral resources	62	690	11.13	2016.0
10	Seismic data acquisition and processing technology based on compressed sensing	224	2 158	9.63	2015.7
11	Research on oil and gas intelligent drilling system and tools	201	3 836	19.08	2015.3
12	System for undisturbed detection of multi-scale pore structures in deep mining processes	352	5 338	15.16	2015.7

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	2014	2015	2016	2017	2018	2019
1	Key technologies for coupling electric vehicles and the smart grid	9	3	3	15	6	4
2	Key technologies for controlled nuclear fusion engineering testing reactor	1	5	6	0	5	9
3	Development of a three-dimensional imaging system for Earth observation	6	9	10	3	4	3
4	Intelligent monitoring and early-warning information collection system for coal mine disasters	59	76	54	47	33	2
5	Key technologies for future electric grids with a high proportion of renewable energy	35	33	50	107	84	113
6	All-solid-state lithium battery with high energy density, long life, and controllable interface	10	5	4	8	15	20
7	Nuclear spent fuel reprocessing and nuclear fuel recycling	1	5	7	6	12	9
8	Nuclear battery technology and applications	7	18	18	23	27	22
9	Research and development of three-dimensional prospecting technology for solid mineral resources	10	14	15	13	10	0
10	Seismic data acquisition and processing technology based on compressed sensing	70	42	40	35	36	1
11	Research on oil and gas intelligent drilling system and tools	84	46	30	17	23	1
12	System for undisturbed detection of multi-scale pore structures in deep mining processes	81	95	65	59	51	1

storage resources to support the establishment of the smart grid. Therefore, the coupling of electric vehicles and the smart grid is considered to be the key factor affecting and promoting the development of the two technologies. This can not only significantly reduce the impact of large-scale electric vehicle charging load on the grid, but also reduce the investment and operation cost of the grid and improve the ability of the smart grid to incorporate renewable energy sources.

The main technical directions of electric vehicle and smart grid coupling include the following: integration technology to integrate the charging and discharging devices and power stations for electric vehicles; the optimized layout and evaluation technology of electric vehicle charging and discharging facilities, considering the integration of transportation and the power grid; large-scale orderly electric vehicle charging control technology and secure, intelligent management of the power grid; business model, communication and data security protection; dispatch control technology for the interaction between electric vehicles and the power grid (V2G); large-scale electric vehicle charging behavior analysis and charging guidance technology based on data mining and artificial intelligence; and cascade utilization technology of electric vehicle power batteries.

With the increasing number of electric vehicles, electric vehicle charging operators and users will realize orderly charging and V2G through intelligent charging and discharging facilities, participate in the optimization of the smart grid operation and the competition of the power market, and help provide considerable regulatory resources for smart grid.

(2) Key technologies for controlled nuclear fusion engineering testing reactor

Nuclear fusion energy, which is clean and abundant, is regarded as the best energy source to fundamentally solve the energy crisis in the future. At present, research on different types of fusion experiment devices around the world indicates that the superconducting tokamak, a type of magnetic confinement nuclear fusion device, such as the International Thermonuclear Experimental Reactor (ITER) and the China Fusion Engineering Test Reactor (CFETR), is the device that is most likely to generate electricity. The ITER program represents an international nuclear fusion research and engineering megaproject and the world's largest magnetic confinement fusion (MCF) device. The machine assembly was launched on 28 July 2020. The construction of the facility is expected to be completed in 2025, and the initial plasma experiments will begin as scheduled. This will be the culmination of the research on tokamaks. China, as one of ITER program's seven members, will continue international cooperation with the ITER research group and assimilate the technology of nuclear fusion experimental reactors. CFETR, designed and developed independently by China, acts as a bridge between the ITER and the fusion demonstration reactor. The implementation of these measures will put China at the forefront of the world's research on the key engineering technology for nuclear fusion experimental reactors.

(3) Development of a three-dimensional imaging system for Earth observation

Three-dimensional imaging for land resource prospecting aims to visualize big data with space-time information, which is obtained by satellite technology, space technology, and land exploration technology. This technology mainly uses satellite remote sensing, satellite geophysics, airborne geophysical exploration, aerial remote sensing, ground infrared spectrum, ground geochemistry, ground geophysical exploration, and other multi-level Earth observation big data obtained using satellite technology, and presents Earth observation big data with space–time information in the form of three-dimensional images using computer technology. This enables the basic problems encountered in geological surveys and in mineral resource exploration and assessment to be solved.

This method optimizes and integrates the data by applying Earth observation big data to geological surveys. At the same time, it displays the results of Earth exploration in the form of three-dimensional images, which is convenient for the use of different types of users. In the future, the establishment of a three-dimensional space–time Earth observation big data system with time information can use data from the past, analyze the current situation, and better understand the rules of geology to ensure the safety of a country's geology and national resources and energy.

(4) Intelligent monitoring and early-warning information collection system for coal mine disasters

An intelligent monitoring and early-warning information collection system of coal mine disasters includes a monitoring network, an early warning system, and a data acquisition and processing module, which cooperate with each other to ensure the safety of underground coal mine operations. Effective monitoring and early warning of coal mine hazards are important to ensure normal coal mine production and the safety of miners. Based on different hazard sources, the system can be divided into five major hazard monitoring and early warning systems: gas, mine pressure and roof, coal dust, water, and fire monitoring systems.

First, the systems of the Internet of Things should be established in coal mines to realize digital and intelligent mining. Intelligent perception systems for major sources of danger and accurate early warning systems should be developed. Second, a unified framework and data standard format for coal mine hazard monitoring and early warning systems should be provided. Finally, hidden danger identification, early warning, and intelligent control should be realized by adopting the data fusion method, the data mining technology, prediction models, and space analysis technology.

(5) Key technologies for future electric grids with a high proportion of renewable energy

It is difficult for the existing power grid system based on fossil energy to promote the development of an environmentally friendly society and continuously support future economic growth. The general trend is to tackle this problem by forming modes of energy consumption that are based on renewable energies, such as solar, wind, and water energy, and thereby build a new power grid with a high proportion of renewable energy as the main feature.

The fluctuation, intermittence, and uncertainty of renewable energies cause a great number of theoretical and technical challenges when planning future power grid with a high proportion of renewable energy. The main technical directions of research are the establishment of a probabilistic theoretical system of high-proportion power system flexibility, analysis theory for stability of the electronic power system, basic theory and planning of the security boundary of the electricity distribution system, simulation of panoramic power grid operation, AC/DC hybrid transmission grid planning, and the efficient and optimized operation of the AC/DC hybrid system.

In the future, research could be further refined and extended to cover the sending and receiving ends of a grid connection with a high proportion of renewable energy and the connection itself. In addition, solar thermal power generation technology and energy storage technology could be important research directions, considering the fact that these technologies may have an important impact on the structure of future power systems.

(6) All-solid-state lithium battery with high energy density, long life, and controllable interface

Lithium-ion batteries are widely used in electronic devices, electric vehicles, and grid storage, but they are severely hindered by the safety issues induced by flammable liquid/gel electrolytes. All-solid-state lithium batteries utilizing solid electrolytes as a substitute for the problematic liquid electrolytes can not only eliminate/alleviate safety problems but also help employ lithium anode or sulfur/oxygen cathode materials with a higher energy density. Solid-state electrolytes can be divided into inorganic electrolytes, solid polymer electrolytes, and plastic crystal electrolytes. Inorganic electrolytes possess a high ionic conductivity comparable to that of liquid electrolytes, but the large interfacial impedance and inadequate stability hamper their practical applications. Solid polymer electrolytes have been in development since the early 2000s, but, currently, the limited room-temperature ionic conductivity of these electrolytes render them unsuitable for practical application. Plastic crystal electrolytes have high ionic conductivities and improved interfacial properties, which are promising for industrial evaluation. Solid polymer electrolytes and plastic crystal electrolytes may be applied on certain occasions in the short term, but the application of solid inorganic electrolytes is desirable in the long term. Polymer plastic crystal electrolytes can be prepared by employing a polymer as the backbone and a plastic crystal as the conducting material. By adjusting the concentration of the lithium salt in the interface layer, it is expected that the interface can be effectively controlled while ensuring the overall conductivity, so as to achieve a solid-state battery with high energy density and long life.

(7) Nuclear spent fuel reprocessing and nuclear fuel recycling

The whole process of preparation, burning during reactor operation, and subsequently reprocessing of nuclear fuel is called the nuclear fuel cycle, which is mainly comprised of three major links. The first is the industrial processing the nuclear fuel before it is used in a nuclear reactor, which includes uranium (thorium) mining, processing, enrichment, and nuclear fuel assembly processing and manufacturing. The second link is the use of the fuel in the reactor to obtain nuclear energy or produce new fission nuclides, etc. The third link involves reprocessing and disposing the nuclear fuel (called “spent fuel”) discharged from the reactor, including the intermediate storage and reprocessing of spent fuel, and the processing and final disposal of spent radioactive wastes.

The reactor is the central link of the nuclear fuel cycle. Thermal reactors are a mature and widely used technology worldwide. The fast reactor is the preferred next-generation reactor for nuclear energy development. When fissile nuclear fuel is consumed, this reactor converts more ^{238}U into ^{239}Pu to realize the proliferation of nuclear materials. At the same time, it can also incinerate and transmutate long-lived high-level radioactive waste in the spent fuel of a pressurized water reactor, which greatly reduces the environmental risk of long-term geological storage of high-level radioactive wastes.

Spent fuel reprocessing is at the core of the back end of nuclear fuel cycle. Its purpose is to process the spent fuel components discharged from nuclear power plants, separate and recover unburned uranium and newly generated plutonium, and process radioactive wastes to meet disposal requirements. Reprocessing is divided into a wet process (also known as water process) and a dry process, according to the existing state of spent fuel when it undergoes the prior main process. The water extraction process is currently the only economical and practical post-treatment process. The commonly used Purex process converts the spent fuel elements of the reactor into an aqueous solution of nitric acid after proper pretreatment, and then organic solvents are used for extraction and separation to recover nuclear fuel and remove fission products. Dry reprocessing has certain advantages for processing high burnup spent fuels, especially fast reactor spent fuels, which is currently an important research direction.

(8) Nuclear battery technology and applications

A nuclear battery system (radioisotope power supply) is a device that converts the energy generated in the process of radioisotope decay into electrical energy. It has a long working life, good environmental adaptability (adaptable to no-light, extremely cold, high-voltage, and other environments), high energy density, high reliability, and is maintenance-free during its lifetime. It is widely used in space exploration, terrestrial extreme environmental area monitoring, deep-sea monitoring, and other fields. The battery system is a key technical bottleneck restricting deep-space exploration and deep-sea deployment and control tasks. There are more than ten types of nuclear battery systems, of which the most mature technology with the widest range of applications is the temperature difference nuclear battery system.

The main research directions pertaining to the thermoelectric nuclear battery system are focused on the production of radioisotope materials, the development of modular heat sources, high-efficiency thermoelectric conversion, heat source safety testing and evaluation, and power supply reliability testing and evaluation, for which radioisotope raw materials are the prerequisite and are important for the development, production, and application of nuclear battery systems. The development of new and efficient thermoelectric conversion material systems and conversion devices has always received a considerable amount of interest in the development of thermoelectric nuclear battery systems. In addition, the materials of the different shell layers of the thermoelectric nuclear battery system influence the internal heat conduction of the battery, the safety of the heat source, the reliability of the power supply, etc., and advancements in terms of key materials, structural design, and manufacturing processes are still needed.

The development trend of thermoelectric nuclear battery systems mainly lies in improving the efficiency of thermoelectric conversion devices and developing high-power and high-efficiency thermoelectric nuclear battery systems. With regard to high-efficiency conversion technology (such as Stirling conversion technology and thermo-photoelectric conversion technology, etc.), improving the maturity of this technology and developing high-power and high-efficiency temperature difference nuclear battery systems is the focus.

(9) Research and development of three-dimensional prospecting technology for solid mineral resources

Three-dimensional prospecting technology for solid mineral resources aims to develop a method for rapid and efficient prospecting using an integrated space–air–ground prospecting approach. This can be achieved by using satellite remote sensing, unmanned aerial vehicle (UAV) hyperspectral remote sensing, airborne geophysical exploration, infrared spectroscopy for land surface and drill core samples, geophysical and geochemical exploration of the land surface, shallow drilling technology, and other modern exploration techniques.

Based on traditional mineral resource prospecting techniques and with the application of modern technology, three-dimensional prospecting technology aims to modernize solid mineral resource exploration and keep up with the forefront of ming technology in the world. The main technical approaches include combining modern mineral deposit theory with modern technology; integrating aerospace, aviation, and ground exploration; selecting important exploration target areas by means of space remote sensing and geophysical techniques; optimizing the exploration target area using hyperspectral remote sensing; determining drilling positions using infrared spectroscopy and ground geophysical and geochemical exploration in target areas; and verifying target areas using shallow drilling technology.

Based on the rapid development of satellite remote sensing technology and UAV technology, three-dimensional prospecting is expected to advance into an intelligent and automatic technology that integrates communication, artificial intelligence, and geophysical–geochemical–remote sensing prospecting.

(10) Seismic data acquisition and processing technology based on compressed sensing

Traditional seismic data acquisition and processing are based on the Fourier transform of regular sampling, which cannot reconstruct ideal results for datasets with a significant amount of missing data. At the same time, the sampling rate requirements must be met, which adds considerable difficulty for actual applications. Seismic data acquisition and processing technology based on compressed sensing effectively combines the acquisition of seismic data in practical scenarios and compression in data processing. The seismic data acquisition points can be flexibly arranged according to the design of the sampling matrix and are no longer limited. Compared to traditional regular and high-density sampling, the aforementioned compressed sensing technique can help overcome the limitations of the traditional method with respect to sampling frequency. Furthermore, it uses the sparsity of seismic signals to realize the reconstruction of missing data, which greatly reduces the sampling cost and time, improves the work efficiency, and enables the large-scale development of density seismic exploration. In other words, the use of compressed sensing technology for seismic data acquisition can greatly reduce the workload of field acquisition, reduce expenditure, and restore and reconstruct high-precision data to complete the geological exploration task. In the future, relevant methods based on the compressed sensing theory should be applied to actual production to improve the production efficiency and continue to mitigate the problems encountered.

(11) Research on oil and gas intelligent drilling systems and tools

Intelligent drilling is a combination of big data, artificial intelligence, downhole control engineering, and other theories and technologies. It achieves advanced detection and completion of oil and gas drilling, closed-loop control, precision guidance, and transformative technology for intelligent decision-making through surface automatic drilling rigs, downhole intelligent actuator devices, intelligent drilling and completion fluids, and intelligent monitoring and decision-making systems. The intelligent drilling system is mainly composed of intelligent surface equipment, downhole tools, completion and fracturing equipment, and an integrated system platform.

Intelligent ground equipment will effectively reduce personnel input, improve drilling efficiency, and reduce drilling risks and costs. The main intelligent ground equipment which should be developed in the future includes automated drilling rigs, integrated driller control systems, drill floor robots, and intelligent pressure control systems. Intelligent downhole tools can provide technical support for rock breaking, real-time acquisition of downhole data, efficient data transmission, precise drilling guidance, and closed-loop control. The development trend of downhole tools includes smart drill bits, smart drill pipes, smart steering drilling systems, smart sensors, and underground microchips. The development of intelligent completion fracturing equipment will enable infinite-level fracturing and intelligent oil and gas development. The development trend of equipment includes infinite-level intelligent fracturing devices, downhole temperature and pressure monitoring and control devices, wireless communication intelligent fracturing casing, and downhole production dynamic monitoring systems. An intelligent drilling and completion integrated system platform is key to realizing intelligent monitoring, diagnosis, and decision-making in drilling engineering. Drilling data management systems, drilling digital twin simulation systems, expert analysis and decision systems, and remote operation support systems will become the development trend of intelligent drilling and completion integrated systems.

(12) System for undisturbed detection of multi-scale pore structures in deep mining processes

In complicated conditions where high crustal stress is encountered in deep mining, high osmotic pressure, high temperature, and severe mining disturbances, the undisturbed system can realize visualized detection, refined dynamic pore structure characterization, and advanced disaster warning of deep deposits via multi non-disturbed detection technologies, thereby guaranteeing the efficiency and safety for deep mining operations.

Major research interests include developing dynamic refined characterization theories of deep deposit structures; exploring real-time accurate positioning and identification methods for deep high-stress compaction regions; constructing a precise positioning and identification model of pores and cracks in multiple stope regions; conducting studies on the non-disturbed identification of pore structure in the time and frequency domains under deep mining dynamic loading; exploring the intelligent identification of mineral deposits based on 3D concentrated inversion technology; and constructing a database of deep deposit intelligent identification and detection data.

This front is focused on *in-situ* fidelity sampling and structure detection of deep mineral deposits, dynamic interaction of multi-scale pore structures under deep mining disturbances, deep irregular rock mechanic behavior detection and characterization, and other key technologies. This system for undisturbed detection of multi-scale pore structures in deep mining processes will provide hardware support for the transparency of the structure and process of China’s mining of deep mineral resources.

2.2 Interpretations for four key engineering development fronts

2.2.1 Key technologies for coupling electric vehicles and the smart grid

The coupling of electric vehicles and smart grid is a key factor affecting and promoting the development of the two technologies. It can not only significantly reduce the impact of large-scale electric vehicle charging load on the grid, but also reduce the investment and operation cost of the grid and help incorporate renewable energy sources into the smart grid.

In 2019, about 2.2 million new energy vehicles were sold worldwide, which represented a year-on-year increase of 10%. The market share of new energy vehicles increased from 2.1% to 2.5%, of which, pure electric vehicles accounted for 74%, with a year-on-year increase of 5%, and plug-in hybrid vehicles accounted for 26%, with a year-on-year decrease of 5%. In 2019, the production and sales of new energy vehicles in China were 1.242 million and 1.206 million, respectively. Of these figures, the production and sales of pure electric vehicles reached 1.02 million and 0.972 million, respectively. The production and sales of plug-in hybrid electric vehicles were 0.22 million and 0.232 million, respectively

According to the latest data released by the International Energy Agency, the number of public charging points for electric vehicles worldwide increased by 60% in 2019, which exceeded the sales of electric vehicles, with 60% of the increase coming from China. By the end of 2019, the total number of public charging piles and private charging piles in China reached 1.219 million, which represented a year-on-year increase of 50.8%.

As listed in Table 2.2.1, the countries with the largest number of core patents published in this field are the United States, Germany, and Japan, with the United States and Germany ranking first and second, accounting for 66.10% and 10.17% of the total number of the core patents, respectively. The proportion of core patents published by Japan was 8.47%.

As tabulated in Table 2.2.2, NIO USA Inc., Qualcomm Inc., and the Witricity Corporation are the institutions with the largest number of core patents published on this research topic, having 19, 7, and 5 core patents, respectively. As shown in Figure 2.2.1, Germany, South Korea, and Switzerland have a greater level of cooperation in this field. Germany collaborates with the largest number of countries as it cooperates with South Korea and Switzerland. As depicted in Figure 2.2.2, on this research front, Witricity Corporation has a strong cooperative relationship with Qualcomm Inc. and Delta Electronics, Inc., so do Better Place GmbH and Renault SAS.

2.2.2 Key technologies for controlled nuclear fusion engineering testing reactor

Compared with the currently used types of energy and the clean energies that are being developed, nuclear fusion energy is an ideal future strategic energy source owing to its safety, economy, durability, and environmentally friendly characteristics. MCF is the use of a specific morphological magnetic field to confine the ultrahigh temperature plasma composed of free electrons and light nuclei, such as deuteron and tritium in a limited volume, which promotes the production of a large number of nuclear fusion reactions under control, and releases energy. At present, there are three types of MCF devices worldwide: tokamak, stellarator, and reversed-field pinch. Each of these has its own advantages and disadvantages. However, a tokamak can most easily get close to fusion conditions and is being developed the fastest. Both the ITER and CFETR are based on tokamak technology to realize fusion energy.

Table 2.2.1 Countries with the greatest output of core patents on “key technologies for coupling electric vehicles and the smart grid”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	39	66.10%	3 684	87.13%	94.46
2	Germany	6	10.17%	114	2.70%	19.00
3	Japan	5	8.47%	124	2.93%	24.80
4	New Zealand	3	5.08%	188	4.45%	62.67
5	Switzerland	2	3.39%	113	2.67%	56.5
6	China	2	3.39%	26	0.61%	13.00
7	South Korea	1	1.69%	18	0.43%	18.00
8	Sweden	1	1.69%	10	0.24%	10.00
9	France	1	1.69%	8	0.19%	8.00
10	UK	1	1.69%	3	0.07%	3.00

Table 2.2.2 Institutions with the greatest output of core patents on "key technologies for coupling electric vehicles and the smart grid"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	NIO USA Inc.	USA	19	32.20%	148	3.50%	7.79
2	Qualcomm Inc.	USA	7	11.86%	770	18.21%	110.00
3	Witricity Corporation	USA	5	8.47%	2789	65.96%	557.80
4	Auckland UniServices Ltd.	New Zealand	3	5.08%	188	4.45%	62.67
5	Better Place GmbH	Switzerland	2	3.39%	344	8.14%	172.00
6	GM Global Technologies Operations Inc.	USA	2	3.39%	65	1.54%	32.50
7	Toyota Motor Co., Ltd.	Japan	2	3.39%	60	1.42%	30.00
8	Nissan Motor Co., Ltd.	Japan	2	3.39%	31	0.73%	15.50
9	Delta Electronics, Inc.	USA	1	1.69%	2086	49.34%	2086.00
10	Renault SAS	France	1	1.69%	271	6.41%	271.00

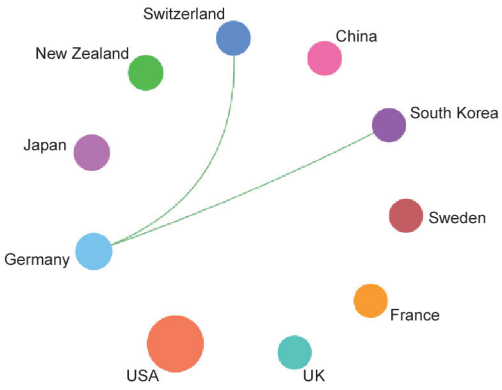

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "key technologies for coupling electric vehicles and the smart grid"

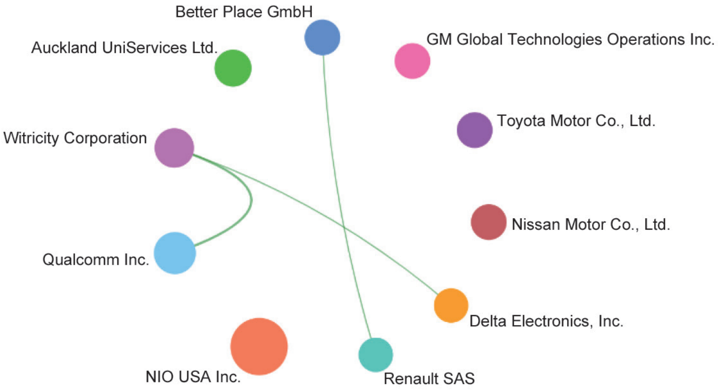

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "key technologies for coupling electric vehicles and the smart grid"

In recent years, significant progress has been made in the field of controllable nuclear fusion. The ITER program, the largest and most far-reaching international scientific project in the world, is jointly undertaken by the European Union, China, South Korea, Russia, Japan, India, and the United States. The ITER program will integrate the main scientific and technological achievements of controlled MCF research and realize the first controlled thermonuclear fusion experimental reactor in the world, which is comparable with a practical future fusion reactor scale, and can solve the key problems that are hindering progress toward fusion power stations. The successful implementation of the ITER program will fully verify the scientific and engineering feasibility of the development and utilization of fusion energy, which is the key step for human controlled thermonuclear fusion research to be practical.

The United States, Japan, the European Union, South Korea, and other major countries and regions have formulated detailed fusion energy development routes. Furthermore, they have built and developed their own next generation of devices and conducted relevant research related to ITER.

China is vigorously supporting the MFC research community to actively participate in the construction and experiments of ITER, promoting the corresponding domestic physical and engineering technology research, and supporting the independent design of CFETR with the goal of obtaining fusion energy. At present, the physical and engineering conceptual design has also been completed in China's self-designed CFETR, and the full construction of CFETR will begin in due course.

The top three countries for core patent disclosure are the United Kingdom, China, and United States. The percentage of core patens published by the United Kingdom and China both are 37.93% (Table 2.2.3). The top three institutions with the highest number of core patents are Tokamak Energy Ltd., the Hefei Institutes of Physical Science of the Chinese Academy of Sciences, and the China National Nuclear Corporation (Table 2.2.4). There is some cooperation between the China National Nuclear Corporation and Beijing Leyfond Vacuum Technology Co., Ltd., as well as between Advanced Research Corporation and the West Virginia University (Figure 2.2.3).

2.2.3 Development of a three-dimensional imaging system for Earth observation

Three-dimensional imaging for land resource prospecting arises from photography. This technique has undergone rapid development because of the progress in computer graphics and image processing technology. Owing to the maturity of aerospace and land exploration technology and rapid access to data obtained from satellite remote sensing, satellite geophysics, airborne geophysical exploration, aerial remote sensing, ground infrared spectrum, ground geochemistry, and ground geophysical exploration, the practical application of space–air–ground three-dimensional imaging for land resource prospecting has finally become possible.

In the 1950s, the US National Aeronautics and Space Administration developed a three-dimensional global elevation model using radar systems. Currently, Google Inc. has a complete 3D map of the Earth (i.e., Google Earth) based on satellite remote sensing images and a three-dimensional elevation model. Three-dimensional imaging has become a major function in many industries, such as UAVs. In July 2017, the Aerospace Information Research Institute, the largest aerospace research institute under the Chinese Academy of Sciences, was established. In November 2019, China launched the Gaofen-7 satellite, which is capable of providing a 1:10 000

Table 2.2.3 Countries with the greatest output of core patents on "key technologies for controlled nuclear fusion engineering testing reactor"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	UK	11	37.93%	91	80.53%	8.27
2	China	11	37.93%	10	8.85%	0.91
3	USA	2	6.90%	4	3.54%	2.00
4	South Korea	2	6.90%	1	0.88%	0.50
5	Russia	2	6.90%	1	0.88%	0.50
6	Japan	1	3.45%	6	5.31%	6.00

Table 2.2.4 Institutions with the greatest output of core patents on “key technologies for controlled nuclear fusion engineering testing reactor”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Tokamak Energy Ltd.	UK	11	37.93%	91	80.53%	8.27
2	Hefei Institute of Physical Sciences, Chinese Academy of Sciences	China	4	13.79%	2	1.77%	0.50
3	China National Nuclear Corporation	China	2	6.90%	0	0.00%	0.00
4	Japan Atomic Energy Agency	Japan	1	3.45%	6	5.31%	6.00
5	Advanced Research Corporation	USA	1	3.45%	3	2.65%	3.00
6	West Virginia University	USA	1	3.45%	3	2.65%	3.00
7	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	China	1	3.45%	2	1.77%	2.00
8	Seoul National University R&DB Foundation	South Korea	1	3.45%	1	0.88%	1.00
9	All-Russia Research Institute of Automatics	Russia	1	3.45%	0	0.00%	0.00
10	Beijing Leyfond Vacuum Technology Co., Ltd.	China	1	3.45%	0	0.00%	0.00

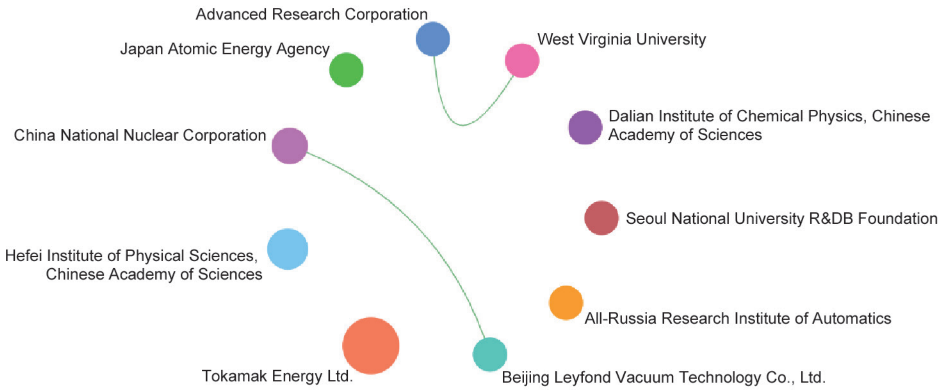

Figure 2.2.3 Collaboration network among major institutions in the engineering development front of “key technologies for controlled nuclear fusion engineering testing reactor”

scale satellite three-dimensional imaging that contributed to the successful three-dimensional imaging of Mount Qomolangma (Mount Everest) in May 2020.

Significant progress has been made in three-dimensional imaging in many countries, and there are connections among these countries. The technical difficulties associated with three-dimensional imaging include the cooperative use of multi-source data and accurate visualization of data, and more studies for this technique are required.

The top three countries with the most published core patents for three-dimensional imaging for land resource prospecting are China (21), the United States (7), and Germany (4). China has the highest percentage (60%) of published core patents and the highest citations (196) for the published core patents. The top three countries with the highest citations per patent are Sweden (27), the United States (16.5), and Germany (10.5) (Table 2.2.5). Institutions with the most published core patents include the Beijing Institute of Technology (5), Lessmueller Lasertechnik GmbH (2), Changchun Institute of Optics, Fine Mechanics and Physics (2), Nanjing University of Science and Technology (2), and Harbin Institute of Technology (2). The institutions with the highest number of citations are Boeing Corporation (44), Lessmueller Lasertechnik GmbH (28), the Beijing Institute of Technology (27), General Electric Company (27), and Zhejiang Sci-Tech University (27) (Table 2.2.6).

Table 2.2.5 Countries with the greatest output of core patents on “development of a three-dimensional imaging system for Earth observation”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	21	60.00%	196	49.00%	9.33
2	USA	7	20.00%	116	29.00%	16.57
3	Germany	4	11.43%	42	10.50%	10.50
4	Japan	2	5.71%	19	4.75%	9.50
5	Sweden	1	2.86%	27	6.75%	27.00

Table 2.2.6 Institutions with the greatest output of core patents on “development of a three-dimensional imaging system for Earth observation”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Beijing Institute of Technology	China	5	14.29%	27	6.75%	5.40
2	Lessmueller Lasertechnik GmbH	Germany	2	5.71%	28	7.00%	14.00
3	Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences	China	2	5.71%	26	6.50%	13.00
4	Nanjing University of Science and Technology	China	2	5.71%	21	5.25%	10.50
5	Harbin Institute of Technology	China	2	5.71%	13	3.25%	6.50
6	Boeing Corporation	USA	1	2.86%	44	11.00%	44.00
7	General Electric Company	USA	1	2.86%	27	6.75%	27.00
8	Zhejiang Sci-Tech University	China	1	2.86%	27	6.75%	27.00
9	KLA-Tencor Corporation	USA	1	2.86%	21	5.25%	21.00
10	Nova Measuring Instruments Ltd.	USA	1	2.86%	17	4.25%	17.00

2.2.4 Intelligent monitoring and early-warning information collection system for coal mine disasters

Based on safety monitoring requirements and early warning of an intelligent fully mechanized mining face, this system studies the real-time monitoring and early warning of five major disasters: water, fire, gas, mine pressure, and dust hazards. Through a comprehensive evaluation model, safety index analysis and early warning of the working face area can be realized, which can guarantee security for the intelligent control of the fully mechanized working face and provide real-time monitoring and analysis data for the safety warning and control of the disaster. It is an important part of the intelligent working face safety warning and control system.

Effective monitoring and early warning of hazards in underground coal mines are important for normal production and the safety of miners.

With the development of the complete equipment technology of fully mechanized faces, the number of intelligent fully mechanized faces is increasing. However, the environmental safety monitoring and management of intelligent fully mechanized faces are still in the stages where they rely on over-limit alarms, manual connections, and verbal warnings. Taking the five aforementioned major coal mine disasters as an example, and considering the situation from the perspectives of basic analysis of data sources, disaster analysis methods, and monitoring analysis results, the status quo of environmental safety monitoring and early warning on working faces is as follows:

(1) Analysis of basic data sources: The analysis process requires manual intervention. The basic data cannot be acquired automatically, and the subjective uncontrollability of human interference cannot be eliminated. Furthermore, the analysis results cannot be produced in real time.

(2) Disaster analysis method: Isolated analysis of water, fire, gas, mineral pressure, and dust, without the overall layout of the working face, integrated analysis, and early warning based on each disaster monitoring.

(3) Results of disaster monitoring and analysis: Most results are in the form of research reports, and research results are submitted for the analysis of staged production processes. Thus, it is impossible to conduct safety analysis, safety tracking, and safety guarantee for the entire production cycle of the working face.

The development trends of this front include: First, establish the Internet of Things in coal mines, build digital and intelligent mines, develop intelligent perception systems of major sources of danger, and establish accurate early warning systems. Second, provide a unified framework and data standard format for coal mine hazard monitoring and early warning systems. Third, establish mine hidden danger identification, early warning, and intelligent control by means of the data fusion method, data mining technology, prediction models, and space analysis technology.

As can be seen from Table 2.2.7, patents related to this development front are mainly concentrated in the United States and China, which account for 94% of all patents. The United States also ranks first in the world in terms of citations and percentage of citations. China ranks second in the world with 39 published patents. Table 2.2.8 lists the major institutions at the forefront of this development front. The results show that the numbers of patents published by Honeywell International Inc. and Johnson Controls Technology Co. are the two highest, accounting for approximately 25% of the global number of patents. As illustrated in Figure 2.2.4, China, the United States, New Zealand, India, and the Czech Republic have established cooperation networks.

Table 2.2.7 Countries with the greatest output of core patents on “intelligent monitoring and early-warning information collection system for coal mine disasters”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	216	79.70%	4 546	83.60%	21.05
2	China	39	14.39%	660	12.14%	16.92
3	Canada	5	1.85%	90	1.66%	18.00
4	Netherlands	4	1.48%	96	1.77%	24.00
5	South Korea	2	0.74%	28	0.51%	14.00
6	United Arab Emirates	1	0.37%	29	0.53%	29.00
7	Czech Republic	1	0.37%	29	0.53%	29.00
8	India	1	0.37%	22	0.40%	22.00
9	Germany	1	0.37%	19	0.35%	19.00
10	New Zealand	1	0.37%	18	0.33%	18.00

Table 2.2.8 Institutions with the greatest output of core patents on “intelligent monitoring and early-warning information collection system for coal mine disasters”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Honeywell International Inc.	USA	48	17.71%	1 274	23.43%	26.54
2	Johnson Controls Technology Co.	USA	22	8.12%	344	6.33%	15.64
3	Emerson Electric Co.	USA	16	5.90%	545	10.02%	34.06
4	Google Inc.	USA	15	5.54%	431	7.93%	28.73
5	EcoFactor Inc.	USA	14	5.17%	214	3.94%	15.29
6	Senseware Inc.	USA	10	3.69%	89	1.64%	8.90
7	Trane International Inc.	USA	8	2.95%	131	2.41%	16.38
8	Philips Lighting Holding BV	USA	4	1.48%	96	1.77%	24.00
9	Gree Electric Appliances, Inc. of Zhuhai	China	4	1.48%	80	1.47%	20.00
10	Siemens Corp.	USA	3	1.11%	39	0.72%	13.00

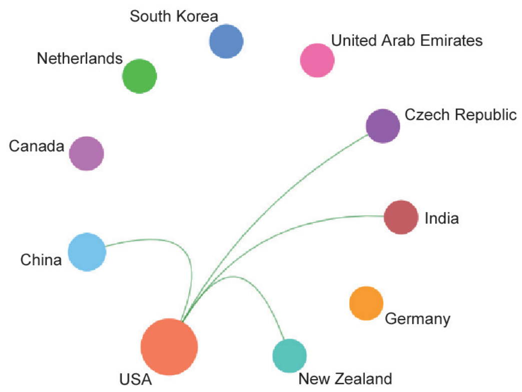

Figure 2.2.4 Collaboration network among major countries in the engineering development front of “intelligent monitoring and early-warning information collection system for coal mine disasters”

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