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TOWARDS PRACTICAL FUSION ENERGY - ENGINEERING CHALLENGES AND DEVELOPMENT STRATEGIES BY THE PERSPECTIVE OF CNPE

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Abstract

Breakthroughs in nuclear fusion technology poised to revolutionize energy production and generate substantial economic benefits, emerging as a key medium-to-long-term development focus in global science, technology, and energy domain; applying engineering-oriented methodologies to advance the transition from experimental fusion reactors to demonstration fusion reactors is of critical significance for conducting fusion reactor research and construction with high efficiency, cost-effectiveness, and quality. This paper presents a systematic analysis of China's strategic framework issues for fusion energy development based on the general situation of the fusion industry. It examines domestic and international progress in fusion reactor engineering across five critical dimensions: safety regulatory systems, design and engineering management, project implementation practices, industrial supply chain cultivation, standardization framework. The study proposes development strategies focusing on the following aspects: leveraging organizational strengths to advance fusion energy development, formulating fusion regulatory policies that balance safety and development, fostering public-private collaboration to cultivate the fusion industry chain, and establishing a top-down design approach for building the fusion standardization system. Regarding the research and engineering management for fusion reactor engineering, as well as the construction of fusion reactors led by specialized enterprises, strategic suggestions are further proposed to efficiently and precisely advance China's fusion reactor engineering implementation, with the goal of achieving a leading position in the international fusion energy industry.

1. BACKGROUND

Controlled nuclear fusion, as one of the ultimate solutions to the energy problems of all mankind, has the advantages of abundant resources, inherent and intrinsic safety and low environmental impact, etc. It can be used as a long-term base load clean energy under the global net zero emission and China's "Carbon Peaking and Carbon Neutrality Goals", and is an important supportive energy source to achieve the global energy transformation and long-term climate goals. Currently controlled nuclear fusion is still in the early stage of the engineering and commercialization, also faces the engineering and technical problems such as plasma control, irradiation resistant structure materials, tritium fuel supply and tritium self-sustaining. To advance the commercialization of FPP (Fusion Power Plant) as soon as possible, CNPE (China Nuclear Power Engineering Co., Ltd.) started from the perspective of engineering and system thinking, combined together the successful practices of the nuclear engineering in fission FOAK (First Of A Kind) nuclear power plant (NPP), including engineering, standardization, the experience of the nuclear industry chain, and finally propose development strategies towards practical fusion energy based on deeply analysis of the current FPP engineering challenges.

2. THE CONCEPT OF FUSION ENGINEERING AND THE DIFFERENCES BETWEEN FISSION AND FUSION

China’s nuclear industry is matured and complete, with the world's largest team of nuclear engineers and technical workers, with more than 40 years continuous experience in the construction of nuclear industry, with excellent technical ability and reliable nuclear safety and quality culture, with continuous research and development innovation of nuclear power equipment and technology, all the above are the good foundation for the FPP. China currently has 102 nuclear reactors in operation or under construction, with a total installed capacity of approximately 113 GW, ranking first globally in nuclear power capacity. So far CNPE has carried out EPCS (Engineering, Procurement, Construction, and Startup) contracting for 29 nuclear power units, 15 of which have been completed and 14 are under construction. CNPE has accumulated experience in the design, construction and management of demonstration projects, including HPR1000 and ACP100.

Breakthroughs in nuclear fusion technology poised to revolutionize energy production and generate substantial economic benefits, emerging as a key medium-to-long-term development focus in global science, technology, and energy domain. The current research on controlled nuclear fusion is transitioning from scientific experiments to engineering practice. The main forces of China's fusion industry include 2 research institutes (SWIP[1] and ASIPP[2]), 3 leading nuclear power EPC companies (CNNC[3], CGN[4], and SPIC[5]), as well as a series of universities and innovative enterprises.

The fusion engineering development strategies proposed by CNPE focused on process management and system thinking to consider the design, construction, operations, decommission, during the transformation of fusion reactor from experimental device to demonstration reactor or commercial reactor. Integrate the industrial construction methodology, such as engineering design method, standardization design, lifecycle management to achieve the engineering reliability, availability, maintainability and inspectability.

TABLE 1. The engineering connotations of different development stages of fusion reactors

Dimension of Engineering	Experimental Facility	Experimental Reactor	Demonstration Reactor	Commercial Reactor
Organizational Model	Led by Research Institutes	Led by Research Institutes with Enterprise Participation	Led by Enterprises with Research Institute Participation	Led by Commercial Operation Companies
Safety Regulatory Systems	Establish Basic Safety Standards	Introduce a Hierarchical Regulatory Framework	Establish a Regulatory and Legal System for Fusion Reactors	Optimize and Iterate the Fusion Reactor Regulatory System
Design and Engineering	——	Full-System Integrated Design	Economic Optimization Design	Factory Standardized Design
Project Implementation	——	Model-Based Systems Engineering (MBSE)	Full-Lifecycle Project Management	Mature Fusion Reactor Project Management System
Industrial Supply Chain	——	Industrial Chain Cultivation	Industrial Chain Cultivation with Diversified Applications	Enhancement of Full-Industrial-Chain Independence
Standardization Framework	——	——	——	Systematization and Independence of Standards

3. FISSION NUCLEAR POWER PLANT AND EPC MANAGEMENT

3.1. The successful practice of CNPE in the fission FOAK Nuclear Power Plant

After decades of development, China's fission nuclear power industry has established a comprehensive regulatory and standards system. Building upon this foundation, the project preparation work, engineering design, and construction of fission NPP are carried out in strict compliance. The project preparation work for NPP projects includes: site investigation and preliminary feasibility study, preparation of the project proposal, feasibility study and project application report, SSAR (Site Safety Assessment Report) and EIA (Environmental Impact Assessment) and the PSAR (Preliminary Safety Analysis Report), final application report for the construction license.

A digital collaborative design platform is utilized to execute the project's conceptual design, general design, preliminary design, and construction design. Additionally, prior to project approval, preparatory work such as

[1] SWIP: Southwestern Institute of Physics

[2] ASIPP: Institute of Plasma Physics, Chinese Academy of Sciences

[3] CNNC: China National Nuclear Corporation

[4] CGN: China General Nuclear Power Corporation

[5] SPIC: State Power Investment Corporation Limited

equipment/material procurement and on-site construction readiness must be advanced and after the project approval, the project will progress through three phases: civil construction, equipment installation, and system commissioning. As the EPCS contractor for nuclear projects, CNPE has developed an integrated lifecycle management system. It continuously enhances its EPCS capabilities across four key areas: project management systems, knowledge engineering, intelligent construction, and industrial collaboration.

3.2. Management system and innovation of CNPE in the EPCS construction of Nuclear Power Plant

A series of management systems and innovations have been formed in the EPCS construction of nuclear power plant, including:

First, the integration of design and construction, unite the engineering and construction units to carry out research on advanced construction technology, jointly promote the research and development of digital software, Internet of Things technology, civil construction technology, installation and erection technology, welding and nondestructive testing technology and engineering application.

Second, to foster an independent and controllable nuclear industrial chain, build an integrated and collaborative platform for design, procurement and manufacturing, and gradually realize the design-procurement-supplier-warehousing-construction "five-in-one" information convergence.

Third, to improve the performance of project management, build a project management system covering the company level, project level and domain level. The first reactor of HPR1000 has achieved the best global Gen III NPP construction performance.

Fourth, to build a high-level talent team covering various specialties such as the research and development, design, procurement, construction, commissioning and project management, all the specialists integrate as one team with high-quality performance and form the core technical talent echelon.

Fifth, to build a digital and intelligent engineering construction platform, supported by the "N Triple1" digitalization scheme of the CNPE with the top-level planning and implementation program integrated into the "N Triple1" digital platform.

Finally, make every effort to improve the safety and quality management, earnestly practicing the company policy of "absolute responsibility, highest standards, systematic operation and experience feedback" resulting the main safety performance indicators are in the domestic top level of the nuclear industry.

4. PROBLEMS AND CHALLENGES RELATED TO FUSION POWER PLANT ENGINEERING

In recent years, controlled nuclear fusion has become a global research and development hotspot. Compared with the fission reactor, the engineering of the FPP still faces many problems in many aspects. Fusion reactor engineering organizations face the dilemma of a disconnect between research institute and enterprise delivery, coupled with talent and engineer mismatch.

4.1. Nuclear safety regulatory principles urgently need to be clarified

The regulations and standards for FPP are far from adequate. It is suggested that based on the different fusion technology configurations to formulate regulatory requirements considering the various aspects of the fusion principal and design and different fusion fuel to clarify the siting and licensing requirements and process of the FPP.

4.2. Engineering design capabilities for fusion reactors need to be enhanced

The FPP engineering and design are still in the early stage, so the technical roadmap, research and development strength are relatively dispersed. While the FPP involves many specialties, which is more complicated than the large pressurized water reactor NPP. Usually, several design and research units shall work together to carry out the engineering design, a set of comprehensive design management system and digital collaborative design platform are necessary to integrate multiple design units and various specialties in design units.

4.3. The understanding of fusion reactor project management and its difficulty needs to be deepened

The FPP engineering construction, taking Tokamak as an example, the FPP systems are gradually complicated and the machine is more and more large-scale, resulting the project investment around hundreds of millions or even billions of dollars. Professional project management team with experience is required to fulfil management work. Meanwhile, due to the FOAK elements and complexity of the Tokamak, rich experience in nuclear engineering management, the ability to solve and coordinate complex engineering problems, and professional engineering construction technology are critical to the construction management.

4.4. There is a contradiction between the development of the fusion reactor supply chain industry and its actual demands

The development of the fusion supply chain and ecosystem as a whole is still in the primary stage, the FPP related materials and key equipment need to be further improved. One important solution is to rely on the current fission nuclear industry supply chain, to evolve into the fusion supply chain. At the same time through promoting technological innovation, research and development, international cooperation and openness and sharing, to accelerate the establishment of fusion supply chain and FPP commercialization.

4.5. Existing standard system is incompatible with fusion reactor engineering

However, fusion reactors differ significantly from fission reactors in terms of basic principles and equipment characteristics. For example, the magnet system, heating system, diagnostic system, and vacuum vessel are all unique to fusion reactors. Unlike fission reactors, fusion reactors do not use fissile materials, do not involve nuclear criticality, and produce less radioactive waste. Instead, they impose special requirements on vacuum levels, cleanliness, and the extreme temperature properties of materials, rendering the existing nuclear fission standard system not fully applicable to fusion reactors.

5. CHINA'S ENGINEERING DEVELOPMENT STRATEGY FOR FUSION REACTORS

5.1. Leverage Organizational Advantages to Promote Fusion Energy Development

— Implement proactive policy guidance.
— Utilize enterprises' strengths in innovation and industrial transformation.

5.2. Formulate Nuclear Fusion Regulatory Policies Balancing Safety and Development

— Clarify the principles of fusion nuclear safety regulation.
— Expand the scope of nuclear material application and research.
— Adhere to the bottom line of nuclear safety culture.

5.3. Public-Private Cooperation to Cultivate the Fusion Industry Chain

— Give play to the development guiding role of management departments.
— Attach importance to the promotion role of industrial alliances.
— Highlight the facilitation role of iterative industrial incubation

5.4. Establish a Nuclear Fusion Standard Framework based on the Top-Level Design

— Implement top-level planning for standards.
— Promote the institutionalized operation of standard formulation.

6. CONCLUSION

In general, FPP engineering is a complex system engineering. In order to accelerate the pace of engineering and commercialization of FPP, it is necessary to use the practical experience of the existing nuclear industry, adopt the system thinking of nuclear engineering, and use scientific project management methods and construction technology to realize efficient engineering construction.

Taking the ITER Tokamak Assembly Project as an example, the CNPE Consortium, relying on its extensive project management experience, has established a project management system focused on the Construction Work Package (CWP) Leader (see Figure 1). The project adopts construction work packages as its basic units, with each work package assigned one CWP Leader who oversees the entire process, including documentation preparation, item procurement, personnel training, on-site implementation, and completion and handover. Under the basic framework of the project organization, a matrix management system with technology at its core has been formed. This innovative management model emphasizes the core role of technology, fully aligns with the engineering characteristics of fusion reactor projects, and can provide strong support for project implementation.

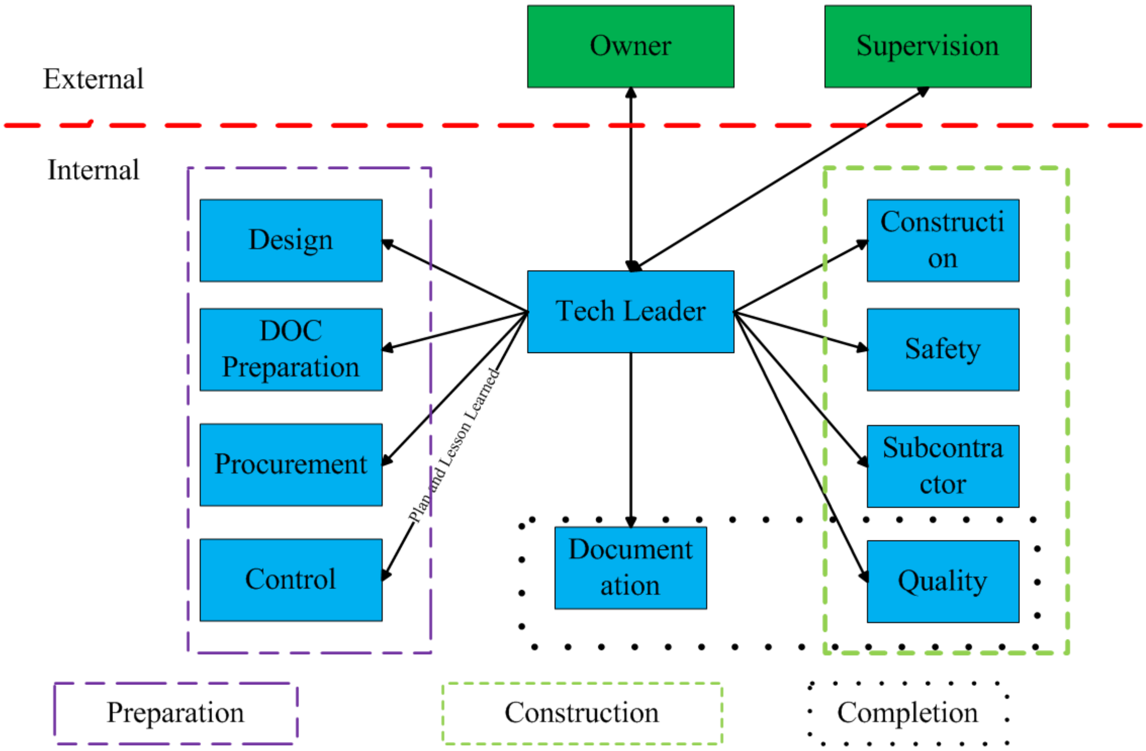

FIG. 1. ITER Project Assembly Management with Technology at its Core

Based on the above analysis, the following suggestions are put forward:

— Research and Establishment of Design Management System for Fusion Reactor Engineering. This system is built and improved based on the existing systems and platforms of the nuclear industry.
— Fusion Reactor Engineering and Construction System led by professional enterprises.
  - Project organization system focused on plant EPC;
  - Project management system with technical management as core;
  - Project control system focused on agile management;
  - Construction management system supported by IT and Digitalization.

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