Analysis of advanced nuclear fuel frontier technology on the basis of the patents

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ABSTRACT

With the increasingly prominent global climate issues and the continuous reduction of traditional energy, nuclear energy, as an efficient and clean energy source, is becoming increasingly important in energy supply. In recent years, countries such as the United States and France have proposed advanced reactor plans to promote the development of fourth-generation advanced nuclear energy systems internationally to further increase the utilization of nuclear energy. Currently, the main nuclear power reactor types in operation worldwide are pressurized water reactors, and high-temperature gas-cooled reactors are the advanced reactor types that have developed rapidly in later stages. As the source of nuclear energy, the design and development of advanced nuclear fuels are the key to developing advanced reactors. High burnup uranium oxide fuel (UO_2 fuel), Accident Tolerant Fuel (ATF), and tri-structural ISOtropic (TRISO) have developed rapidly in areas such as fuel pellet design, fuel component performance improvement, and detection analysis. Patents, as important commercial and technological information resources, reflect future technological development trends. In order to fully understand the current status and trends of scientific and technological development of nuclear fuels in recent years, we conducted quantitative and qualitative analysis of global patents related to nuclear fuels, studied the technological source of advanced nuclear fuel technologies and the status of innovation, analyzed the competitive hotspots of technology research and development, and revealed the future development trends of advanced reactor types such as UO_2, ATF, and TRISO.

Keywords: UO_2 fuel, Accident Tolerant Fuel, tri-structural ISOtropic particle fuel, patent

1. INTRODUCTION

As an environmentally friendly and efficient clean energy source, nuclear energy has been increasingly valued by countries under the global dual carbon target[1]. Countries such as the United States and France have proposed advanced reactor plans and nuclear fuel technology has also developed along with the research and development of reactor technology. Among them, UO_2, ATF, and TRISO have seen more technological innovations in recent years. Pressurized water reactors (PWR) are the most common type of nuclear power plants globally, and countries with large nuclear power outputs such as the United States, France, and China continue to design and improve UO_2 fuel in terms of fuel rods, fuel assemblies, and fuel pellets. ATF fuel, as a representative of improving fuel reliability, has developed rapidly in terms of fuel pellets and cladding[2,3]. The US Westinghouse Electric has designed the ADOPT® fuel pellet with a U_3Si_2/UN composite composition[4], and launched the EnCore® brand; Framatome has designed high-performance GAIA fuel assemblies. TRISO (Tri-structural ISOtropic) fuel[5] is the main fuel type for high-temperature gas-cooled reactors.

Patents integrate technical information, legal information, and economic information into one body, making them an important information resource[6]. By conducting patent technology analysis of advanced nuclear fuels, it is possible to clarify the latest technological development trends of global nuclear fuels, providing support for subsequent technical research and development.

2. METHODS

In view of the large number of innovative technologies in the field of nuclear fuel in recent years, the global public patents from December 1, 2017, to December 1, 2023, were selected as the data source. By combining keywords and IPC classification numbers in the field of nuclear fuel, a patent search strategy is constructed, as shown in Table 1. Patent literature searches are conducted in databases such as Patsnap, Himmpat, WIPO, and EPO. Quantitative analysis was

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carried out from the perspectives of technology origin, innovation subject, and technology distribution, while qualitative analysis was carried out from the perspectives of technical focus points, main innovative technology content, and so on.

Table 1. Patent search strategy.

Classification	Search content
Keywords	Nuclear fuel, fuel assembly, fuel assemblies, fuel pellet, ATF、TRISO, MOX, UO_2, uranium dioxide, uranium, Plutonium, mix*, fuel rod, pipe, tube, tubular product, tubing
IPC	G21C3/00, G21C3/02, G21C3/04, G21C3/06, G21C3/07, G21C3/08, G21C3/10, G21C3/12, G21C3/14, G21C3/16, G21C3/30, G21C3/40

3. RESULTS

3.1 The origin of technology

In the field of nuclear fuel, 3577 patents have been applied for in the past six years, and there is a large difference in the number of patents among different countries, as shown in Figure 1, presenting a pattern of China and the United States as the two giants. The amount of patents in these two countries accounts for 72% of the total global patents. In recent years, China and the United States have both exceeded 1,000 patents, ranking in the first tier. China has continuously promoted the stable development of the nuclear power industry, with a total of 1,536 patents; since implementing the Advanced Reactor Demonstration Program (ARDP), the United States has accelerated research on advanced nuclear fuel, with a total of 1,015 patents. France, South Korea, and Russia--three countries with significant nuclear capabilities--each hold approximately 200 patents, positioning them in the second tier of nuclear technology innovation. Japan, Sweden, Canada, and other countries rank in the third tier.

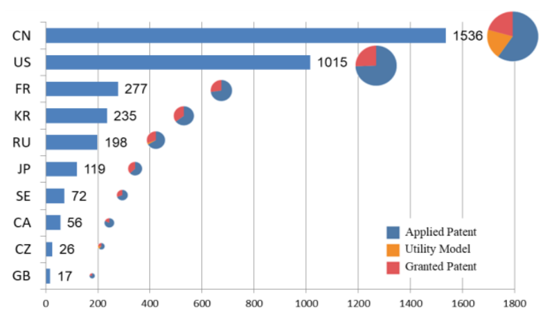

Figure 1. The distribution of technology origin countries.

3.2 The top patent applicants

The innovation entities in the field of nuclear fuel in China, the United States, France, Russia, and South Korea have a clear trend of concentration, as shown in Figure 2. Among them, Russia is the most significant. The patent applications in Russia are concentrated in Rosatom, which was established in 2007 and has 435 units covering most of the nuclear fuel research and development subjects in Russia. The Westinghouse Company has been the main innovation subject in the field of nuclear fuel in the United States in recent years. French nuclear fuel technological innovation is concentrated in Framatome and CEA. Framatome has designed GAIA frames to improve and enhance the safety and combustion efficiency of fuel components.

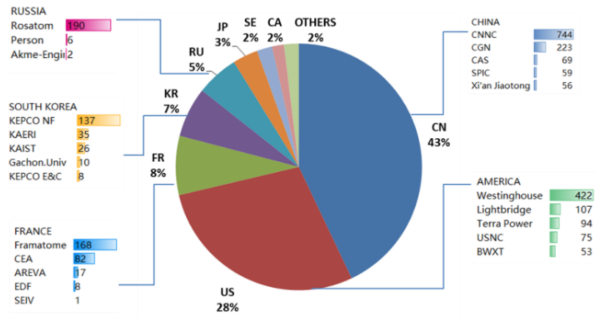

Figure 2. Top patent applicants.

3.3 Technology fields

At present, PWR is the most common type of nuclear power plant in the world, and the UO_2 nuclear fuel used in PWR has attracted attention from countries such as the United States, China, and France. As shown in Figure 3, the UO_2 nuclear fuel for PWR has the most patents, accounting for 79% of the total, focusing on the design and improvement of fuel rods, fuel assembly, fuel pellet and framework; the recently rapidly developing hotspot technologies such as TRISO fuel, ATF fuel, annular fuel and MOX fuel has also a large number of patents, accounting for a total of 15%; other advanced reactor fuels such as fast reactor, molten salt reactor, supercritical water-cooled reactor have not many patents but also have outstanding representative technologies.

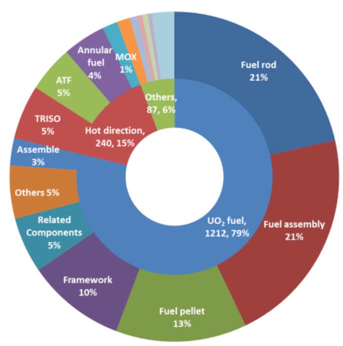

Figure 3. The distribution of technology fields.

3.4 The top patent applicants

(1) UO_2 Fuel

As the world's main nuclear power type, PWR has continuously advanced research on the economic and reliability of UO_2 fuel in countries such as the United States, France, and Russia. The main focus is on fuel rod structural design and guide tube material for fuel assemblies. The following analysis will be carried out from the perspective of patents to analyze UO_2 fuel technology.

Fuel rod structural design: Westinghouse has improved fuel rod cladding materials, designed low creep AXIOM fuel rods with ZIRLO alloy cladding, and applied ZIRLO alloy cladding to AP1000 fuel assemblies. They have also patented zirconium-based alloy cladding tubes and cladding coating (EP3907742A1, US20180371601A1). The KEPCO has adopted a new zirconium alloy material with better corrosion resistance and radiation resistance for PLUS7 fuel rods.

Improvements in fuel assembly design: Framatome has increased the cross-sectional size of guide tubes and selected a new Q12TM material to improve the stiffness, radiation resistance to deformation, and creep resistance of fuel assemblies. Westinghouse has designed guide tubes with a tube-in-tube design, placing a buffer tube at the lower end of the guide tube and using a buffer tube end plug to accurately locate the buffer tube within the guide tube (US10446277B2). The KEPCO has used a reinforced casing with a guide tube to improve seismic performance (KR102075648B1).

(2) ATF Fuel

After the Fukushima accident in Japan, nuclear power countries have increased research on the safety and stability of nuclear power. The United States has proposed the ATF fuel concept and various nuclear fuel suppliers have launched ATF fuel research[7]. Westinghouse constructed the ADOPT® fuel pellet with U_3Si_2/UN composite composition (US62472659P0) in 2017; Framatome has launched the next generation of high-performance GAIA fuel components, and conducted research on fuel lattice frames and Cr_2O_3 doping pellets[8,9]; Russia has improved fuel lattice frames and designed high-uranium density pellets (RU2691628C1) to enhance nuclear fuel safety performance. High-assay low-enriched uranium (HALEU) refers to enriched uranium with an abundance of U^{235} greater than 5% and less than 20%. It has received attention from research institutes in recent years[10]. The United Kingdom invested 300 million pounds in 2024 to develop advanced nuclear fuel and launch the HALEU research program; the US DOE launched a plan to stimulate the development of high-assay low-enriched uranium supply, and promoted Centrus Energy Corp to carry out HALEU production; Framatome has designed improvements for the HALEU fuel pellet (US10847275B2). It can be seen that HALEU fuel is the development trend of high burnup fuel and an important method to improve ATF economy.

(3) TRISO Fuel

TRISO fuel is an advanced new nuclear fuel that differs from the traditional UO_2 columnar fuel structure. It adopts a multi-layer structure, with graphite cladding on the outside and fuel particles dispersed in the graphite matrix inside[11,12]. The fuel particles consist of fuel pellets (UO_2, UC, UN, etc.) and multi-layer coating structures[13,14]. Several countries, including the United States, Germany, and China, have conducted research on TRISO fuel. Currently, the only TRISO fuel production enterprise in the United States has restarted its production line in 2020. China has commercialized the ball-bed module high-temperature gas-cooled reactor using self-designed TRISO fuel. In addition, countries such as the United States and India are combining TRISO fuel with HALEU for space reactor research[15,16].

4. CONCLUSION

4.1 China and the United States are the main technological sources

In the past six years, China and the United States have dominated the field of nuclear fuel element technology, with both countries having a significant number of patents in this area. This has created a dual-giant pattern, with both China and the United States having more than 1,000 patents, far outpacing France, which is in third place with 277 patent applications. Westinghouse, BWXT, and other enterprises continue to carry out a number of national patent bureaus in the technical direction of fuel assembly structure, cladding material and coating improvement, fuel consumption performance improvement, and so on.

4.2 UO_2 fuel patents account for the main share, and each enterprise focuses on different technologies

UO_2 fuel patents account for the majority of advanced nuclear fuel patents, with 1,212 patents representing 79% of the total. The top three countries in terms of patent applications are China, the United States, and France. Rosatom has been actively improving VVER fuel component technology and holds the largest number of patents in this area, accounting for 41% of the total. CEA has focused its efforts on MOX fuel pellet production. The remaining companies' patents are primarily concentrated on pressurized water reactor UO_2 fuel.

4.3 Advancements in high burnup and safety performance will continue to drive the development of advanced fuels

The cladding of nuclear fuel assemblies, when exposed to the high-temperature, high-pressure water environment within a nuclear reactor, can lead to corrosion or oxidation on the cladding surface, potentially resulting in metal embrittlement that affects the performance, lifespan, and safety margin of the nuclear fuel. The development of ATF and TRISO fuels, which offer higher burnup and corrosion resistance, is expected to continue, with a predicted increase in the number of patents related to cladding materials and coatings, large-grained doped fuel pellets, and HALEU pellets.

REFERENCES

[1] Ko, J., Kim, J. W., Min, H. W. and Kim, Y., [Review of manufacturing technologies for coated accident tolerant fuel cladding], Elsevier, Amsterdam, (2022).

[2] Sheng, L., Xiu, J. and Cen, X., "Recent studies on potential accident-tolerant fuel-cladding systems in light water reactors," Nuclear Science and Techniques 31(03), 3-32 (2020).

[3] Qiu, B., Wang, J., Deng, Y., Wang, M., Wu, Y. and Qiu, S. Z., "A review on thermohydraulic and mechanical-physical properties of SiC, FeCrAl and Ti," Korean Nuclear Society 52, 1-13 (2020).

[4] Frazer, D., Maiorov, B., Carvajal-Nuñez, U., Evans, J., Kardoulaki, E., Dunwoody, J., Saleh, T. A. and White J. T. [High Temperature Mechanical Properties of Fluorite Crystal Structured Materials (CeO_2, ThO_2, and UO_2) and Advanced Accident Tolerant Fuels (U_3Si_2, UN, and UB_2)], Elsevier, Amsterdam, (2021).

[5] Gougar, H. D., Petti, D. A., Demkowicz, P. A., Windes, W. E., Strydom, G. and Kinsey, J. C., "The US department of energy's high temperature reactor research and development program-progress as of 2019," Nuclear Engineering and Design 358, 110397 (2020).

[6] Liu, W., Tao, Y. and Bi, K., [Capturing Information on Global Knowledge Flows from Patent Transfers: An Empirical Study Using USPTO Patents], Elsevier, Amsterdam, (2022).

[7] Yadav, K. K., Pal, U. and Karthikeyan, R., [Concept of Accident Tolerant Fuel in Nuclear Reactors], Elsevier, Amsterdam, (2023).

[8] Liu, Y. H., Li, Y., Wang, H. Y., Qi, M., Huang, Y. Z., Wang, L. and Miao, Y. F., "The design characteristic of advanced nuclear fuel assembly," Science & Technology Vision 5, 5-6 (2017).

[9] Xu, Y., Chen, P. and Guo, X., "Design characteristics and development direction of pressurized water reactor nuclear fuel," Science and Technology Innovation Herald 16(06), 62-64+67 (2019).

[10] DeHart, M. D., Bess, J. D. and IIas, G., "A Review of Candidates for a Validation Data Set for High-Assay Low-Enrichment Uranium Fuels," J. Nucl. Eng. 4(3), 602-624 (2023).

[11] Chuirazzi, W. C., Kane, J. J., Cordes, N. L., Stempien, J. D., Kancharla, R. R. and Xu, F., [Seeing the Whole Picture: Methods for Getting the Most from Micro X-ray Computed Tomography of TRISO Nuclear Fuel Particles], Elsevier, Amsterdam, (2023).

[12] Griesbach, C., Gerczak, T., Zhang, Y. and Thevamaran, R., [Microstructural Heterogeneity of the Buffer Layer of TRISO Nuclear Fuel Particles], Elsevier, Amsterdam, (2023).

[13] Michael, M., Zilong, H., Kevin, V., et al., "Accelerated thermal property mapping of TRISO advanced nuclear fuel," Materials Today Advances 21, 100455 (2024).

[14] Paul, A. D., Bing, L. and John, D. H., "Coated particle fuel: Historical perspectives and current progress," Journal of Nuclear Materials 515, 434-450 (2019).

[15] Aiden, P. and Ben, L., "A review of nuclear electric fission space reactor technologies for achieving high-power output and operating with HALEU fuel," Progress in Nuclear Energy 163, 104815 (2023).

[16] Beeshm, R. K., Sripathi, S., Pruthviraja, R. V. and Pannaga, S. [HALEU-TRISO Particle Fuel Based Nuclear Reactor for Celestial Body Exploration], Elsevier, Amsterdam, (2023).