

IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Energy and Mining Engineering Group are shown in Table 1.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these 12 research fronts, “regulation and control of theories and methods in power systems using a high proportion of renewable energy”, “low-cost direct air carbon capture (DAC)”, and “design of key materials for high-efficiency proton exchange membrane (PEM) hydrogen production reactor” represent energy and electrical science, technology, and engineering research fronts; “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism,

and multidisciplinary strong coupling mechanism”, “mechanism and coupling experiments of digital reactor with multi-physical field and multi-space-time scale”, and “physical and experimental verification of China Fusion Engineering Test Reactor (CFETR)” represent nuclear science, technology, and engineering research fronts; “key technologies and challenges for natural gas hydrate exploitation”, “research on climate change based on the Earth System Model (ESM)”, and “efficient breaking mechanism of hard rock by high temperature and compression” represent geology resources science, technology, and engineering research fronts; and “multi-information perception and early warning of hidden danger of mine disasters”, “fundamental theory for the efficient exploitation of shale oil”, and “rock burst mechanism and early warning methodology” represent research fronts of mining science, technology, and engineering.

The annual publication status of the core papers related to each frontier from 2015 to 2020 is shown in Table 1.1.2.

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

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Regulation and control of theories and methods in power systems using a high proportion of renewable energy	202	5 390	26.68	2018.0
2	Research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism	384	2 084	5.43	2017.5
3	Key technologies and challenges for natural gas hydrate exploitation	99	2 319	23.42	2018.3
4	Multi-information perception and early warning of hidden danger of mine disasters	375	3 226	8.60	2018.0
5	Low-cost direct air carbon capture (DAC)	274	6 614	24.14	2018.4
6	Design of key materials for high-efficiency proton exchange membrane (PEM) hydrogen production reactor	103	2 228	21.63	2018.2
7	Mechanism and coupling experiments of digital reactor with multi-physical field and multi-space-time scale	110	450	4.09	2017.7
8	Physical and experimental verification of China Fusion Engineering Test Reactor (CFETR)	186	1 210	6.51	2018.2
9	Research on climate change based on the Earth System Model (ESM)	47	1 649	35.09	2019.0
10	Efficient breaking mechanism of hard rock by high temperature and compression	421	2 686	6.38	2017.9
11	Fundamental theory for the efficient exploitation of shale oil	52	1 886	36.27	2018.0
12	Rock burst mechanism and early warning methodology	63	840	13.33	2018.2

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

No.	Engineering research front	2015	2016	2017	2018	2019	2020
1	Regulation and control of theories and methods in power systems using a high proportion of renewable energy	23	25	28	40	35	51
2	Research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism	61	64	74	61	62	62
3	Key technologies and challenges for natural gas hydrate exploitation	5	14	8	17	30	25
4	Multi-information perception and early warning of hidden danger of mine disasters	51	40	50	64	68	102
5	Low-cost direct air carbon capture (DAC)	25	19	37	29	65	99
6	Design of key materials for high-efficiency proton exchange membrane (PEM) hydrogen production reactor	10	8	19	11	24	31
7	Mechanism and coupling experiments of digital reactor with multi-physical field and multi-space-time scale	9	20	21	21	18	21
8	Physical and experimental verification of China Fusion Engineering Test Reactor (CFETR)	17	16	23	38	33	59
9	Research on climate change based on the Earth System Model (ESM)	0	1	1	9	21	15
10	Efficient breaking mechanism of hard rock by high temperature and compression	46	56	57	85	74	103
11	Fundamental theory for the efficient exploitation of shale oil	2	7	7	15	16	5
12	Rock burst mechanism and early warning methodology	11	0	8	11	12	21

(1) Regulation and control of theories and methods in power systems using a high proportion of renewable energy

High-proportion renewable energy power systems mainly refer to new power systems using renewable energy that accounts for more than 30% of total power generation. Renewable energy such as wind power and photovoltaics power will replace fossil energy for power supply, significantly changing the characteristics of power systems. The power system changes ① from the deterministic system to the strongly random system, where a deterministic system dominated by thermal power units and regular power loads shifts to a random system with strong uncontrollability in both power generation and load demands. Traditional control and operation methods cannot meet the developmental requirements of power systems. Existing research focuses on the modeling and impact assessment of uncertainty factors, decision-making under uncertainty, and stability evaluation in an uncertain environment. The spatio-temporal and seasonal power and electricity balance problems need to be solved urgently; ② from the electromechanical system to the power electronics dominated system. The basic characteristics of power systems evolve from the electromechanical transient process dominated by rotating electric machines to the

electromagnetic transient process with power electronics, thereby, changing the stability mechanism. Existing research focuses on the dynamic behavior characteristics of power electronics devices and basic theories of new stability problems. In the future, it will be necessary to accurately describe the operational stability boundary of the high-proportion renewable energy power system; and ③ from a single power system to an integrated energy system. The existing power system will be interconnected with heating power pipelines, natural gas pipelines, and transportation networks to form a complex energy system. Existing research focuses on the coupling and interaction modeling of power systems and other energy networks. In the future, it will be necessary to conduct in-depth research of the integrated cross-energy systems.

(2) Research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism

Inherently safe nuclear reactors are an important aspect of reactor design research. The water-cooled reactor possesses inherent safety characteristics, which indicates natural shutdown in case of water loss. Fully Ceramic Microencapsulated (FCM) fuel has potentially inherent safety

characteristics owing to its multiple encapsulated structure of fission products, high mechanical stability, and excellent thermal conductivity compared to other fuel forms. The composite silicon carbide cladding has high-temperature mechanics and strong oxidation resistance. The combination of these two approaches, in addition to features based on advanced core and structural design can conduct the residual heat of the core to the final heat sink through thermal radiation and structural heat conduction, without relying on external safety facilities under the hypothetical most serious accident conditions (loss of cooling), to ensure that the core does not melt and the reactor structure remains intact. This eliminates the risk of large-scale radioactive material release, fundamentally eliminating serious accidents, and achieving inherent safety in preventing off-site emergencies. At the same time, the high-temperature tolerance of the fuel allows the core to directly generate superheated steam for direct circulation, thereby, simplifying the system and improving the thermoelectric conversion efficiency, which enhances the economy of the power system. The research involves many scientific issues and key technologies such as the inherent safety mechanism characteristics of small superheated direct cycle water-cooled reactors based on FCM fuel, multidisciplinary strong coupling core design technology for complex behavior in the reactor, FCM fuel design, and manufacturing coupling mechanisms, all of which are difficult to implement.

(3) Key technologies and challenges for natural gas hydrate exploitation

Natural gas hydrate is an ice-like solid crystal composed of natural gas and water molecules. Natural gas is mainly composed of methane, commonly known as combustible ice that can be ignited in the air. The basic idea of natural gas hydrate recovery is to decompose the hydrate into water and natural gas underground to extract the gas. The biggest difference between the hydrate reservoir and the conventional natural gas reservoir is that there is no sealing or diagenesis; thus, the conventional natural gas exploitation method cannot be easily applied to hydrated natural gas exploitation. The large-scale development of natural gas hydrate mainly relies on four key technologies: natural gas hydrate reservoir reconstruction and protection technology, natural gas hydrate reservoir drilling and completion technology and equipment, bottom hole gas-water rapid separation technology and equipment, and technologies and processes for improving the

mining energy efficiency of natural gas hydrates.

To date, more than 100 wells have been drilled globally for natural gas hydrate research and exploration, mainly concentrated in North America and the Asia-Pacific region. With the gradual acceleration of global energy transition, natural gas hydrate has significant resource potential as a large-scale and efficient type of new clean energy, attracting increasing attention globally. At present, there are many problems associated with the exploitation of natural gas hydrates. First, there are technical challenges of effectiveness and safety; second, there are challenges of reducing costs and improving production efficiency; third, the exploitation of natural gas hydrates produces environmental problems; and finally, geological disasters also pose a challenge. These problems currently restrict the large-scale and effective development of natural gas hydrates and are also research directions for key technologies for natural gas hydrate development in the future.

(4) Multi-information perception and early warning of hidden danger of mine disasters

With the increase in mining depth and intensity of coal resources, the risk of dynamic disasters such as rock bursts, coal and gas outbursts, fires, and water inrush increases significantly. Due to unclear understanding of the formation process and evolution mechanism of dynamic disasters under the coupling multiphase conditions and multi-physical fields, the backward technology of disaster precursor information collection, sensing, transmission, and mining identification and the lack of disaster risk identification and early warning module, the early identification of dynamic disaster risk is still subjective, blind, and uncertain.

To meet the major needs of coal mine typical dynamic disaster prevention and control, it is urgent to research identification, monitoring, and early warning mechanisms and key technologies of typical coal mine dynamic disaster risks; study the dynamic mechanism of coal mine rockburst instability and multi field coupling disaster mechanism; the disaster mechanism of coal and gas outburst and breeding mechanism of compound dynamic disaster; study the breeding and evolution law of coal spontaneous combustion disaster under high temperature environment; research the space-time breeding and evolution law of water inrush disaster, develop an intelligent identification and early warning theory and technology of multi parameter precursor

information of typical coal mine dynamic disaster; study new sensing and multi network fusion transmission methods and technical equipment of precursor information of typical coal mine dynamic disasters; develop multi information mining and analysis technology of typical coal mine dynamic disasters based on data fusion; form an early warning method of typical coal mine dynamic disasters based on big data and cloud technology; provide support for the early warning and prevention and control of potential mine disasters; and ensure the efficient mining of deep coal resources.

(5) Low-cost direct air carbon capture (DAC)

Direct air carbon capture (DAC) refers to the extraction of CO₂ from the atmosphere by absorption or adsorption. Absorption/adsorption-based DAC and subsequent sequestration or utilization provide effective negative emission pathways to remove CO₂ from the air, reduce the negative shadow of fossil fuel utilization, and establish a closed carbon cycle. DAC technology was originally used for air pre-purification in air separation units and trace CO₂ removal in confined spaces such as submarines and spacecrafts. At present, DAC has become a research hotspot due to the threat of global climate change. Early DAC systems used alkali or alkaline earth metal hydroxide absorbers to extract CO₂ by causticizing or substituting causticizing processes. Such absorption processes require high-quality heat sources (~ 900 °C) for regeneration, thus limiting the application scenarios and increasing operating costs. In contrast, large-scale deployment of DAC by adsorption is technically and economically feasible and is expected to capture 1% of global annual CO₂ emissions in the near future. The energy consumption of the DAC system based on the adsorbent reached 0.113–0.145 MJ/mol CO₂. If the system is applied to a DAC on a large scale, the capture cost will be reduced to USD 60–190 /t CO₂. The DAC is still in its early stages of deployment. The development of low-cost adsorbents with large adsorption capacities, fast kinetics, and low decay rates is critical for reducing the operating and maintenance costs of the DAC process. In addition, in the development of DAC technology, attention should be paid to the pressure drop in the adsorber system. New gas-solid contactors with structured adsorbents can effectively reduce the power consumption of fans, and steam purge at negative pressure can reduce the regeneration temperature of the DAC, making it possible to couple renewable energy or regenerate industrial waste heat.

(6) Design of key materials for high-efficiency proton exchange membrane (PEM) hydrogen production reactor

Water electrolysis based on proton exchange membrane (PEM) has many advantages, including a compact structure, low ohmic loss, high current density, and high hydrogen purity. However, high voltage and strong oxidizing environments pose much higher requirements for the durability of key materials of water electrolysis stacks based on PEM. PEM-based water electrolysis cell stacks are mainly composed of membrane electron assemblies (MEAs), gas diffusion layers (GDLs), bipolar plates, collector plates, and endplates. The MEA is composed of anode and cathode catalytic layers on both sides of the PEM. The durability of PEMs and electrocatalysts for hydrogen evolution and oxygen evolution has always required and urgent and efficient action/solution. In addition, the cost of PEM water electrolysis cannot be ignored. Both the anode and cathode GDLs of PEM water electrolysis are made of titanium, as it is difficult for the carbon fiber to meet the corrosion resistance requirement. As the anode bipolar plates, collector plates, and endplates should be more resistant to corrosion, they are also mainly made of titanium; however, the cathode can be made from graphite, stainless steel, and other metal materials that will require special treatment. The formation of a passive film on the surface of titanium materials increases the ohmic loss; thus, pretreatment is required, such as platinum plating. In addition, it is also difficult, time-consuming, and expensive to process titanium materials.

(7) Mechanism and coupling experiments of digital reactor with multi-physical field and multi-space-time scale

With the development of information technology, numerical algorithms, and the improvement in supercomputing capabilities, the design, development, and operation of reactors are becoming digitalized and intelligentized. Digital reactors have adopted model-based systems engineering methods, large amounts of test data, and high-precision calculation software. On the one hand, digitalization and intelligent algorithms can promote the rapid iterative optimization of the forward design of the reactor; on the other hand, multi-professional high-precision software can be used to verify and predict the behavior characteristics of the reactor to support design verification and operation, so as to save research and development cost, shorten research and development cycle, and improve reactor performance. The successful research and development of digital reactors must

solve the following key problems: neutron transport, working fluid flow and heat transfer, fuel material behavior evolution and other professional mechanism problems, accurate and stable solutions of coupling problems across multiple time and space scales in multiphysics, support for universal use mechanism tests and precise measurements required for advanced model research, large amounts of reactor operation and test data, comprehensive integration of multi-source heterogeneous data and software in various disciplines, multi-objective comprehensive optimization algorithms, and efficient parallel algorithms. Currently, digital reactors are mainly used in pressurized water reactors. In the future, they will continue to be expanded to other types of reactors to improve reactor research and development, design, operation, and maintenance capabilities.

(8) Physical and experimental verification of China Fusion Engineering Test Reactor (CFETR)

The China Fusion Engineering Test Reactor (CFETR) is the next tokamak fusion device planned in the magnetic confinement fusion development roadmap of China, whose operation will be divided into two phases: In the first phase, 200 MW fusion power and tritium self-sustained steady-state operation will be realized; in the second stage, 1 000 MW fusion power will be achieved, and the fusion power output will be demonstrated. CFETR will focus on solving the physical and technical engineering problems between international thermonuclear fusion experimental reactor program (ITER) and Fusion Demonstration Reactor (DEMO), including the realization of steady-state operation of deuterium-tritium fusion, the proliferation and cyclic self-sustainment of kilogram-level tritium, and the development of material technology that can withstand high thermal load and strong neutron irradiation for a long time, to lay a solid foundation for China to independently build fusion power stations by 2050. In recent years, the overall design team of the national magnetic confinement fusion reactor has conducted a detailed physical engineering design of the CFETR and established a world-class research and development platform.

The physical design and integrated engineering design of CFETR (large radius is 7.2 m, small radius is 2.2 m) are currently in progress. In terms of physical design, the overall design team of the national magnetic confinement fusion reactor is conducting research on the corresponding operation schemes of the steady-state and hybrid operating modes of

CFETR based on the 1.5-dimensional integrated simulation program under the OMFIT framework, comparing it with the 0-dimensional program. OMFIT uses more advanced and accurate physical models to perform detailed integrated simulations for the device, which can predict the performance of the fusion reactor and optimize the auxiliary heating systems and diverter components more accurately. In terms of engineering design, the detailed design of superconducting magnets and cryogenics, vacuum chambers and internal components of the device (cladding, diverter, etc.), cladding and tritium plants, and remote operation and maintenance systems have been performed. The “Integrated Research Facility for the Key System of Fusion Reactor” project, a major scientific and technological infrastructure in the 13th Five Year Plan of Hefei Comprehensive National Science Center, is under construction, and the CFETR integrated engineering design research project (2017–2021) is progressing smoothly. This research and its progress, projects, and implementation will lay a solid foundation for developing fusion energy in China.

(9) Research on climate change based on the Earth System Model (ESM)

The Earth system is composed of the atmosphere, hydrosphere, cryosphere, biosphere, lithosphere, mantle, core, solar-terrestrial space, and human activities. Using a holistic view of the Earth system, climate change research based on Earth System Model (ESM) studies the impact of the Earth’s spheres, subsystems, endogenous and exogenous interactions, and the evolution of human activities on climate change and feedback mechanisms; from the Earth evolution perspective, it studies the critical thresholds and triggers for climate change and evaluates the impact of climate change on the evolution of life. The ESM uses the idea of the Anthropocene to establish the status and role of human activities in global changes, quantitatively studying the cascading effects of human activities such as carbon dioxide, methane, and other greenhouse gas emissions on the Earth system, especially the magnitude, rate, and driving mechanism of changes in key global climate and environmental parameters on time scales from ten to 100 years. Furthermore, the ESM quantitatively predicts the catastrophic consequences that human activities may bring to the Earth’s climate and environment, clarifies the human carrying capacity, and critical threshold of the Earth system establishes an early warning mechanism to respond to sudden

extreme climate events, and proposes overall scientific solutions.

(10) Efficient breaking mechanism of hard rock by high temperature and compression

The Earth's crust contains a large amount of precious mineral resources. Decades of continuous large-scale mining has led to the depletion of shallow mineral resources in China. The development of mineral resources in the future will be at a greater depth (1 000–2 000 m). Deep mining of deeply buried metals will become the norm. On one hand, high ground stress increases the probability of engineering disasters in a deep mining environment, significantly inhibiting the large-scale production of mines. A high subsurface temperature will also reduce labor productivity, induce industrial accidents, and influence the performance of equipment. On the other hand, under the condition of deep high stress, tremendous energy is stored in subsurface hard rocks. Once an appropriate method of inducing fractures is found, catastrophic damage to the rocks can be damaged under controlled conditions. This safe and efficient mining of deeply buried minerals can be conducted under these circumstances.

To date, cutting-edge studies on mining include in situ mechanical behavior of deeply buried mines, long-term stability of deeply buried surrounding rock, stress field and disaster dynamics, multi-field and multiphase seepage under strong disturbance and long-term potentiation, stress and energy fields of deeply buried mines, simulation and visualization, high-stress induction and energy control, rock deformation monitoring, and early warning systems. Non-blasting mining will become the main method for high-temperature and high-stress breaking of hard rocks in the future; it is expected to realize high-stress induced mechanized continuous mining, making deep mining more efficient, intelligent, green, and safe.

(11) Fundamental theory for the efficient exploitation of shale oil

Shale oil generally refers to oil trapped in source rocks, such as shale. Shale oil resources are abundant in continental basins in China and have been preliminarily estimated to have a technically recoverable resource of 7.4–37.2 billion tons. Shale oil is a key strategic replacement resource for oil and gas accumulation and has great significance in alleviating the outer dependency on oil and gas and ensuring national energy security. There are significant differences

in geological conditions between the continental shale oil in China and marine shale oil in North America, including unclear enrichment characteristics and uncertain “sweet-spot” distribution. The exploitation of shale oil in China also faces challenges from an engineering perspective with complicated exploration and development conditions, including a harsh engineering environment and poor resource endowment. Consequently, given these differences, adept shale oil and gas exploitation technology in North America is not applicable to China. In summary, the “sweet-spot” of shale oil and gas exploitation technology in China is still at an early stage, and it is urgent to explore the related theory and technology suitable for the exploration and development of continental shale in China. The main research areas include continental shale oil occurrence mechanism and quality evaluation index system, shale oil reservoir geophysical prediction technology, key ultra-long horizontal well drilling technology, horizontal well “one trip drilling” technology, anti-collapse drilling fluid technology for shale formation, multi-scale complex fracture network fracturing technology in the whole-well section of shale oil reservoirs, shale oil geology-fracturing integrated technology, and shale oil well factory multi-layer system 3D development technology. Breaking through the basic theory and technology of efficient exploitation of shale oil, realizing large-scale shale oil production and accumulation, and triggering the shale oil revolution in China will provide a solid guarantee for China's energy security.

(12) Rock burst mechanism and early warning methodology

Rock bursts are a power destabilization disaster caused by the rapid release of accumulated elastic energy from the hard and brittle surrounding rock in a high-stress state under the action of engineering excavation or other load disturbances, resulting in rock exfoliation, fragmentation, and ejection. Rock bursts have the characteristics of suddenness and danger, threatening the safety of construction personnel, machinery, and other equipment. Its main research directions include rock explosion mechanisms, classification, breeding processes, and prediction and control measures. Technical findings show that it is difficult to accurately identify the calm period of microseismic sequences, and it is necessary to find more short-term precursor information. The range of predicted rock burst locations is generally larger than the actual occurrence range, unfavorable for effective rock burst prevention and control. Thus, it is necessary to explore the micro-seismic prediction of high explosive risk areas in

conjunction with other physical techniques to achieve more accurate predictions and improve the efficiency of rock explosion prevention and control. As the manual processing of microseismic monitoring data is certain to have human errors and low work efficiency, it is necessary to further study intelligent methods for automatic, efficient, and accurate processing and analysis of microseismic data and the rapid prediction and forecasting of rock bursts.

1.2 Interpretations for four key engineering research fronts

1.2.1 Regulation and control of theories and methods in power systems using a high proportion of renewable energy

As the largest energy producer and consumer in the world, China's resource endowment determines that the energy structure of China is based on fossil energy. To achieve carbon peak and neutralization goals in 2030 and 2060, respectively, and promote the transformation of the energy system, it is necessary to build a "clean, low-carbon, safe, and efficient" energy system in which a new generation of electric power systems with a high proportion of new energy is an important link.

Compared with existing power systems, the high proportion of renewable energy will result in strong uncertainty in the power system. The power side has gradually evolved to be dominated by new energy sources such as wind power and photovoltaic power generation, which have a strong uncertainty and uncontrollability in both time and space. On the load side, high electrification leads to a diversified load structure. The active features of the electricity utilization are prominent, and the unpredictability of the load increases. Therefore, the "boundary conditions" of the future power system will be more diversified. To achieve power balance and sufficient capacity of the power system, relevant research needs to change from deterministic to probabilistic thinking to ensure the safety of the entire system.

The grid connection, transmission, and consumption of a high proportion of new energy rely on power electronics devices, leading to a significant trend in power electronization in the power system. It is difficult to apply the basic theory of traditional power systems based on AC technology. The low inertia, weak immunity, and multi-time scale response

characteristics of power electronics devices make the time constant of the power system smaller, the frequency domain wider, and the safety domain more complicated. In the case of disturbance, the electromechanical transient and electromagnetic oscillations of the system interact significantly. To ensure the stable and optimized operation of the future power system, it is necessary to redefine its stability zone, system short-circuit rate, and other indicators.

In addition, to give full play to the flexibility of the energy system, in the future, barriers in different energy fields such as electricity, heating, gas, and transportation will be broken, realizing the interconnection of different energy networks, and energy supply and demand balance on a larger scale. Current research in this direction mainly focuses on a small area; as it matures, it is necessary to further consider the impact of factors such as scale effects or network transmission restrictions on its cost and performance.

In the engineering research front of "regulation and control of theories and methods in power systems using a high proportion of renewable energy", the top three countries in terms of the number of core papers published (Table 1.2.1) are the USA, China, and the UK, all of which have been cited more than 23 times. Among the Top 10 countries with the most published papers, the USA and China have more cooperation, followed by Iran and Portugal (Figure 1.2.1). The institutions that produce a large number of core papers include Tsinghua University, University of Lisbon, and Imperial College London (Table 1.2.2). Among these 10 institutions, University of Lisbon has more cooperation with the University of Beira Interior and University of Porto (Figure 1.2.2). In the amount of citing core papers, the top three countries are China, the USA, and the UK (Table 1.2.3). The main output institutions of citing core papers are the North China Electric Power University, Tsinghua University, and Aalborg University (Table 1.2.4).

1.2.2 Research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism

Small-scale water-cooled reactors are currently the mainstream of small-scale reactor research and development because of their better technical foundation; its main development direction is high system simplification and module integration. However, the current small-scale reactor technology has not broken through the scope of the current pressurized water

Table 1.2.1 Countries with the greatest output of core papers on “regulation and control of theories and methods in power systems using a high proportion of renewable energy”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	56	27.72%	1 458	26.04	2017.9
2	China	45	22.28%	1 059	23.53	2018.3
3	UK	22	10.89%	565	25.68	2018.5
4	Iran	21	10.40%	353	16.81	2018.6
5	Australia	15	7.43%	570	38.00	2017.9
6	Denmark	13	6.44%	311	23.92	2018.1
7	Italy	13	6.44%	148	11.38	2018.8
8	Portugal	12	5.94%	285	23.75	2016.9
9	Germany	11	5.45%	354	32.18	2017.2
10	Spain	10	4.95%	194	19.40	2017.9

Table 1.2.2 Institutions with the greatest output of core papers on “regulation and control of theories and methods in power systems using a high proportion of renewable energy”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Tsinghua University	11	5.45%	214	19.45	2018.0
2	University of Lisbon	8	3.96%	221	27.62	2016.9
3	Imperial College London	8	3.96%	120	15.00	2018.5
4	Argonne National Laboratory	6	2.97%	341	56.83	2018.0
5	University of Beira Interior	6	2.97%	149	24.83	2017.2
6	University of California, Berkeley	5	2.48%	130	26.00	2017.0
7	National Renewable Energy Laboratory	5	2.48%	118	23.60	2018.2
8	University of Porto	5	2.48%	100	20.00	2018.6
9	Aalborg University	5	2.48%	86	17.20	2018.6
10	Massachusetts Institute of Technology	4	1.98%	140	35.00	2019.0

Table 1.2.3 Countries with the greatest output of citing papers on “regulation and control of theories and methods in power systems using a high proportion of renewable energy”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	1 287	29.14%	2019.3
2	USA	715	16.19%	2019.1
3	UK	411	9.30%	2019.2
4	Iran	390	8.83%	2019.3
5	Australia	292	6.61%	2019.1
6	Germany	284	6.43%	2018.8
7	Italy	263	5.95%	2019.1
8	Denmark	234	5.30%	2019.2
9	Spain	226	5.12%	2019.2
10	India	179	4.05%	2019.0

Table 1.2.4 Institutions with the greatest output of citing papers on “regulation and control of theories and methods in power systems using a high proportion of renewable energy”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	North China Electric Power University	165	18.13%	2019.2
2	Tsinghua University	130	14.29%	2019.1
3	Aalborg University	119	13.08%	2019.4
4	Islamic Azad University	79	8.68%	2019.3
5	Technical University of Denmark	77	8.46%	2018.9
6	COMSATS Institute of Information Technology	61	6.70%	2018.0
7	Xi’an Jiaotong University	60	6.59%	2019.4
8	Huazhong University of Science and Technology	59	6.48%	2019.6
9	Imperial College London	54	5.93%	2018.9
10	University of Porto	53	5.82%	2018.7



Figure 1.2.1 Collaboration network among major countries in the engineering research front of “regulation and control of theories and methods in power systems using a high proportion of renewable energy”

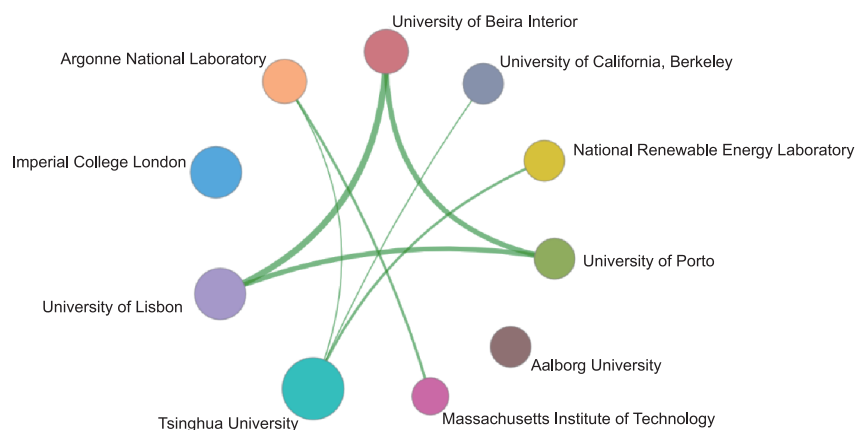


Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “regulation and control of theories and methods in power systems using a high proportion of renewable energy”

reactor in terms of design concepts and safety mechanisms and cannot fundamentally achieve inherent safety. Special safety facilities are still required to alleviate serious accidents. At present, the FCM fuel at home and abroad is mainly focused on replacing existing light water reactor fuel assemblies, and there is no systematic and innovative research on reactor design technology and safety mechanisms. Without breakthroughs in mechanism innovation, inherent safety cannot be realized.

Based on the innovative FCM fuel and advanced core design, superheated steam is generated in the reactor to achieve the ultimate simplification of the system and improve the thermoelectric conversion efficiency. In the event of an accident, the reactor can be shut down automatically, and the residual core heat can be automatically removed by radiation heat exchange to eliminate the risk of large-scale radioactive release and fundamentally achieve inherent safety. This topic can significantly improve small-scale, inherently safe reactor technology research and development capabilities and independent innovation in China.

After the Fukushima incident, the nuclear industry has paid more attention to accident-tolerant fuels. FCM fuel has potential inherent properties owing to its fission product multiple encapsulation structure, high mechanical stability, and excellent thermal conductivity compared to other fuel forms. Safety features are one of the important fuel forms that meet the design requirements of small reactors. The Oak Ridge National Laboratory (ORNL) of the USA conducted an experimental study on the oxidation performance of FCM fuel in a high-temperature water vapor environment, demonstrating its strong corrosion resistance. The Korea Atomic Energy Research Institute (KAERI) and ORNL have jointly conducted research on the use of FCM fuel to replace the current fuel assembly of light water reactors. The preliminary results of this research indicated that FCM fuel has a sufficient safety margin for loss-of-flow accidents and loss-of-water accidents. Domestically, Nuclear Power Institute of China has performed design evaluation for small modular-integrated pressurized water reactors (SM-IPWRs) using the FCM fuel and completed the conceptual design of the FCM fuel assembly, neutronic performance evaluation, thermal performance analysis, and radiation-thermal-mechanical coupling performance. Numerical research and other studies have been conducted on the concept of an ultra-safe smart microreactor. Xi'an Jiaotong

University conducted a neutronics design study on a SM-IPWR using the FCM fuel. Results showed that the SM-IPWR concept meets the design standards. Furthermore, Harbin Engineering University launched an innovative conceptual design based on FCM fuel.

The design of a new type of reactor that can achieve inherent safety based on innovative fuels is an important direction for the current reactor design.

According to Table 1.2.5, the countries with the highest output of core papers in this direction are the USA, China, Germany, and South Korea, with the USA accounting for 34.11%, China accounting for 11.46%, Germany accounting for 8.85%, and South Korea accounting for 8.59%. Figure 1.2.3 indicates that China, Germany, and South Korea have relatively close cooperation with the USA.

Table 1.2.6 and Figure 1.2.4 show that the institutions with the largest number of core papers in this research direction are the Idaho National Laboratory, the ORNL, and Los Alamos National Laboratory.

1.2.3 Key technologies and challenges for natural gas hydrate exploitation

The basic idea of natural gas hydrate exploitation is to decompose it into water and natural gas underground and extract the gas. Owing to the high energy density of natural gas hydrate, 1 m³ of natural gas hydrate will ideally release 164 m³ of natural gas. The biggest difference between a hydrate reservoir and conventional gas reservoir is that there is no capping rock or diagenesis, leading to the fact that the conventional natural gas production method is not suitable for hydrated natural gas production. The exploitation of natural gas hydrate, worldwide, is still in the experimental and exploratory stages. Its resource environment is very complex, and the exploitation process may cause environmental and safety problems. Therefore, we should be very cautious about the large-scale commercial exploitation of natural gas hydrates worldwide. At present, research in this field is still in the stage of mechanism discussion, exploiting technology demonstration, and small-scale experimental production. The safe and efficient utilization of natural gas hydrate resources depends on innovations and breakthroughs in engineering technology theory.

There is an urgent need to focus on the four key technologies

Table 1.2.5 Countries with the greatest output of core papers on “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	USA	131	34.11%	995	7.60	2017.6
2	China	44	11.46%	256	5.82	2017.4
3	Germany	34	8.85%	247	7.26	2017.6
4	South Korea	33	8.59%	149	4.52	2017.3
5	India	26	6.77%	53	2.04	2018.0
6	France	25	6.51%	214	8.56	2017.2
7	Russia	24	6.25%	42	1.75	2017.5
8	Japan	20	5.21%	115	5.75	2017.0
9	UK	19	4.95%	175	9.21	2018.2
10	Switzerland	14	3.65%	74	5.29	2017.9

Table 1.2.6 Institutions with the greatest output of core papers on “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Idaho National Laboratory	30	7.81%	222	7.40	2018.4
2	Oak Ridge National Laboratory	26	6.77%	185	7.12	2017.6
3	Los Alamos National Laboratory	14	3.65%	238	17.00	2017.1
4	European Commission	12	3.12%	62	5.17	2018.0
5	Massachusetts Institute of Technology	10	2.60%	59	5.90	2017.6
6	Pacific Northwest National Laboratory	10	2.60%	42	4.20	2018.6
7	City University of Hong Kong	9	2.34%	101	11.22	2016.1
8	Korea Atomic Energy Research Institute	9	2.34%	66	7.33	2017.1
9	Penn State University	7	1.82%	232	33.14	2017.0
10	Paul Scherrer Institute	7	1.82%	48	6.86	2017.6

Table 1.2.7 Countries with the greatest output of citing papers on “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	USA	537	30.81%	2019.1
2	China	380	21.80%	2019.3
3	South Korea	147	8.43%	2018.9
4	UK	125	7.17%	2019.2
5	France	115	6.60%	2019.3
6	Germany	112	6.43%	2019.1
7	Russia	88	5.05%	2019.3
8	Canada	76	4.36%	2019.1
9	Japan	67	3.84%	2019.0
10	India	51	2.93%	2019.2

Table 1.2.8 Institutions with the greatest output of citing papers on “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Idaho National Laboratory	130	20.41%	2019.4
2	Oak Ridge National Laboratory	98	15.38%	2019.1
3	Chinese Academy of Sciences	66	10.36%	2018.9
4	Los Alamos National Laboratory	63	9.89%	2019.1
5	Korea Atomic Energy Research Institute	54	8.48%	2018.7
6	Nuclear Power Institute of China	46	7.22%	2020.1
7	Xi’an Jiaotong University	42	6.59%	2019.7
8	University of Tennessee	39	6.12%	2019.7
9	Massachusetts Institute of Technology	34	5.34%	2018.9
10	Argonne National Laboratory	33	5.18%	2019.4



Figure 1.2.3 Collaboration network among major countries in the engineering research front of “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism”

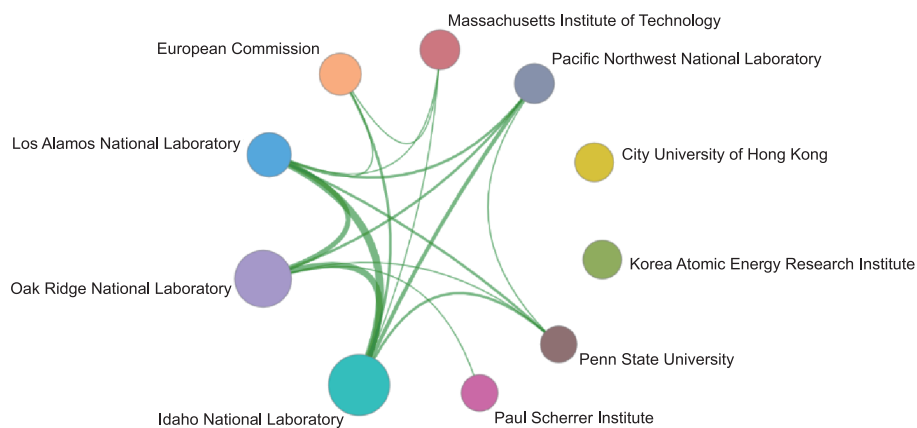


Figure 1.2.4 Collaboration network among major institutions in the engineering research front of “research on inherent safety of nuclear fuel, characteristics of reactor safety mechanism, and multidisciplinary strong coupling mechanism”

for a long time in the future, including natural gas hydrate reservoir reconstruction and protection technology, natural gas hydrate reservoir drilling and completion technology and equipment, well bottom gas and water rapid separation technology and equipment, and technology and processes to improve the energy efficiency of hydrate exploitation. With the progress of theory and engineering technology, the exploitation cost of natural gas hydrate will continue to decrease, causing this large-scale clean energy to be eventually used throughout society.

At present, a large number of key papers in this field have been published by countries such as China, Singapore, and India. The number of key papers in China accounts for 65.66%, with a citation frequency of more than 1 500 times (Table 1.2.9). The

three scientific research institutions that published the largest number of core papers were from China, which are Chinese Academy of Sciences, Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development, and China University of Petroleum, accounting for 38.38% (Table 1.2.10). The countries that focus on cooperation in this field include India and Singapore (Figure 1.2.5). The institutions with the most cooperation are Chinese Academy of Sciences and Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development (Figure 1.2.6). The main output countries citing core papers include China, the USA, and India, with a proportion of core paper citations close to 70% (Table 1.2.11). The main output institutions of citing core papers include Chinese Academy of Sciences,

Table 1.2.9 Countries with the greatest output of core papers on “key technologies and challenges for natural gas hydrate exploitation”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	65	65.66%	1 573	24.20	2018.3
2	Singapore	7	7.07%	882	126.00	2018.3
3	India	7	7.07%	209	29.86	2018.6
4	Japan	5	5.05%	218	43.60	2017.6
5	USA	5	5.05%	200	40.00	2018.6
6	South Korea	4	4.04%	130	32.50	2017.2
7	Norway	4	4.04%	73	18.25	2018.0
8	Canada	4	4.04%	26	6.50	2018.5
9	UK	3	3.03%	37	12.33	2019.7
10	Germany	3	3.03%	31	10.33	2020.0

Table 1.2.10 Institutions with the greatest output of core papers on “key technologies and challenges for natural gas hydrate exploitation”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	16	16.16%	1 089	68.06	2017.6
2	Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development	11	11.11%	350	31.82	2018.1
3	China University of Petroleum	11	11.11%	49	4.45	2019.0
4	Dalian University of Technology	9	9.09%	156	17.33	2018.0
5	National University of Singapore	7	7.07%	882	126.00	2018.3
6	China University of Petroleum (East China)	7	7.07%	60	8.57	2018.9
7	Jilin University	6	6.06%	111	18.50	2018.5
8	Indian Institute of Technology Madras	6	6.06%	73	12.17	2019.0
9	Qingdao Institute of Marine Geology, China Geological Survey	5	5.05%	80	16.00	2017.2
10	China University of Geosciences	4	4.04%	65	16.25	2018.5

Dalian University of Technology, and China University of Petroleum (Table 1.2.12).

1.2.4 Multi-information perception and early warning of hidden danger of mine disasters

With the great demand for coal production, the gradual reduction of shallow coal resources, and the continuous increase in mining depth and intensity, the risk of dynamic disasters such as rock bursts, coal and gas outbursts, fires, and water inrush increases, significantly restricting the safe and efficient production of coal mines and posing a severe threat to miners' safety. The formation process and evolution mechanism of typical dynamic disasters under the condition of multiphase and multi-field coupling are still unclear, and the disaster precursor information collection,

sensing, transmission technology, and mining identification technology are still backward, resulting in a lack of disaster risk identification and early warning modules and making early warning of disaster risk difficult. To meet the major needs of coal mine power disaster prevention and control, it is urgent to research the accurate identification, monitoring, and early warning mechanisms and key technologies of coal mine power disaster risk.

The main research in this field includes three aspects: The first is research on the disaster mechanism of typical disasters, including the research on the dynamic mechanism of coal mine rock burst instability and multi-field coupling disaster mechanism, the disaster mechanism of coal and gas outburst, the breeding law of coal spontaneous combustion disaster under a high-temperature environment, and the space-time

Table 1.2.11 Countries with the greatest output of citing papers on “key technologies and challenges for natural gas hydrate exploitation”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	796	51.39%	2019.3
2	USA	175	11.30%	2019.3
3	India	94	6.07%	2018.9
4	Singapore	93	6.00%	2018.4
5	Japan	83	5.36%	2019.1
6	South Korea	70	4.52%	2018.8
7	Russia	59	3.81%	2018.9
8	UK	54	3.49%	2019.7
9	Canada	48	3.10%	2019.5
10	Germany	41	2.65%	2019.4

Table 1.2.12 Institutions with the greatest output of citing papers on “key technologies and challenges for natural gas hydrate exploitation”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	Chinese Academy of Sciences	169	19.43%	2019.1
2	Dalian University of Technology	129	14.83%	2019.3
3	China University of Petroleum	103	11.84%	2019.4
4	China University of Petroleum (East China)	97	11.15%	2019.4
5	National University of Singapore	91	10.46%	2018.4
6	Guangdong Provincial Key Laboratory of New and Renewable Energy Research and Development	80	9.20%	2019.1
7	Jilin University	43	4.94%	2019.4
8	China University of Geosciences	42	4.83%	2019.7
9	Chongqing University	41	4.71%	2019.3
10	Southwest Petroleum University	41	4.71%	2019.4



Figure 1.2.5 Collaboration network among major countries in the engineering research front of “key technologies and challenges for natural gas hydrate exploitation”

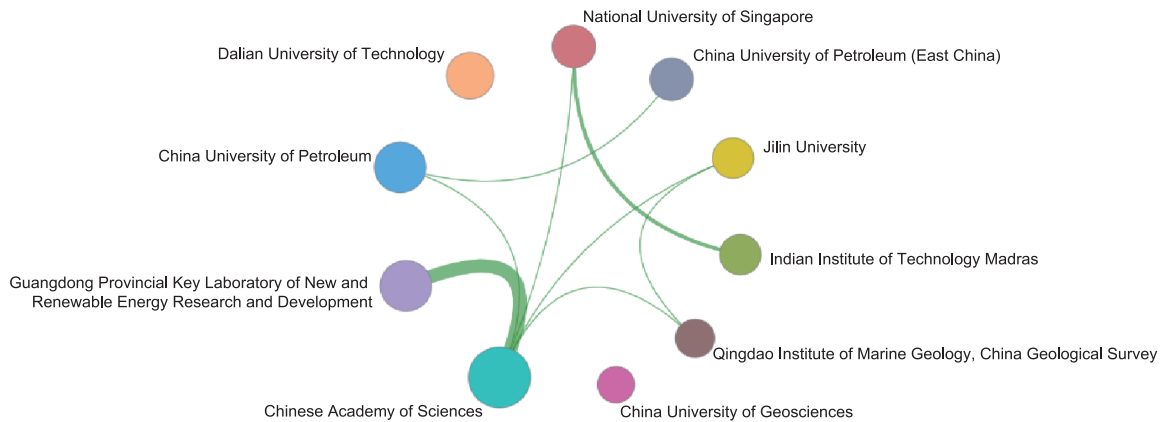


Figure 1.2.6 Collaboration network among major institutions in the engineering research front of “key technologies and challenges for natural gas hydrate exploitation”

breeding and evolution law of water inrush disasters. The second is the research on information perception technology, which, with the help of the key technologies and equipment of the mine, the Internet of Things, and human-machine-environment state, multiple information reflecting the temporal and spatial state characteristics and internal key information of various external and internal disasters can be perceived and obtained in real-time. As such, scientific, reasonable, and effective multi-information perception and early warning analysis methods have been proposed, and the theory and technology of intelligent identification and early warning of multi-parameter precursor information of typical dynamic disasters in coal mines has been developed. The last part is the research on multivariate data processing methods. Based on multivariate heterogeneous big data, the

multivariate and massive information is integrated to inversely deduce the temporal and spatial evolution law of mine disasters by utilizing data mining, artificial intelligence, cloud computing, and other means to realize the quantitative and accurate identification of precursor characteristics throughout the process of single major disasters, coupling disasters, and derivative/secondary disaster evolution dynamic risk capture and automatic early warning to reduce major risks and hidden dangers, providing support to improve the accuracy and soundness of mine disaster supervision.

Among the major coal-producing countries in the world, China faces the most serious security threat caused by deep mining and has invested more in research and development. Regarding the engineering research front of “multi-

information perception and early warning of hidden danger of mine disasters”, China and the USA have the largest number of core papers, accounting for 69.86%, while the UK and Italy have the highest number of citations per paper (Table 1.2.13). The institutions with the highest output of core papers are China University of Mining and Technology, University of Science and Technology Beijing, and Xi’an University of Science and Technology (Table 1.2.14). China, the USA, and Australia have more cooperation (Figure 1.2.7). In the institutions with a large output of papers, China University of Mining and Technology have the closest cooperation (Figure 1.2.8) with University of Science and Technology Beijing. The main output countries of citing core papers are China and the

USA, accounting for more than 60% of the total publication. The citation year was concentrated in 2019 (Table 1.2.15). The main output institutions of citing core papers are China University of Mining and Technology, Chinese Academy of Sciences, and Shandong University of Science and Technology, accounting for 49.62% (Table 1.2.16).

2 Engineering development fronts

2.1 Trends in Top 12 engineering development fronts

The Top 12 engineering development fronts assessed by the

Table 1.2.13 Countries with the greatest output of core papers on “multi-information perception and early warning of hidden danger of mine disasters”

No.	Country	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China	221	58.93%	1 724	7.80	2018.2
2	USA	41	10.93%	353	8.61	2018.3
3	India	20	5.33%	24	1.20	2017.6
4	Australia	17	4.53%	269	15.82	2018.8
5	Germany	14	3.73%	357	25.50	2017.1
6	Canada	13	3.47%	147	11.31	2018.2
7	Brazil	11	2.93%	188	17.09	2018.1
8	Japan	10	2.67%	22	2.20	2017.2
9	UK	9	2.40%	322	35.78	2018.3
10	Italy	8	2.13%	226	28.25	2017.5

Table 1.2.14 Institutions with the greatest output of core papers on the “multi-information perception and early warning of hidden danger of mine disasters”

No.	Institution	Core papers	Percentage of core papers	Citations	Citations per paper	Mean year
1	China University of Mining and Technology	41	10.93%	638	15.56	2018.2
2	University of Science and Technology Beijing	19	5.07%	92	4.84	2018.2
3	Xi’an University of Science and Technology	18	4.80%	194	10.78	2018.1
4	Chinese Academy of Sciences	14	3.73%	203	14.50	2018.2
5	Shandong University of Science and Technology	14	3.73%	120	8.57	2018.4
6	Anhui University of Science and Technology	12	3.20%	49	4.08	2018.7
7	Central South University	7	1.87%	89	12.71	2018.0
8	China University of Geosciences	7	1.87%	50	7.14	2018.4
9	Henan Polytechnic University	7	1.87%	14	2.00	2017.7
10	Wuhan University	6	1.60%	81	13.50	2018.7

Table 1.2.15 Countries with the greatest output of citing papers on “multi-information perception and early warning of hidden danger of mine disasters”

No.	Country	Citing papers	Percentage of citing papers	Mean year
1	China	1 490	48.88%	2019.6
2	USA	354	11.61%	2019.4
3	Iran	191	6.27%	2019.6
4	Australia	156	5.12%	2019.4
5	India	152	4.99%	2019.4
6	Brazil	148	4.86%	2019.6
7	UK	144	4.72%	2019.3
8	South Korea	120	3.94%	2019.3
9	Canada	102	3.35%	2019.2
10	Germany	96	3.15%	2019.0



Figure 1.2.7 Collaboration network among major countries in the engineering research front of “multi-information perception and early warning of hidden danger of mine disasters”

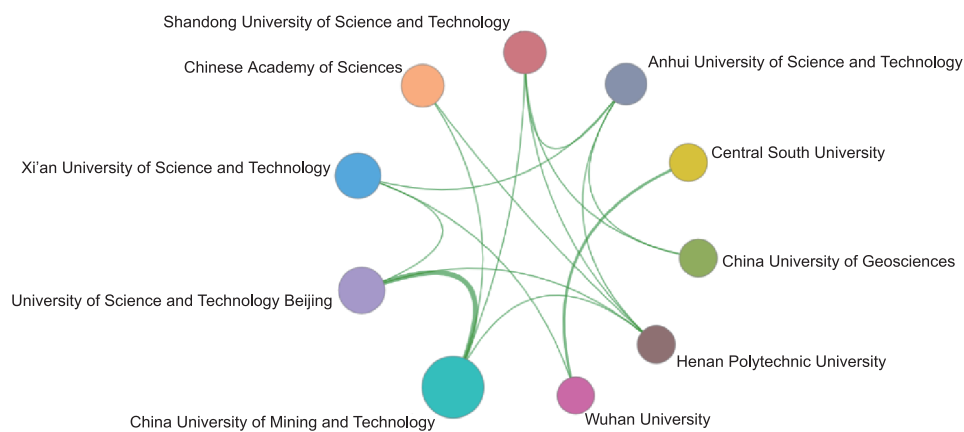


Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “multi-information perception and early warning of hidden danger of mine disasters”

Energy and Mining Engineering Group are shown in Table 2.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and

engineering; and mining science, technology, and engineering. Among these 12 engineering development fronts, “key technologies for low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)”, “technology for scalable

Table 1.2.16 Institutions with the greatest output of citing papers on “multi-information perception and early warning of hidden danger of mine disasters”

No.	Institution	Citing papers	Percentage of citing papers	Mean year
1	China University of Mining and Technology	298	28.11%	2019.6
2	Chinese Academy of Sciences	125	11.79%	2019.2
3	Shandong University of Science and Technology	103	9.72%	2019.4
4	Chongqing University	94	8.87%	2019.4
5	Xi'an University of Science and Technology	76	7.17%	2019.8
6	Duy Tan University	71	6.70%	2019.8
7	University of Science and Technology Beijing	65	6.13%	2019.8
8	China University of Mining and Technology-Beijing	60	5.66%	2020.2
9	Wuhan University	58	5.47%	2019.2
10	Anhui University of Science and Technology	58	5.47%	2020.0

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 low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)	264	700	2.65	2017.9
2	Research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors	61	464	7.61	2016.4
3	Intelligent and efficient drilling tool assembly and drilling and completion technology	172	2 124	12.35	2016.4
4	High temperature resistant tool and system of measurement for drilling	69	782	11.33	2016.3
5	Technology for scalable fabrication of large-area perovskite solar cell modules	89	3 359	37.74	2016.6
6	All-solid-state battery materials and technology	135	4 249	31.47	2016.8
7	Development and core technology of smart nuclear heating system	74	349	4.72	2017.2
8	Research and development of high-performance large-scale superconducting magnets and fusion reactor cladding materials	70	234	3.34	2017.1
9	Research and development of downhole high-efficiency fracturing fluid and dynamic fracturing monitoring technology	223	3 381	15.16	2016.4
10	Full-field 3D scanning mapping and imaging technology for geological bodies	179	2 766	15.45	2016.6
11	Key technologies for fire control and ecological restoration in large-area coalfields	24	63	2.63	2016.4
12	Technology research and development for improving the accuracy of microseismic positioning in mines	49	517	10.55	2017.4

fabrication of large-area perovskite solar cell modules”, and “all-solid-state battery materials and technology” represent the engineering development front of energy and electrical science; “research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors”, “development and core technology of smart nuclear heating system”, and “research and development of high-performance large-scale superconducting magnets and fusion reactor cladding materials” represent the engineering development front of nuclear science, technology, and engineering; “intelligent and efficient drilling tool assembly and drilling and completion technology”, “research and development of downhole high-efficiency fracturing fluid and dynamic fracturing monitoring technology”, and “full-field 3D scanning mapping and imaging technology for geological bodies” represent the engineering development front of geology resources science, technology, and engineering; “high temperature resistant tool and system of measurement for drilling”, “key technologies for fire control and ecological restoration in large-area coalfields”, and “technology research and development for improving the

accuracy of microseismic positioning in mines” represent the engineering development front of mining science, technology, and engineering.

The disclosure of core patents involved in each development front from 2015 to 2020 is presented in Table 2.1.2.

(1) Key technologies for low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)

Alkaline water electrolysis (AWE) is the most advanced water electrolysis technology, holding a dominant position in the market; it is especially suitable for large-scale water electrolysis. AWE generates hydrogen and oxygen through diaphragm separation and electrolysis using a potassium hydroxide aqueous solution as the electrolyte. In an alkaline working environment, non-precious metal electrocatalysts (such as Ni, Fe, Co, and Mn) can be used, significantly reducing the cost of AWE. However, the as-produced gas (H_2 and O_2) carries an alkaline solution, leading to a lower H_2 purity than that produced by PEM water electrolysis and corroding electrolytic equipment. Therefore, an auxiliary device is required to purify the gas. In addition, it is also difficult for

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	2015	2016	2017	2018	2019	2020
1	Key technologies for low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)	7	10	10	17	7	17
2	Research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors	6	5	9	10	11	6
3	Intelligent and efficient drilling tool assembly and drilling and completion technology	72	34	25	17	21	3
4	High temperature resistant tool and system of measurement for drilling	8	11	5	7	11	12
5	Technology for scalable fabrication of large-area perovskite solar cell modules	24	23	18	14	10	0
6	All-solid-state battery materials and technology	26	37	31	26	15	0
7	Development and core technology of smart nuclear heating system	2	15	12	13	13	12
8	Research and development of high-performance large-scale superconducting magnets and fusion reactor cladding materials	7	7	8	8	14	14
9	Research and development of downhole high-efficiency fracturing fluid and dynamic fracturing monitoring technology	82	49	44	21	23	4
10	Full-field 3D scanning mapping and imaging technology for geological bodies	49	42	35	30	23	0
11	Key technologies for fire control and ecological restoration in large-area coalfields	2	7	6	1	2	2
12	Technology research and development for improving the accuracy of microseismic positioning in mines	5	6	13	13	12	0

AWE to start rapidly or change the load quickly and adapt to renewable energy. To efficiently separate hydrogen and oxygen, the design of the electrolytic cell and the development of a new separator are very important. The replacement of liquid electrolytes and separators with solid electrolytes is an important development direction in the future. AWE is a promising clean and sustainable platform for large-scale hydrogen production. If breakthroughs are made in the mass manufacturing of key materials and core components, it will significantly benefit renewable energy development in the future.

(2) Research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors

High-temperature gas-cooled reactor biomass hydrogen production uses the high-temperature process heat of gas-cooled reactors as the main heat source and agricultural and forestry biomass as raw materials to achieve large-scale and stable hydrogen production. Among the many methods of biomass hydrogen production, biomass hydrogenation technology, using methane as an intermediate, has the highest heat utilization efficiency in the reactor process and is the main development trend of nuclear biomass hydrogen production technology. The technology consists of processes such as methane production by biomass hydrogenation, hydrogen production by methane steam reforming, and high-temperature gas-cooled reactor heating for the reforming reaction. The heat required for the strong endothermic reforming process of methane is supplied by a high-temperature gas-cooled reactor. Key issues include research on the coupling technology of biomass hydrogen production processes and high-temperature gas-cooled reactors, the process optimization of biomass gasification and methane reforming hydrogen production, and the design and preparation of high-efficiency catalysts. In addition, the overall plan of the nuclear hydrogen production energy system; simulation of the entire process; optimization of key indicators such as energy utilization, carbon conversion rate, and carbon emissions; and analysis of technology, economy, and life cycle are also very important.

(3) Intelligent and efficient drilling tool assembly and drilling and completion technology

An intelligent and efficient drilling tool assembly and drilling and completion technology is to establish an information

transmission channel between the ground and well using intelligent drilling equipment such as intelligent drill pipes and intelligent drilling rig and downhole data transmission and communication systems; this also includes using the downhole information acquisition system to detect, perceive, and transmit information about the downhole conditions in the process of drilling and completion in real-time. Intelligent analysis and decision-making are conducted through the data analysis and feedback system; then, the instructions are issued to the corresponding downhole executive equipment to realize the intelligent closed-loop control of the drilling process and the drilling and completion optimization technology of well completion and stimulation. The main research contents and technical directions can be roughly divided into downhole information acquisition technology and equipment, downhole data transmission and communication systems and equipment, decision-making and control systems, and downhole execution devices. At present, intelligent drilling rigs, intelligent bit drill strings, intelligent guidance, anti-stick-slip tools, intelligent well completion and fracturing slip sleeves, downhole information acquisition and transmission systems, remote intelligent drilling decision control systems, and other systems combined with intelligent well drilling and completion equipment have been developed. In the future, intelligent production equipment embedded with the Internet of Things, machine vision, deep learning, and other technologies will significantly reduce production costs and improve production efficiency.

(4) High temperature resistant tool and system of measurement for drilling

During the drilling process, various measurement tools such as measurement while drilling (MWD) and logging while drilling (LWD) are used to obtain information such as downhole geological parameters and engineering parameters, key to understanding the downhole environment, safety, and efficient drilling. The deep (> 4 500 m) and ultra-deep (> 6 000 m) oil and gas resources in China are 76.3 billion tons of oil equivalent, accounting for 35% of the total oil and gas resources, are significantly important for increasing future oil and gas reserves and production in China. The formation temperature of deep and ultra-deep layers often exceeds 150 °C, and some wells even exceed 200 °C, making it difficult for existing MWD tools to work steadily and severely restricting the exploration and development of deep and ultra-deep oil and gas in China. Thus, there is an urgent need to develop MWD tools that can

continuously work in a high-temperature environment for extended periods. The main technical directions are low-cost and high-temperature-resistant electronic and sensor components, high-temperature packaging technology, active cooling systems for downhole circuits, and high-efficiency transmission technology for high-temperature downhole information. The development of high-temperature-resistant MWD tools and systems will fill the domestic technical gaps, improve high-end domestic equipment, and provide technical support for exploiting deep oil and gas resources. It is of significant practical and strategic significance in building a solid oil and gas resource foundation for energy security in China.

(5) Technology for scalable fabrication of large-area perovskite solar cell modules

With the rapid progress of lead halide perovskite solar cells, the power conversion efficiency of perovskite solar cells has increased to a certified value of 25.5%, comparable to that of commercial crystalline silicon and is promising for low-cost and high-efficiency photovoltaics. In addition to the stability issue, the main challenge for the commercialization of perovskite solar cells is the scalable fabrication of large-area perovskite solar cell modules. The main technical challenges include the reproducible deposition technology for the scalable perovskite light absorption layer and preparation of the corresponding electron transport layer, hole transport layer, and contact electrode in perovskite devices. In addition, it is necessary and important to explore the influence of perovskite device configuration, fabrication process, and integration on the module reliability and stability during operation. Developing sealants and encapsulation techniques for perovskite solar cell modules is also critical to ensure the durability of perovskite solar cells under operating conditions, improving the stability of cells and preventing potential lead leakage. Although the recent progress in preparing large-area perovskite solar cell modules is encouraging, much more research should be conducted to improve efficiency, increase stability, and reduce costs. In addition to the perovskite light absorption layer, the efficient and stable hole transport layer and contact electrode have a significant impact on the efficiency and stability of the device, which is a key bottleneck in the preparation of large-area perovskite solar cell modules. In summary, the technology for scalable fabrication of large-area perovskite solar cell modules is at the forefront of

engineering development to realize low-cost renewable solar electricity based on high-efficiency and low-cost perovskite photovoltaics.

(6) All-solid-state battery materials and technology

All-solid-state batteries are batteries in which all components are in a solid state. The core of all-solid-state batteries is the substitution of flammable liquid/gel electrolytes with solid-state electrolytes to significantly enhance the safety of batteries. In addition, they have higher energy densities and manufacturing advantages than traditional batteries. As a consequence, all-solid-state battery technologies have been of significant concern worldwide in both academia and industry. Solid-state electrolytes can be roughly divided into solid polymer electrolytes, inorganic solid electrolytes, and composite solid electrolytes. Solid polymer electrolytes have suitable processing ability, a wide electrochemical window, and excellent stability, but their limited ionic conductivity and transference number at ambient temperature are severely impeded. The inorganic solid electrolyte is close to the existing liquid electrolyte in terms of ionic conductivity, but its poor stability and huge interfacial impedance with the electrode materials seriously hinder its application. The composite solid electrolyte combines the advantages of polymer and inorganic electrolytes. This is expected to lead to technological breakthroughs in the all-solid-state battery industry if the solid interface between electrolytes and electrodes and the active loading of electrodes can be addressed.

(7) Development and core technology of smart nuclear heating system

A low-temperature nuclear heating reactor is an ideal coal-fired alternative energy source, crucial for achieving the “3060 Target”. However, the current overly conservative design and the low level of digitalization and intelligence have severely restricted the efficiency of the nuclear energy heating system, thereby affecting the economy of nuclear energy heating. Developing a smart nuclear heating station is an effective measure to further improve heating efficiency and an inevitable method of energy innovation. The core of the so-called smart nuclear heating station is digitalization and intelligentization. Digitalization involves digitalizing objects (nuclear heating stations) (3D digital models, equipment functions, fuel and material properties, etc.), the design process, process control and real-time

information, business processing and operation, production and operation management, and business decision-making. Intelligentization is the realization of intelligent scheduling, management, and control of the production and operation of nuclear heating stations by introducing advanced science and technology such as big data, cloud computing, the Internet of Things, modern control, information processing, and communications based on digitalization. As nuclear energy engineering is a high-tech engineering technology of public concern, it is necessary to select a relatively easy-to-achieve nuclear heating reactor for a demonstration before commercialization. The pool-type low-temperature heating reactor has the following advantages: its system, operation, and maintenance are simple; its heating system and physical processes (nuclear, heat, material, and force) are easier to model; its intelligent and autonomous operation is easy to realize; and, most importantly, it is inherently safe, which is conducive to simplifying safety supervision requirements. There is an urgent need to develop an intelligent pool-type low-temperature nuclear heating reactor to realize full digitalization design, intelligentization of equipment, intelligentization of fault diagnosis and maintenance, and coordinate with the internal and external environment, equipment, nuclear fuel, and heating network of heating stations to finally realize safe, economical, efficient, environmentally-friendly, autonomous, and optimized operation in an environment of “no intervention and few people on duty”.

(8) Research and development of high-performance large-scale superconducting magnets and fusion reactor cladding materials

The CFETR superconducting magnet system is composed of a central solenoid (CS), a polar field coil, a longitudinal field (TF) coil, and a correction field coil, which generates a magnetic field to drive and constrain the plasma and control the plasma position, shape, and vertical instability. All superconducting coils of CFETR are wound with an in-tube cable conductor inside, cooled by 4.5 K supercritical helium. The total mass of the CFETR superconducting magnet system is expected to reach more than 10 000 tons. To solve the key scientific problems in the solenoid design and operation of the CFETR center and to master the core technology in the manufacturing process of large-scale Nb₃Sn magnets, the Institute of Plasma Physics of the Chinese Academy of Sciences launched the

CFETR CS model coil research and development project in 2014. To achieve the physical and engineering goals of CFETR Phase II, the highest magnetic field generated by the magnet system on the CS and TF coil conductors may reach more than 15 T. At this time, the use of Nb₃Sn conductors cannot meet these requirements. Therefore, it is necessary to develop new high-temperature superconducting conductors. With the development of high-temperature superconducting material technology, in the future, CFETR CS coils may use Bi-2212 high-temperature superconducting conductors in the high-field area (operating at a temperature of 10–30 K and a magnetic field strength of 25–30 T) and use an Nb₃Sn low-temperature superconducting conductor in the low-field area.

The CFETR cladding is composed of tritium multiplication cladding and shielding cladding. Multiplying cladding is one of the most critical and technically challenging components in the CFETR design. For the design of the breeder blanket, there are currently three alternative technical solutions after physical and engineering considerations, among which the helium cooling solution is determined as the preferred solution for the CFETR tritium breeder blanket, while the water-cooling solution and the Li-Pb liquid metal cooling are alternative solutions. To obtain a higher tritium multiplication rate, the design of the multiplication blanket (and the tritium plant) must be optimized. The tritium fuel recovery and reuse system (tritium plant) consists of three subsystems. The internal circulation system includes three processes: tritium recovery, isotope separation, and re-injection into the vacuum chamber. External circulation includes tritium extraction, separation, purification, and other processes. The third subsystem includes processes such as tritium shielding and tritium-containing water removal.

(9) Research and development of downhole high-efficiency fracturing fluid and dynamic fracturing monitoring technology

A high-efficiency fracturing fluid refers to the fluid (used in reservoir fracturing stimulation) that enters the well. It is usually prepared by the main agent and a variety of functional additives in a certain proportion. Compared with the conventional fracturing fluid, it has better fracture making, sand carrying, and low damage properties. In recent years, new fracturing fluid systems, such as intelligent fracturing fluids, anhydrous fracturing fluids, and fracturing displacement-integrated fracturing fluids, have attracted significant attention because of their unique performance.

In addition, to meet the challenge of low oil prices, the proportion of low-cost fracturing fluid is increasing yearly on the premise of meeting the fracturing demand. The fracturing dynamic monitoring technology measures various parameters of the operating formation in real-time without affecting the fracturing treatment and sends the test results to the ground for processing in real-time to dynamically optimize the design of the fracturing parameters. Fracturing dynamic monitoring technology has developed rapidly in recent years, from microearthquakes to distributed optical fibers, electrical methods, and various acoustic methods. In the future, matching real-time monitoring and interpretation technology should be developed for different types of reservoirs, the data acquisition accuracy and processing efficiency should be continuously improved, and the data accuracy and reliability should be enhanced.

(10) Full-field 3D scanning mapping and imaging technology for geological bodies

“Full-field 3D scanning mapping and imaging technology for geological bodies” involves scanning various fields, such as electric field, magnetic field and electromagnetic field, seismic field, and ultrasonic field of geological bodies, to obtain the 3D data of natural and artificial signal fields, such as electrical signal, magnetic signal, electromagnetic signal, sonar signal, and seismic signal from geological bodies and to show the full-field image of geological bodies. Moreover, this technology can be used in analyzing stratum rock and soil structure, accurately positioning the 3D position of underground deep ore bodies, predicting and evaluating 3D prospecting, and providing basic data for ore body mining. The main objective is 3D scanning and imaging of geological bodies, involving three technologies: the first is the full-field scanning equipment, a comprehensive signal equipment for obtaining various signals such as electric fields, magnetic fields, electromagnetic fields, and ultrasonic fields. The second is whole-field signal processing, which can effectively and comprehensively process all types of field signals, such as electric, magnetic, electromagnetic, and seismic fields, and obtain the most useful signals to qualitatively and quantitatively describe the electrical, magnetic, seismic, sonar, and other properties of geological bodies. The last one is the imaging of the 3D structure of the geological body by using the whole-field data, obtaining the 3D comprehensive structure of the underground geological body by using various signals such as electricity, magnetism, earthquake, and sonar, to comprehensively

analyze the physical properties of the geological body. Using the whole-field data in the same period can analyze the underground structure more accurately in a restrictive way to achieve a breakthrough in prospecting and provide geological data for engineering construction. The future development direction is miniaturization and portabilization to be used by unmanned aerial vehicles to quickly measure and image the 3D physical structure of an underground geological body in a certain area. This technology is significant for the inverse deduction of underground geological structures and geological prospecting.

(11) Key technologies for fire control and ecological restoration in large-area coalfields

Coalfield fire refers to a large-area fire that occurs in the outcrop or shallow part of the coalfield coal seam, affecting coalfield development, causing significant coal loss, threatening production safety, and severely polluting the environment. The ecological management of coalfield fires is a global problem. Traditionally, stripping drilling water injection/grouting covering and other means are mainly used, requiring a significant amount of work, wasting precious water resources, and causing the secondary destruction of the originally fragile ecological environment. In addition, traditional coalfield fire control methods only consider the removal of heat energy in the fire area but do not consider the utilization of high-quality heat. According to statistics, the annual global energy generated by underground coal combustion is equivalent to 2.5 times the total capacity of global nuclear power, more than the total energy produced by hydropower. Therefore, the key technologies of large-area coalfield fire control and ecological restoration are widely considered by scholars and industry worldwide.

At present, the main research hotspots focus on the following aspects: ① coal fire detection, monitoring, and prevention technology to realize the integration of efficient and accurate prevention and control and energy saving; ② mathematical model, evaluation, and prediction analysis of multiphase pollution and carbon emissions in coalfield fires under the background of double carbon to develop carbon emission reduction, carbon cycle, and carbon utilization technology; ③ the key technology system of fire area ecological restoration to form a comprehensive, efficient, and green coal fire area treatment and ecological restoration system with Chinese characteristics. Future developments will focus

on major technological changes in resource utilization and ecological restoration, such as underground coalfield fire carbon emission reduction and thermal energy, and lead coal fire governance to a new path focusing on the virtuous cycle of ecosystems and effective prevention and control of environmental risks.

(12) Technology research and development for improving the accuracy of microseismic positioning in mines

Micro-seismic monitoring can record the micro-seismic signals generated during the rupture of a coal rock mass and accurately position the micro-seismic source. The positioning results can be used to predict the location, time, and scale of the occurrence of impact ground pressure and be used as the main parameters for evaluating the fracture pattern and spreading pattern of coal seams after hydraulic fracturing. At present, it is a widely used method to obtain the micro-seismic activity pattern by deploying the microseismic monitoring system and calculating the energy of vibration to determine the possibility of the occurrence of impact ground pressure. The main technical directions include the optimal arrangement of the station network, microseismic waveform identification, microseismic source location, source mechanism analysis, and micro-seismic activity prediction; of these, micro-seismic waveform identification and source location are the two most critical and core technologies that need to be improved. Making these devices strongly noise-resistant and eliminating the influence of the velocity model and other factors on microseismic location is the development trend of future research and will become one of the mainstream directions for micro-seismic localization research in the future. In addition, to achieve fast and accurate automatic microseismic localization, it is also necessary to develop high-quality seismic phase identification technology.

2.2 Interpretations for four key engineering development fronts

2.2.1 Key technologies for low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)

Hydrogen is mainly used in the chemical industry, especially in the petrochemical industry and industrial ammonia synthesis. In recent years, environmental problems caused by fossil energy consumption have become more serious; thus, more countries worldwide have developed new energy

sources, especially hydrogen energy. Water electrolysis production is the greenest and sustainable way for large-scale hydrogen application, achieving zero carbon emissions. By using PGM-free electrocatalysts, AWE can effectively reduce costs while maintaining an excellent durability of up to 20 years. Japan has the most solid research foundation for the development of hydrogen energy and accounts for 47.44% of the patents in the world regarding AWE hydrogen production. China and South Korea have also conducted related research, with patents accounting for 23.08% and 20.51%, respectively. In addition, the US, the Czech Republic, India, and Italy have also joined the competition for AWE development. However, the high cost of the AEM system impedes the wide application of hydrogen production via water electrolysis. Therefore, it is challenging to produce cheap hydrogen from electrolytic water to gradually replace fossil fuels. Two aspects can contribute significantly to the cost reduction of the AWE system. Renewable energy from solar, wind, and tidal energy can provide an alternative way to convert excess electric energy into chemical fuels and improve the utilization rate of renewable energy. However, it is necessary to further improve the overall electrochemical efficiency of electrolytic water to reduce the cost of hydrogen production. In addition, the as-produced gas from AWE inevitably contains an alkaline solution, leading to the corrosion of the system and a lower gas purity compared with PEM water electrolysis and the necessity for additional equipment for gas purification. Moreover, as it is difficult to achieve a rapid start or quick load change in the AWE system, it is unsuitable to deploy using a combination of electric generation via these renewable energies. Although significant progress has been made in the research of AWE catalysts, it is still difficult to develop an ideal PGM-free electrocatalyst with high activity and long durability at low costs. Furthermore, the design of the electrolysis cell and the study of the diaphragm are also significant to separate the generated hydrogen and oxygen. With the better utilization of renewable energy, low-cost hydrogen production has gradually become a major trend. As a clean and sustainable large-scale hydrogen production platform, AWE is promising for future mass applications.

The top three countries owning the most patents related to “key technologies for low-cost, high-power, and high-efficiency AWE” are China, Japan, and South Korea, with average citation numbers of 1.86, 4.29, and 1.5, respectively (Table 2.2.1). The top three institutions with the most patents

are Asahi Kasei Corporation, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, and De Nora Permelec Ltd., as shown in Table 2.2.2.

2.2.2 Research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors

Hydrogen energy will play an important role reforming China's energy structure to achieve the goal of "carbon peak and carbon neutrality". High-temperature gas-cooled reactors have high output steam parameters and a wide range of

applications and can be coupled with a clean hydrogen production device to achieve large-scale zero-emission hydrogen production. These reactors are recognized as the most suitable type of reactor for nuclear hydrogen production. Biomass is the only renewable resource that contains carbon, which has a significant advantage in carbon neutrality. The method of preparing hydrogen with biomass as raw material and high-temperature gas-cooled reactor process heat as the heat source has the advantages of high energy efficiency and zero net carbon emissions. In addition, hydrogen production from biomass can reduce the current air pollution caused by improper processing of biomass waste and, at the same time,

Table 2.2.1 Countries with the greatest output of core patents on "key technologies for low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)"

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	170	64.39%	316	45.14%	1.86
2	Japan	56	21.21%	240	34.29%	4.29
3	South Korea	14	5.30%	21	3.00%	1.50
4	USA	7	2.65%	16	2.29%	2.29
5	France	3	1.14%	28	4.00%	9.33
6	Italy	2	0.76%	33	4.71%	16.50
7	India	2	0.76%	13	1.86%	6.50
8	Canada	2	0.76%	9	1.29%	4.50
9	UK	2	0.76%	6	0.86%	3.00
10	Germany	2	0.76%	1	0.14%	0.50

Table 2.2.2 Institutions with the greatest output of core patents on "key technologies for low-cost, high-power, and high-efficiency alkaline water electrolysis (AWE)"

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Asahi Kasei Corporation	Japan	20	7.58%	142	20.29%	7.10
2	Dalian Institute of Chemical Physics, Chinese Academy of Sciences	China	15	5.68%	80	11.43%	5.33
3	De Nora Permelec Ltd.	Japan	10	3.79%	72	10.29%	7.20
4	Hempel Heating Power Development Co., Ltd.	China	7	2.65%	6	0.86%	0.86
5	Hitachi Maxell	Japan	6	2.27%	9	1.29%	1.50
6	Fudan University	China	5	1.89%	25	3.57%	5.00
7	Nantong Ansizhuo New Energy Co., Ltd.	China	5	1.89%	5	0.71%	1.00
8	Tongji University	China	5	1.89%	0	0.00%	0.00
9	Tosoh Corporation	Japan	4	1.52%	33	4.71%	8.25
10	Tianjin Mainland Hydrogen Equipment Co., Ltd.	China	4	1.52%	18	2.57%	4.50

increase farmers' income, with multiple positive significance. Biomass raw materials can be selected from agricultural and forestry wastes such as straw, wood, branches, and firewood, or industrial biomass such as sugar bagasse, sludge, and pharmaceutical fungus residues to alleviate the seasonality and transportation radius of a single biomass raw material.

Biomass hydrogen production mainly includes biological fermentation and thermochemical methods, of which the latter is mainly used as it can effectively use nuclear energy for heating. Biomass thermochemical hydrogen production can be divided into gasification, pyrolysis, and supercritical water conversion, of which biomass gasification can make the most effective use of reactor high-temperature process heat. The biomass gasification hydrogen production method using methane as an intermediate comprises two steps: biomass and hydrogen gasification to produce methane and methane reforming to produce hydrogen. This method can effectively avoid the abrasion of solid particles on the helium heat loop and will be the main trend in developing nuclear biomass hydrogen production in the future. Key technical issues include research on the coupling technology of biomass hydrogen production processes and high-temperature gas-cooled reactors, process optimization of biomass gasification and methane reforming hydrogen production, high-efficiency catalyst design and preparation, continuous feed of biomass raw materials, the entire process of process simulation, and technical economy and life cycle analysis. The key equipment to be developed includes hydrogenation furnaces, methane reforming reactors, and the corresponding intermediate heat exchangers of high-temperature gas-cooled reactors. Methane production by adding hydrogen to biomass through nuclear energy biomass hydrogen production technology using methane as an intermediate is currently in the laboratory research stage (Tsinghua University, East China University of Science and Technology). The pilot demonstration of coal-to-hydrogenation technology (ENN Group) and methane reforming hydrogen production technology refers to mature technologies in the petrochemical and coal chemical fields.

The main countries that have conducted nuclear energy high-temperature process thermal research include Germany, the USA, Japan, Russia, the UK, South Korea, and Poland. However, there are few reports on the research directly related to hydrogen production using nuclear energy biomass gasification. Existing research uses coal as a raw

material, such as the prototype power plant (PNP) of the lignite hydrogenation nuclear thermal process in Germany. In the development of intermediate heat exchangers, the PNP project in Germany built a KVK high-temperature helium circuit and conducted engineering verifications at 950 °C for spiral tubes and U-tube 10 MW intermediate heat exchangers. The JAEA in Japan independently developed high-temperature alloys, designed and manufactured a spiral tube intermediate heat exchanger with a power of 10 MW, testing it at 950 °C on the test loop.

It has been nearly half a century since the development of coal plus hydrogenation technology, from the Gas Technology Institute (IGT) fluidized bed process in the USA to the ARCH-entrained bed gasification process in Japan. IGT adopts a fluidized bed for the coal-to-hydrogenation reaction, and Rockwell uses an entrained bed reactor to overcome the deficiency of coal powder cohesion and defluidization in the IGT technology; however, the preheating of hydrogen requires a large amount of oxygen. The BG-OG (British Gas and Osaka Gas company) process, jointly developed by Osaka Gas Company in Japan and the British Gas Company, adopts an entrained-flow bed with gas circulation and a hydrogenation reactor, which does not require partial combustion of oxygen and hydrogen to preheat hydrogen. Based on foreign coal-to-hydrogenation technology, the ENN Group in China has developed a new technology for the coal-to-hydrogenation and co-production of methane and aromatics. In 2011, it completed a 50 t/d pilot demonstration, which had been in operation for a long time. Moreover, it is currently constructing a 400 t/d demonstration plant. Biomass hydrogenation can be learned from the existing technology for coal hydrogenation to accelerate industrialization.

Tsinghua University expects to complete research on key hydrogen production technologies, intermediate heat exchangers, and other key equipment in 2023 to complete industrial scale-up by 2025 and begin constructing industrialization projects.

According to Table 2.2.3, the countries with the largest output of core patents in this direction are China, the USA, and Canada; the patents in China account for 67.21%, those of the USA account for 9.84%, and those of Canada account for 4.92%.

As shown in Table 2.2.4, the institutions with the largest

output of core patents in this research direction are Sundrop Fuels, Inc. in the USA, and Tsinghua University and PetroChina Company Limited in China. In addition, Jiangsu University, Sun Yat-sen University, and Sedin Engineering Co., Ltd., China, have conducted relevant research on this subject.

2.2.3 Intelligent and efficient drilling tool assembly and drilling and completion technology

Intelligent technology can be considered the engine and core driving force of scientific and technological innovation. The application of intelligent technology to oil and gas development has become a developing trend in the oil

industry. The realization of intelligence in the oil and gas industry is inseparable from intelligent, automatic, and efficient drilling and completion tools and systems. The intelligent and efficient drilling tool assembly and the drilling and completion technology is to establish an information transmission channel between the ground and the well by using intelligent drilling equipment such as intelligent drill pipes, intelligent drilling rig, and downhole data transmission and communication systems, using the downhole information acquisition system to detect, perceive, and transmit information about the downhole conditions in the process of drilling and completion in real-time. Intelligent analysis and decision-making are performed through the data analysis

Table 2.2.3 Countries with the greatest output of core patents on “research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	China	41	67.21%	86	18.53%	2.10
2	USA	6	9.84%	172	37.07%	28.67
3	Canada	3	4.92%	114	24.57%	38.00
4	South Korea	3	4.92%	3	0.65%	1.00
5	Germany	2	3.28%	78	16.81%	39.00
6	Netherlands	1	1.64%	11	2.37%	11.00
7	UK	1	1.64%	0	0.00%	0.00
8	India	1	1.64%	0	0.00%	0.00
9	Mexico	1	1.64%	0	0.00%	0.00
10	Russia	1	1.64%	0	0.00%	0.00

Table 2.2.4 Institutions with the greatest output of core patents on “research and development of key technologies and equipment for the biomass hydrogen production mechanism in high-temperature gas-cooled reactors”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Sundrop Fuels, Inc.	USA	3	4.92%	71	15.30%	23.67
2	Tsinghua University	China	3	4.92%	2	0.43%	0.67
3	PetroChina Company Limited	China	3	4.92%	0	0.00%	0.00
4	Jiangsu University	China	2	3.28%	10	2.16%	5.00
5	Sun Yat-sen University	China	2	3.28%	4	0.86%	2.00
6	Sedin Engineering Co., Ltd.	China	2	3.28%	0	0.00%	0.00
7	G4 Insights Inc.	Canada	1	1.64%	114	24.57%	114.00
8	Ostsee Maritime GmbH	Germany	1	1.64%	63	13.58%	63.00
9	Gas Technology Institute	USA	1	1.64%	49	10.56%	49.00
10	Sustainable Energy and Environment Coalition	USA	1	1.64%	30	6.47%	30.00

and feedback system. Then, the instructions are sent to the corresponding downhole executive equipment to realize the intelligent closed-loop control of the drilling process and the drilling and completion optimization technology of well completion and stimulation. The main research contents and technical directions can be roughly divided into downhole information acquisition technology and equipment, downhole data transmission and communication systems and equipment, decision-making and control systems, and downhole execution devices. Downhole information acquisition technology and equipment can provide downhole data support for drilling and completion. This is the key element of an intelligent and efficient drilling tool assembly. Underground data transmission and communication provide data transmission channels for the ground and underground locations to assist in comprehensive decision-making. Decision control systems and downhole execution devices can process downhole data and make comprehensive decisions, control downhole intelligent tools, and finally achieve intelligent drilling and completion.

At present, intelligent drilling rigs, intelligent bit drill strings, intelligent guidance, anti-stick-slip tools, intelligent well completion and fracturing slip sleeves, downhole information acquisition and transmission, remote intelligent drilling decision control systems, and other systems combined with intelligent well drilling and completion equipment have been developed. In the future, the intelligent level of petroleum exploration, development, and production equipment will increase. Intelligent production equipment embedded in the

Internet of Things, machine vision, deep learning, and other technologies will significantly reduce production costs and improve production efficiency. Drilling and data processing and interpretation will be more intelligent and efficient. Analysis technologies such as data mining and mathematical statistics will be more mature in the field of oil exploration and development, computer vision, cloud computing, and other technologies can more efficiently analyze, interpret, and process a large number of logging images, geological images, and instrument data generated during the drilling process. Professional software and information systems related to intelligent drilling and completion have matured. Cognitive intelligence and human-computer interaction technology will be applied to the intelligent drilling and completion systems to provide intelligent drilling decision-making and optimize drilling schemes, with the interaction and integration between it and intelligent equipment becoming optimal.

The output of patents in this field is mainly from the USA, with 151 disclosed patents accounting for 87.79%. China ranks fourth with 11 patents, behind Canada and the Netherlands, accounting for 6.40%. The most frequently cited country is the USA, more than 1 800 times (Table 2.2.5), accounting for 88.75%. Chinese patents were cited 91 times (4.28%). The main patent output institutions are mainly from the USA. Out of the Top 10 output institutions, nine are oil service companies in the USA, of which Halliburton and Schlumberger ranked first with 30 patents. China Petroleum and Chemical Corporation ranked tenth with four patents, accounting for 2.33% (Table 2.2.6). The USA, Canada, France, the Netherlands,

Table 2.2.5 Countries with the greatest output of core patents on “intelligent and efficient drilling tool assembly and drilling and completion technology”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	151	87.79%	1 885	88.75%	12.48
2	Canada	16	9.30%	219	10.31%	13.69
3	Netherlands	13	7.56%	148	6.97%	11.38
4	China	11	6.40%	91	4.28%	8.27
5	France	10	5.81%	121	5.70%	12.10
6	Germany	10	5.81%	61	2.87%	6.10
7	Norway	2	1.16%	24	1.13%	12.00
8	Saudi Arabia	2	1.16%	18	0.85%	9.00
9	United Arab Emirates	1	0.58%	4	0.19%	4.00
10	Australia	1	0.58%	2	0.09%	2.00

Germany, and other European and American countries emphasize cooperation in the field; there is also some cooperation between China and the USA (Figure 2.2.1). The cooperation between US oil service companies is relatively close, and the most cooperative institutions are Schlumberger and Prad Technologies from the USA (Figure 2.2.2).

2.2.4 High temperature resistant tool and system of measurement for drilling

During the drilling process, it is necessary to obtain as much information as possible about the downhole environment

(such as geological parameters, engineering parameters, and process parameters) to control drilling risks, ensure drilling quality, and improve drilling efficiency. Hence, various measuring tools are installed near the bottom of the drilling column, such as MWD tools and LWD tools. The circuit system on these tools includes various electronic components or sensing elements for data collection, processing, storage, and transmission. With the accelerated development of deep-sea, deep-earth, and geothermal energy, the number of deep wells (greater than 4 500 m) and ultra-deep wells (greater than 6 000 m) has gradually increased. Moreover, drilling engineering has higher requirements for downhole

Table 2.2.6 Institutions with the greatest output of core patents on “intelligent and efficient drilling tool assembly and drilling and completion technology”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Halliburton	USA	30	17.44%	406	19.11%	13.53
2	Schlumberger	USA	30	17.44%	371	17.47%	12.37
3	Baker Hughes	USA	17	9.88%	160	7.53%	9.41
4	Prad Technologies	USA	11	6.40%	170	8.00%	15.45
5	Weatherford	USA	10	5.81%	123	5.79%	12.30
6	APS Technology, Inc.	USA	8	4.65%	129	6.07%	16.13
7	Nabors Drilling Technologies USA, Inc.	USA	8	4.65%	116	5.46%	14.50
8	Motive Drilling Technologies, Inc.	USA	6	3.49%	72	3.39%	12.00
9	Hunt Advanced Drilling Technologies, LLC	USA	4	2.33%	78	3.67%	19.50
10	China Petroleum and Chemical Corporation	China	4	2.33%	47	2.21%	11.75

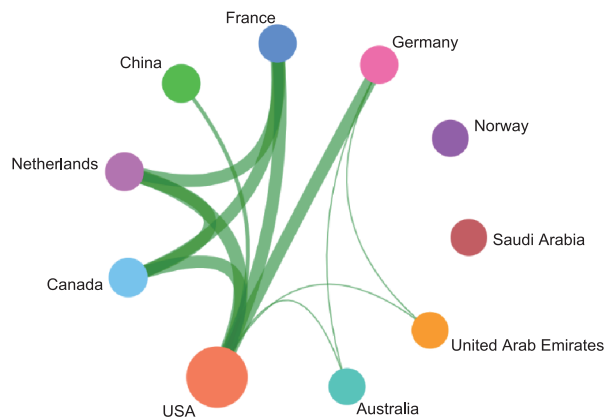


Figure 2.2.1 Collaboration network among major countries in the engineering development front of “intelligent and efficient drilling tool assembly and drilling and completion technology”

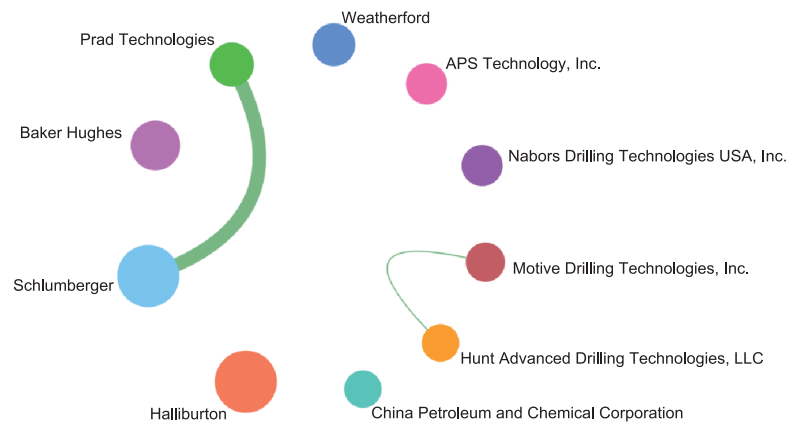


Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “intelligent and efficient drilling tool assembly and drilling and completion technology”

measurement tools. It is difficult for conventional downhole measurement tools to work steadily for a long time under high temperature, high pressure, high vibration, high friction, high corrosion, and ultra-low space conditions, among which the high-temperature environment is the most influential factor. The temperatures of deep and ultra-deep formations often exceed 150 °C, while some wells even exceed 200 °C. These circuit devices are prone to failure in high-temperature downhole environments. The failure caused by high temperatures would interrupt drilling activities and require tripping to replace the circuit system, significantly increasing the drilling time and costs. Therefore, to ensure the quality of the wellbore and reduce the drilling cost, it is necessary to develop high-temperature resistant tools and systems for MWD.

The research and development of MWD tools for drilling in high-and ultra-high-temperature formations has always posed a great challenge to the petroleum industry. Oil and gas companies and research institutions at home and abroad have done much work, achieving noteworthy results. The TeleScope ICE ultra-high-temperature and high-pressure MWD system of Schlumberger, equipped with a high-temperature resistant multi-chip module, successfully worked continuously for 35 000 hours in a 200 °C test environment with 2 million shocks; it can run steadily for a long time while transmitting various downhole measurement information to the ground at a high speed. Halliburton developed the extreme sensor series (greater than 175 °C) and Ultra sensor series (greater than 230 °C) with high-temperature resistance. Its Quasar Trio MWD system can resist an ultra-high temperature of 200 °C, which

won the “World Petroleum Best Drilling Technology Award” in 2016. Baker Hughes also developed MWD tools that can run steadily in harsh environments, such as high temperatures (greater than 175 °C) and strong vibrations. The China National Petroleum Corporation has performed important work in the active cooling system of downhole circuits, and China Petroleum and Chemical Corporation has also conducted research on the development of high-temperature resistance MWD tools; however, on the whole, there is still a significant gap with the advanced technology of foreign countries.

By enhancing the temperature resistance of the circuit system of underground instruments and developing downhole cooling devices as the core, a high-temperature resistant tool and the MWD system combines passive bearing and active control to broaden the temperature applicability of the MWD tool and system, meeting the MWD requirements of engineering and geological parameters in deep and ultra-deep oil and gas exploration and development underground high-temperature environments. The key parts of the MWD tool and system for high-temperature environments include high-temperature resistance downhole sensors, high-temperature resistance electronic components, and high-temperature packaging technology. High-temperature resistance methods mainly include the development of high-temperature resistance devices and active cooling systems for downhole circuits. In developing high-temperature resistant sensors, it is necessary to consider selecting sensor body materials, forging materials, cast-in-melted parts, and solders, and adopt special welding techniques to ensure the stable operation of the sensor at high temperatures. In developing

high-temperature-resistant electronic components, it is necessary to select materials that are more stable in high-temperature environments to separate and remove chemical substances prone to react under high-temperature and ultra-high-temperature conditions. In developing high-temperature packaging technology, it is necessary to refer to the military and aviation multi-chip module and other electronic packaging technologies. In developing active cooling systems, it is necessary to study the application of various electronic component cooling technologies, such as cooling plates, frequency conversion cooling, thermal insulation packaging, and refrigerant technology in MWD tools and systems for high-temperature environments.

The top two countries that have published the most core

patents for high-temperature-resistant tools and systems of MWD are the USA and China, accounting for 50.72% and 37.68%, respectively, while those of other countries are lower than 5% (Table 2.2.7). The USA has the highest percentage (50.72%) and the highest percentage of citations (89.51%) for the published core patents. Institutions with the most published core patents include Schlumberger, Halliburton, PetroChina Company Limited, and Baker Hughes, in which Halliburton has the highest number of citations (Table 2.2.8). Countries that focus the most on cooperation include the USA, the Netherlands, and France (Figure 2.2.3), and the cooperative research between the institutions is concentrated in Schlumberger and Prad Technologies (Figure 2.2.4).

Table 2.2.7 Countries with the greatest output of core patents on “high temperature resistant tool and system of measurement for drilling”

No.	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	USA	35	50.72%	700	89.51%	20.00
2	China	26	37.68%	15	1.92%	0.58
3	Saudi Arabia	3	4.35%	43	5.50%	14.33
4	UK	2	2.90%	9	1.15%	4.50
5	Japan	2	2.90%	2	0.26%	1.00
6	Malta	1	1.45%	13	1.66%	13.00
7	France	1	1.45%	4	0.51%	4.00
8	Netherlands	1	1.45%	4	0.51%	4.00

Table 2.2.8 Institutions with the greatest output of core patents on “high temperature resistant tool and system of measurement for drilling”

No.	Institution	Country	Published patents	Percentage of published patents	Citations	Percentage of citations	Citations per patent
1	Schlumberger	USA	8	11.59%	85	10.87%	10.63
2	Halliburton	USA	7	10.14%	281	35.93%	40.14
3	PetroChina Company Limited	China	6	8.70%	5	0.64%	0.83
4	Baker Hughes	USA	5	7.25%	41	5.24%	8.20
5	Institute of Exploration Technology, Chinese Academy of Geological Sciences	China	4	5.80%	1	0.13%	0.25
6	Smith International, Inc.	USA	3	4.35%	49	6.27%	16.33
7	Saudi Arabian Oil Company	USA	3	4.35%	43	5.50%	14.33
8	Fastcap Systems Corporation	USA	2	2.90%	160	20.46%	80.00
9	Prad Technologies	USA	2	2.90%	65	8.31%	32.50
10	Dover Corporation	USA	2	2.90%	43	5.50%	21.50

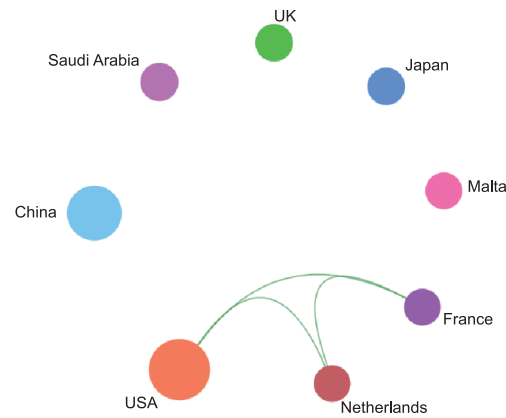


Figure 2.2.3 Collaboration network among major countries in the engineering development front of "high temperature resistant tool and system of measurement for drilling"

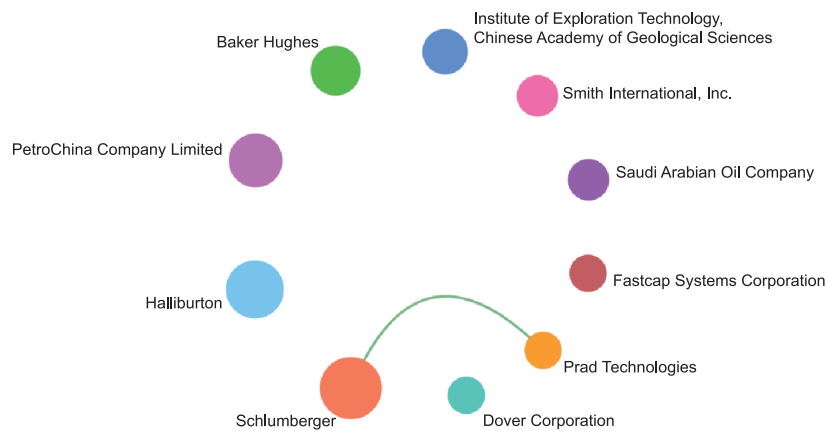


Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "high temperature resistant tool and system of measurement for drilling"

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