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Development Strategy for Nuclear Energy Mineral Resources

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Abstract: Nuclear energy mineral resources refer to uranium and thorium resources, which have various potential applications. However, presently, they mainly refer to uranium resources. The inhomogeneous distribution of global uranium resources calls for the market to adjust the supply-demand relationship. A secured supply of uranium resources is the basis of building a strong nuclear power industry. By developing its nuclear energy mineral resources, China aims at becoming a strong nuclear power with both naturally endowed and overseas-controlled uranium resources. There are five major indicators for a strong power of nuclear energy mineral resources, namely capability of securing the resource supply, technological research ability, corporate capacity, international management capability, and potential for sustainable development. To build a strong nuclear energy mineral resource capability, a large number of key scientific and technological innovation projects as well as demonstration projects must be initiated. In addition, a group of uranium resource bases with 1000-t capacity must be built. Moreover, emphasis needs to be placed on international cooperation, particularly on enhancing cooperation with countries along the Belt and Road. Finally, national policy support on technological innovation, industrial upgrades, and overseas development is also critical.
Keywords: nuclear energy mineral resources; uranium resources; indicator system

1 Introduction

Nuclear energy mineral resources refer to uranium and thorium resources, which have various potential applications. However, currently, they mainly refer to uranium resources. As an important strategic asset for both military and civilian use, nuclear energy mineral resources underpin the development of the nuclear industry. For China, to develop from a big nuclear power into a strong nuclear power, a secure supply of nuclear energy mineral resources is key. Therefore, China needs to identify its insufficiencies by sizing up both the domestic and global resource situation, and study the development strategy of nuclear energy mineral resources as well as the key tasks to execute such strategy.

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2 Status and supply-demand trends of nuclear energy mineral resources

2.1 Status of nuclear energy mineral resources

The status of nuclear energy mineral resources in the world is as follows: as of January 1, 2015, there were 7.641×10^6 t of recoverable uranium resources, with a recovery cost below $260/kgU in the world (total in-situ uranium resources of 1.019×10^7 t). However, the distribution and production output are extremely uneven. The top ten countries—Australia, Kazakhstan, Canada, Russia, the United States, Namibia, South Africa, Niger, Brazil, and China—contribute with 80.25% of the world's total uranium resources [1]. According to the World Nuclear Energy Association (WNA), the global production of natural uranium was 60 514 t in 2015, 89% of which was contributed by the top ten uranium mining companies—Kazatomprom, Cameco, Areva, ARMZ (including U-one), RioTinto, Navoi, BHP Billton, Paladin, China National Nuclear Corporation (CNNC), and China General Nuclear Power Group (CGN).

Concerning the status of nuclear energy mineral resources in China, it is as follows: by the end of 2017, more than 360 uranium deposits have been identified in China. There are mainly four types of uranium deposits, among which sandstone-hosted uranium resources account for 45.51%; granite-related uranium resources for 21.84%; volcanic rock-related uranium resources for 16.38%; carbon-silica-mudstone-related (black shale) uranium resources for 8.14%; and the rest accounts for 8.13%. Uranium mineralization conditions in China are generally good. Based on the latest forecasts, there are over 2×10^6 t of potential conventional uranium resources and more than 1×10^6 t of unconventional uranium resources; thus, it can be stated that China is a country with relatively good potential for uranium resources [2]. Furthermore, China has a sound uranium exploration, mining, and milling system. With respect to the uranium exploration system, systematic geological theories as well as integrated techniques of satellite–airborne–surface–underground prospecting are formed. The exploration and prospecting have extended to 500–1500 m underground. Over the past decade, six sandstone-hosted uranium bases with resources of 10 000–100 000 t have been identified in North China. As for the mining and milling processes, China has fairly mature techniques, e.g., in-situ leaching (ISL), conventional mining-heap leaching, and conventional mining-stirring/agitation leaching techniques. The so-called Generation-III mining technique of ISL with $CO_2 + O_2$ has been developed. Over the past ten years, multiple modern ISL mines have been built in Xinjiang and Inner Mongolia. The first 1000-t ISL uranium base was built in Yili, Xinjiang in 2017. Uranium production through ISL has accounted for over 70% of the total in China.

2.2 Supply-demand trends

Most nuclear power countries in the world have maintained the momentum of nuclear development, with expected further growth of the global nuclear power output. By the end of 2017, there were 448 operating nuclear power units with a total installed capacity of 391.74 GWe worldwide, and 60 power units with a total installed capacity of 60.96 GWe under construction. In 2016, 2490 TW·h of electricity was produced from nuclear power, accounting for 10.6% of the total power generation worldwide [3]. The global production of natural uranium was 62 366 tU in 2016. Global uranium resources are currently abundant enough to supply the demand of nuclear power development. Based on forecasts of modest demand, the total installed capacity of nuclear power will increase to 418.608 GWe by 2035, and the corresponding demand for natural uranium will increase to 66 995 tU/a. Meanwhile, according to such high demand scenario, the total installed capacity of nuclear power will increase to 682.753 GWe, and the corresponding demand for natural uranium will increase to 104 740 tU/a.

China's nuclear power construction will continue to grow in terms of both its scale and proportion. Nuclear power will become an important part of green energy. By the end of 2017, there were 37 operating nuclear power units with a total installed capacity of 3.581×10^7 kW in China, ranking fourth in the world. There were 20 nuclear power units under construction with a total installed capacity of 2.287×10^7 kW, topping the world in terms of construction scale. Those operating nuclear power units contributed with 2.02% of the national total installed capacity of electricity. In 2017, 2.475×10^{11} t kW·h of electricity was produced by nuclear power, accounting for 3.94% of the total power generation nationwide, which is still far below the world average [3]. If the forecast were made based on the regular pace of development, China would build and operate a total installed capacity of 1.18×10^8 kW (minimum target) by 2030. The required natural uranium in that year would be 2.2×10^4 t, and the consumed uranium resources and reserves would be 3.14×10^4 t. Assuming a full life of 60 years for a nuclear power plant, all nuclear power plants to be built by 2030 would consume up to 1.8×10^6 t of uranium reserves. If the forecast were made based on a rapid pace of development, the demand for uranium resources would be much

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greater [4].

The inhomogeneous distribution of global uranium resources requires an adjustment in the market for supply-demand relations. China's nuclear energy mineral resources supply still falls short of its future demand, necessitating a long-term development strategy. Specifically, to become one of the strong powers of nuclear energy mineral resources in the world at an early date, China should pursue the following twofold strategy: it should increase the intensity of exploration and development at home to secure a resource supply while simultaneously aiming globally and making greater use of overseas resources.

3 Main characteristics of the strong powers of nuclear energy mineral resources in the world as well as the development strategy in China

3.1 Definition and indicators of a strong power of nuclear energy mineral resources

A strong power of nuclear energy mineral resources, by definition, refers to a country with a safe and reliable resource supply, advanced science and technology, robust corporate capacity, strong international management capability, immense potential for sustainable development, and internationally leading overall national strength. Based on this definition, 5 Class-A indicators and 19 Class-B indicators are listed below (See Table 1).

Table 1. Indicators fora strong power of nuclear energy mineral resources.

Class-A indicators	Class-B indicators
Capability to secure domestic resource supply	Ranking among the world's top three uranium resource suppliers Capable of supplying no less than one-third of the domestic resource demand
Scientific and technological strength	Scientific and technological capability Equipment Technological innovation capability Investment intensity in R&D
Corporate capacity	Ranking among the world's top ten uranium mining companies Corporate diversification degree (including industry extension level) Profitability
International management capability	Resource control capability Product processing capability Transport control capability Market control capability Equity protection ability
Sustainable development potential	Intensity of investment in resource exploration Comprehensive utilization level of mineral resources Mine environmental protection level Mine safety level Energy and water consumption level

3.2 Main characteristics of the strong powers of nuclear energy mineral resources in the world and the development strategy in China

A big or strong power of nuclear energy mineral resources refers either to a country with abundant natural uranium resources or to a country that controls uranium overseas resources with its technology, capital, and overall national strength, or both. Based on this definition and the above-mentioned indicators, ten countries—Canada, Australia, Kazakhstan, Russia, France, the United States, China, Japan, Namibia, and Niger—are listed as the big powers of nuclear energy mineral resources in the world, among which the top six—Canada, Australia, Russia, the United States, France, and Kazakhstan—are referred to as the strong powers of nuclear energy mineral resources worldwide. Big and strong powers of nuclear energy mineral resources can be placed into three categories: endowed-resources type (Type A), controlled-resources type (Type B), and mixed type of endowed and controlled resources (Type A+B).

Endowed-resources type (Type A) refers to countries naturally endowed with abundant uranium resources; however, the resources are controlled by foreign companies. Nuclear industry is usually underdeveloped in such countries, and there is a lack of financial support and mature metallurgical techniques at home. Thus, the produced uranium products would be sold overseas. The purpose of resource exploration and development in such countries is to attract foreign investment, create more jobs, and drive the local economy. Examples are Namibia and Niger.

Controlled-resources type (Type B) concerns countries that exhibit a lack of uranium resources or limited uranium exploration to protect resources yet control a considerable number of uranium resources overseas. They are commonly equipped with advanced exploration and metallurgical techniques as well as sufficient funding. Nuclear power constitutes a large proportion in the national energy mix; thus, controlled overseas resources are necessary to secure the domestic energy supply and compete for dominance in the global uranium resource market. Examples of countries of this type are France and Japan.

Mixed type of endowed and controlled resources (Type A+B) refers to countries that are naturally endowed with an abundance of uranium resources and, additionally, control a large amount of the premium uranium resources overseas. These countries have a considerably mature capital market, advanced exploration, and metallurgical techniques, as well as the ability to dominate the global market trends of natural uranium. Nuclear power is developed in most of these countries, which generates a robust demand for uranium resources. Such countries include the United States, Russia, Australia, Canada, and Kazakhstan. Among them, Kazakhstan is an exception, as its overall national strength does not stand out and nuclear power is not developed, but it has managed to control a part of uranium resources overseas with its absolute advantages in indigenous uranium resource endowment.

With respect to the development strategy of nuclear energy mineral resources in China, according to nuclear power development trends, geological settings, and uranium resource characteristics in China, our strategic goal for the development of resources is to be a Type-(A+B) strong power of nuclear energy mineral resources.

4 Our insufficiencies compared with the world’s strong powers of nuclear energy mineral resources

The quantity of measured uranium resources in China is generally not in proportion with its share of nuclear power in the world. Based on the goal of becoming a strong power of nuclear energy mineral resources as well as our present national realities, China should be among the world’s top three in terms of the total controlled uranium resources, supplying no less than one-third of the domestic demand for natural uranium. As of now, the following insufficiencies still exist.

Despite relatively rich uranium resources at home, China is not endowed with as many large high-grade uranium deposits as Canada, Australia, and Kazakhstan. The amount of measured uranium resources is still limited, and the grade is relatively low. There are not many large or ultra-large uranium deposits in China, and the exploration degree is considerably low. In general, there is a lack of capital input in basic geological studies and exploration. Overall planning at national level is not yet in place. Nearly half of the explored national land is at a considerably low level of exploration, and little exploration has been carried out at 500 m underground.

As for the uranium exploration capability, China still lags behind some of the world’s strong powers of nuclear energy mineral resources in terms of digitalization, IT application, prospecting instrument sophistication, and R&D capability. Many short links still exist in basic geological studies and evaluation of mineralization potential at medium-to-large scale.

With regard to uranium development capability, uranium production in China is slightly low. The pressure to meet the goal of securing no less than one-third of the domestic demand for natural uranium by 2020 remains. The overall corporate capacity is yet to be enhanced. China still lags far behind the world’s strong powers of nuclear energy mineral resources in terms of metallurgical automation as well as scaled, intensified, and digitalized uranium production. The instruments used for underground mining are obsolete, and there is still room for improvement in safety control and environmental protection.

China started late in investing in the development of overseas uranium resources. The quantity and scale of uranium resources it controls overseas is still limited. Its international management capability still needs to be strengthened, and there is also a lack of international mining talent. The uranium resources China has gotten control of overseas so far are not only small-scaled with lack of quality but also are uncompetitive in the global market.

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5 Key tasks for executing the development strategy of nuclear energy mineral resources

5.1 To implement several key innovation projects

Innovation projects include technical studies on constructing a global uranium resource information database and big-data application, studies on uranium prospecting at depth, R&D in uranium exploration instruments and analytical devices, studies on Generation-IV ISL techniques, studies on the redevelopment and application of ISL, technical studies on coordinated mining of uranium and coal in large sedimentary basins, studies on the comprehensive utilization of uranium polymetallic associated elements, technical studies on waste water disposal and groundwater rehabilitation of ISL, and technical studies on the minimization of waste from conventional metallurgy.

5.2 To implement several key demonstration projects

Key demonstration projects include digitalized uranium mines with integrated exploration and mining, systematic prognosis and resource enlargement of key uranium mineralization zones, detailed geological evaluation of key uranium mines or mineralization zones, application of distributed ISL techniques, green and highly efficient ISL in mines with 1000-t capacity, intensified development of key uranium mines, prospecting uranium resources overseas, hard-rock mines in South China with the least environmental impact and safety monitoring and warning systems, environmental impact monitoring and groundwater rehabilitation of ISL in sandstone-hosted mines of North China, and environmental impact and precautions of coordinated mining of uranium and coal in key basins.

5.3 To build a group of uranium resource bases

Most of the measured uranium resources in China are concentrated in nearly 30 uranium ore fields or mineralization concentration areas, making it easier to build large uranium bases. China will continue to increase exploration activities in terms of both scale and intensity to build a group of uranium resource bases, with measured uranium resources of 10 000–100 000 t and a production capacity of natural uranium reaching 1000 t. China aims to develop an industry layout with sandstone-hosted uranium deposits in the north and hard-rock uranium deposits in the south.

5.4 To strengthen uranium exploration and development overseas

The Belt and Road initiative should be vigorously responded to. Countries along the Belt and Road have abundant uranium resources, as these 15 countries, including Kazakhstan, Russia, Ukraine, Mongolia, India, Czech Republic, and Uzbekistan, contribute with 32.6% of the world's total recoverable uranium resources. Six countries, namely Kazakhstan, Russia, Uzbekistan, Ukraine, Czech Republic, and Romania, produced about 31 000 t in 2015, accounting for 50.6% of global uranium production. Kazakhstan, in particular, produced 39.3% of the world's total uranium that year, ranking first. It is evident that the countries along the Belt and Road play a vital role in global uranium resource production. Therefore, it is imperative for us to enhance cooperation with countries along the Belt and Road and make them our key partners in supplying natural uranium.

China should continue to steadily push forward cooperation with African countries and open the market in Australia, Canada, and other resource-rich countries. Because of its rich uranium resources, which strongly complement China's capabilities, the space for cooperation with Africa is very broad. Australia and Canada are the world's strong powers of uranium resources. Both countries enjoy political stability as well as sound and stable laws and regulations in mining and investment. There are 1.78×10^6 t of measured recoverable uranium resources, with a recovery cost < 260 USD/kgU in Australia, ranking first worldwide. Its production output in recent years has been maintained at 5000–6000 t/a, ranking third in the world. Canada is renowned for its large quantities and high grade of uranium resources. There are 7.04×10^4 t of measured recoverable uranium resources, with a recovery cost < 260 USD/kgU, and its production output over the past decade has been maintained at 9000–10 000 t/a, leading the world until 2009. In addition, China should actively explore potential cooperation with other emerging countries of uranium resources, such as Greenland and Argentina.

China should further enhance its international management capability and advance trade in uranium resources to enlarge its uranium reserves. During periods of low global uranium price, China should purchase more uranium resources overseas to make sure that domestic demand can be secured. During periods of high global uranium price, China should sell some of its uranium stockpiles overseas.

6 Safeguards and recommendations

6.1 To pursue innovation-driven development

Increased investment in basic studies is necessary for more creative results, deepening the research on metallogenic theories of hydrothermal and sandstone-hosted uranium deposits to identify new types of deposits in new areas. Furthermore, additional effort should be placed on basic theoretical studies of uranium mining and milling, while continuing to optimize Generation-III ISL techniques with CO_2 + O_2 and strive for Generation-IV ISL techniques with Intelligence +X.

The innovation capacity system needs to be further strengthened by setting up more platforms to enhance innovation capacity, such as building national key laboratories for uranium resource exploration, key laboratories of science and technology for national defense, and innovation incubators. In addition, cooperation with international academic institutions and research institutes is strongly recommended. Setting up joint research institutes might also be beneficial.

China should build a multi-tier talent cultivation system. Through this, the instruction for radioactive geology and uranium metallurgy in institutions of higher education can be improved, and specific plans for talent cultivation should be put forth to cultivate a rich pool of talent for building a strong power of nuclear energy mineral resources.

6.2 To optimize industrial layout and improve industrial policies

More input is needed in geological exploration. China should secure more funds for the basic and strategic exploration of uranium resources for the public good. A strong capacity-building system for geological exploration is called for. Furthermore, a stable and enduring financial input mechanism should be established by setting up special funds for nuclear geological exploration.

China should further deepen industrial structural adjustment by intensifying the exploration and development of sandstone-hosted uranium deposits in the north. A coordinated industrial layout between the north and south should be the goal. As for uranium exploration, continuing the approach of protective development featured by “mining the large deposits and leaving out the small ones” as well as “more exploration and less mining” would build a globally competitive natural uranium industrial system.

Policies related to mining property rights should be improved, and resources should be utilized more efficiently. Overall planning should be carried out in areas or basins hosted with multiple associated resources. Mining property rights are granted according to the overall planning, and exploration will then be lawfully conducted in an orderly manner. Mining property rights of solid minerals can overlap with that of oil and gas under the premise of ensuring safety and environmental protection. Special regulations should be formulated for the overlapping of the mining property rights of uranium, coal, oil, and gas. The principle of giving priority to uranium mining with spatial isolation and temporal staggering will be followed, and a regular coordinated mechanism needs to be arranged.

Innovative cooperation models should be encouraged; for instance, China can adopt the model of joint-stock partnership with one liable entity and multiple shareholders. In the technical field, techniques of recovering associated resources, such as uranium-iron, uranium-phosphorus, uranium-molybdenum, uranium-beryllium, and uranium-rare-earth, should be studied and developed to reduce the impact on the environment and to carry out a comprehensive utilization of resources.

Environmental protection policies should also be improved. Companies should be encouraged to research and develop new technologies to improve the efficiency of resource utilization. Fiscal fund and bank loans would favor circular economy projects in the mining sector. More inputs should be given to rehabilitating the geological environment of the mines as well as land reclamation of the mining area. R&D on key technologies for minimizing waste as well as groundwater and soil rehabilitation from uranium metallurgy should also be given attention. In addition, tailings of the uranium mines and nuclear facilities after decommissioning should be better managed.

6.3 To improve the policy of going global

Chinese companies entered the global uranium market significantly late; thus, more capital and technology inputs are required to secure a larger market share. Against the backdrop of continuous low global market price of

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natural uranium, China faces many problems in the exploration and development of uranium resources overseas, such as increasing financing difficulties, weakening profitability, rising exploration cost, and growing technical difficulties in exploration. To address these problems, more financial support should be provided, and policy coordination should be strengthened. First, during periods of extremely low global uranium price, China should set up a special fund for overseas uranium exploration to support companies in the merger and acquisition of venture exploration projects. Second, more state capital needs to be made available. The government intends to set up an overseas investment platform and provide more state capital for uranium development projects. Third, policy coordination needs to be strengthened. Relevant government authorities are expected to strengthen the coordination among them. Financial institutions could introduce special financing policies and channels to help companies globalize. Finally, during periods of continuously low uranium price in the global market, China should seize the opportunity to control part of the premium uranium resources overseas and secure the uranium trade reserve.

7 Conclusions

Through more than sixty years of exploration and development in nuclear energy mineral resources, China has built a sound capacity system, together with a complete and advanced nuclear industrial chain, facilitating its arrival into the ranks of the strong powers of nuclear energy mineral resources in the world. In the coming years, by continuing to follow the principle of innovation-driven development and open cooperation, putting talent cultivation high on the priority list for core capacity building, and maximizing our advantages in systems, institutions, and policies, the development strategy of nuclear energy mineral resources is bound to be successfully executed.

Note: The personnel involved in this study also include Li Guangya, Chen Yuehui, Zhang Weixing, Xue Yingxi, Zhang Jianyong, Zhu Bo, Xue Jianxin, Fan Honghai, Xiao Shiwei, and Zhou Mei.

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