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From Chooz to the Ling'ao NPP: The Technology Transfer of Pressurized Water Reactor Technology from France to China

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Abstract: The transfer of pressurized water reactor (PWR) technology from France to China is an important event in the history of Sino-French scientific and technological relations. China has gradually achieved self-reliance in the field of PWR technology through the introduction and subsequent absorption of France's 900 MW reactors. Compared with the process of introducing and absorbing similar technology from the United States by France, China's experience has been more complicated. This circumstance reflects the differences in the nuclear power technology systems between the two countries. France's industrial strength and early acquisition of nuclear power technology laid a solid foundation for mastering PWR technology. On the other hand, although China established a weak foundation through the implementation of the "728 Project," and tried hard to negotiate with France, the substantive content of the technology transfer was very limited. By way of the policy transition from "unhooking of technology and trade" to "integration of technology and trade," China ultimately accomplished the absorption and innovation of PWR technology through the Ling'ao NPP.
Keywords: pressurized water reactor (PWR), technology transfer, Sino-French relations, Chooz NPP, Daya Bay NPP, Ling'ao NPP

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摘　要：压水堆技术从法国向中国的转移是中法科技关系史上的重要事件。中国通过引进法国的 90 万千瓦级反应堆，在消化吸收之后逐步实现了压水堆领域的自立自强。与法国引进吸收美国同类技术的过程相比，中国的进展较为曲折。这反映了中法两国核电技术体系的差异。法国的工业实力与早期核电技术的积累为掌握压水堆技术打下了坚实基础。中国虽然通过“728 工程”的实施建立起与法国的核电对话体系，但技术转移的内容非常有限。通过从“技贸脱钩”到“技贸结合”的转变，中国最终完成了压水堆技术的吸收与创新。
关键词：压水堆技术，技术转移，中法关系，舒兹核电站，大亚湾核电站，岭澳核电站

Pressurized water reactor (PWR) technology has long held a dominant position in the history of international nuclear power technology development, and technology transfer has been an important means for the spread of this technology worldwide. On the basis of the localization of technology, different countries have independently engaged in international competition surrounding PWR technology. Among them, France and China are typical but special cases, where American technology was initially transferred to France and then, having absorbed the technology, France subsequently transferred it to China. The origins of this transfer can be traced back to the period when Charles de Gaulle was in power (1958–1969). At that time, France experimented with the introduction of related technology, obtaining a license from the American company Westinghouse. During the period when Georges Pompidou was in power (1969–1974), France introduced and absorbed PWR technology, and after further innovations, nuclear power accounted for a majority of its electricity production. France’s ambition to expand its nuclear power worldwide and China’s need to master the technology led to the initial “technology and trade cooperation” between the two countries in introducing PWR. Subsequently, the Daya Bay Nuclear Power Plant (NPP) and the Ling’ao NPP were constructed. Based on this foundation, China, through its own on-going independent innovation, developed the generation II+ pressurized water reactor CPR1000, and has laid the technological foundations and accumulated technical capabilities for developing generation III nuclear power technology.

Currently, China’s nuclear power technology has a global impact, but specialized research on the history of this technology is still rare. One major difficulty lies in the fact that relevant archival materials are mostly kept within relatively closed Chinese nuclear power enterprises, making it extremely difficult to access these internal documents. However, Chinese nuclear power specialists have published numerous compilations of materials, retrospective accounts, and thematic summaries concerning early nuclear power plants. These published documents provide a rich source of clues for conducting historical research, disclosing important technical parameters, engineering priorities, and implement processes.[1] Retrospectives on the construction of Chinese power plants and cooperation between China and foreign countries also bring to light some details.[2] One can also find specialized publications that discuss the development of Chinese nuclear power equipment manufacturing technology,[3] or expound on the path of China's nuclear power institutionalization and internationalization.[4] In addition, some of the data comes from professional journals, such as *China Nuclear Industry* (*Zhongguo hegongye* 中国核工业), *Foreign Nuclear News* (*Guowai he xinwen* 国外核新闻), *Nuclear Power Engineering and Technology* (*Hedian gongcheng yu jishu* 核电工程与技术), *China Electric Power* (*Zhongguo dianli* 中国电力), and *Nuclear Economy Research* (*He jingji yanjiu* 核经济研究), as well as specialized papers in various power industry journals. An important work published in France, *Le chemin partagé: Une histoire d'EDF en Chine (1983–2011)*, provides a detailed account of the cooperation between Électricité de France (EDF) and China, including the transfer and development of nuclear power technology from Daya Bay to the Ling'ao NPP. The author utilizes corporate archives and interview materials, focusing on commercial negotiations and nuclear power plant construction. The same author, together with Boris Dänzer-Kantof, subsequently published *L'Energie de la France: De Zoé aux EPR, l'histoire du programme nucléaire*, which traces the history of French nuclear power with a focus on the role of EDF in French nuclear power generation. This is currently the most comprehensive work in this field and includes chapters on nuclear power cooperation between France and China. These two works are basically institutional and corporate histories. Taking a historical perspective, this paper focuses on how France introduced American PWR technology and achieved its own localization, and how China subsequently accomplished its own localization based on the introduction and absorption of French PWR technology at different stages. The paper reassesses and

1 For example, there are compilations including *The System and Operation of the Daya Bay Nuclear Power Plant* (*Daya Wan Hedianzhan xitong ji yunxing* 大亚湾核电站系统及运行), *A Compilation of the Construction Experience of the Daya Bay Nuclear Power Plant* (*Daya Wan Hedianzhan jianshe jingyan huibian* 大亚湾核电站建设经验汇编), *A Collection of Essays on Equipment Localization at the Ling'ao Nuclear Power Plant* (*Ling'ao hedian shebei guochanhua wenji* 岭澳核电设备国产化文集), and *Construction and Innovation of the Ling'ao Nuclear Power Plant Phase II Project of China's Million-Kilowatt Nuclear Power Self-Reliance Project* (*Zhongguo baiwan qianwa ji hedian zizhuhua yituo gongcheng: Ling'ao Hedianzhan erqi gongcheng jianshe yu chuangxin* 中国百万千瓦级核电自主化依托工程 岭澳核电站二期工程建设与创新).

2 See, for instance, *Nuclear Reactors and Nuclear Power Generation* (*He fanyingdui yu heneng fadian* 核反应堆与核能发电) and *Qinshan Nuclear Power Plant: A Pearl by the Hangzhou Bay* (*Hangzhouwan pan yi mingzhu: Qinshan Hedianzhan* 杭州湾畔一明珠——秦山核电站).

3 For example, *A History of China's Major Technical Equipment: Chinese Nuclear Power Equipment Manufacturing* (*Zhongguo zhongda jishu zhuangbei shihua: Zhongguo hedian zhuangbei zhizao* 中国重大技术装备史话——中国核电装备制造).

4 For example, *The History of China's Electric Power Industry (Nuclear Power Generation Volume)* (*Zhongguo dianli gongye shi: Heneng fadian juan* 中国电力工业史［核能发电卷］).

integrates Sino-French archives, literature, and related research to discuss these questions. Meanwhile, it also explores and analyzes specific issues, including how indigenous French nuclear power technology achieved self-reliance and innovation, how Sino-French cooperation in nuclear power started, and exactly what technology was transferred.

1 The introduction and localization of US PWR technology in France

As early as 1952, following a consensus reached by the French government and the *Commissariat à l'énergie atomique* (CEA), the French Fourth Republic launched the Five-Year Nuclear Energy Plan. Considering the contradiction between future national power demand and limited domestic resources, EDF decided to participate in the plan and carry out power generation experiments. On September 28, 1956, the first graphite-gas cooled reactor of the five-year plan, G1, initiated the generation of nuclear electricity on the European continent through an energy recovery device built by EDF. In April 1959 and April 1960, the G2 and G3 reactors were successfully connected to the grid and started generating electricity (Dänzer-Kantof and Torres 2013, 70–73). Thus, France became the fourth country to achieve grid-connected nuclear electricity generation after the Soviet Union, the United Kingdom, and the United States. The cooperation between the CEA and the EDF established France as one of the world-leaders in the field of natural uranium graphite gas-cooled nuclear power plants. France also established a comprehensive nuclear industry system, forming a collaboration between public institutions, state-owned enterprises, and private businesses. Companies including Groupe Schneider and Alsthom, as subcontractors, satisfied the construction needs of domestic nuclear power plants (Dänzer-Kantof and Torres 2013, 61–65). At the same time, France adopted a multi-technology route, which led to the introduction of US PWR technology.

The introduction of Westinghouse PWR technology in France began in 1958 when Charles de Gaulle regained power. After a comprehensive examination of the environment at home and abroad and confirming that France's military nuclear development would not be restricted by cooperation with the United States on civilian nuclear energy (Dänzer-Kantof and Torres 2013, 105–107), the administration approved the plan to jointly build a nuclear power plant with Belgium on November 28, 1958 (with France having a 50% controlling interest). Following negotiations, the plant was located at a bend in the Meuse River near the village of Chooz (Électricité de France 2001, 50–52). An open tendering process was adopted for the Chooz NPP. To participate in the bidding, Franco-Américaine de Constructions Atomiques (Framatome), which was established in December 1958 and was controlled by Groupe Schneider, obtained the technical license for the PWR from Westinghouse on February

16, 1959. Its 245 MW reactor design won the bid. Thus, the Chooz NPP became the first PWR nuclear power plant in France (Dänzer-Kantof and Torres 2013, 134–135). It was connected to the grid on April 3, 1967. In September of the same year, its generating capacity reached the 245 MW promised by Framatome. After improvements, the reactor generating capacity was increased to 305 MW, making it the most powerful PWR in the world at that time.

As a "turnkey" project, the PWR technology, whether regarding generating capacity increases or major technical innovations, was completed by Americans and strict confidentiality measures were enforced. The United States even used outdated manual control devices at the time (Dänzer-Kantof and Torres 2013, 134–135). However, the Chooz NPP was not a simple "turnkey" project. As subcontractors, French companies finished various equipment manufacturing tasks and made contributions to the evolution of the technology. The most important case in this regard was the pressure vessel. High-strength pressure vessels are prone to brittle fracture, and their design and manufacturing were major bottlenecks in light water reactor technology at that time. Benefiting from the manufacturing experience of steel pressure vessels applied in local graphite gas-cooled reactors, Groupe Schneider's Creusot factory innovatively used the finite element method to optimize the composition of the steel, successfully manufacturing qualified pressure vessels with new welding techniques. This aroused great interest from Westinghouse, promoting the resolution of brittle fracture problems by the company several years later and laying the foundation for a significant increase in light water reactor power (Dänzer-Kantof and Torres 2013, 136–137; Lamiral 1988, tome 1, 79–81, 356–357).

After the success of the Chooz NPP, according to the requirements of the project, another nuclear power plant was to be built in Tihange, Belgium, 30 kilometers southeast of Liège. The planned generating capacity was between 600 and 700 MW, and the Westinghouse PWR technology from Framatome was applied. In September 1967, the French government commission Production d'énergie d'origine nucléaire (PEON) adopted a positive attitude towards this cooperation, but requested deeper understanding and mastery of the technical information of PWR nuclear power plants (Lamiral 1988, tome 1, 104–105, 149–152). The French realized that holding a license might not be enough. Westinghouse did not have full confidence in the reliability of the design and sometimes found it difficult to explain the causes of accidents (Dänzer-Kantof and Torres 2013, 138; Floquet 1995, 90–91). On December 7, 1967, France held a *Conseil restreint* on civilian nuclear plans, approving the plan to jointly build the Tihange Nuclear Power Station with Belgium. Charles de Gaulle pointed out that France must gain experience in using enriched uranium reactors ("Relevé de décisions" [1967] 1988).

The Tihange Nuclear Power Station marked the beginning of France's comprehensive mastery of PWR technology. This project did not adopt the same unilateral introduction scheme as the Chooz NPP. In order to get command of this technology, EDF obtained more information than before about reactor operations and power plant design from Westinghouse (Dänzer-Kantof and Torres 2013, 171). Groupe Schneider would be entirely responsible for the Nuclear Steam Supply System (NSS) (Électricité de France 2001, 82). Framatome gained the right to manufacture nuclear reactor equipment instead of merely assembling equipment from Westinghouse. This allowed them to break the boundary between design and construction and undertake partial research on neutrons and the thermodynamics of reactors, thereby obtaining the ability to optimize related designs. Framatome's goal was to master the manufacturing technology of PWR equipment, including pressure vessels, reactor internal equipment, coolant pumps, auxiliary circuits, boosters, and so on, and make contributions to the development of the technology while further enhancing coordination among subcontractors (Électricité de France 2001, 171–175; Pintat and Chauvet 1985, 72–73). Framatome's optimization design of the reactor mainly focused on the three coolant pumps. The case and impeller of each pump were made of stainless steel to resist corrosion. The coolant pump adopted a centrifugal working principle with a power of 4630 kW and a rotational speed of up to 1500 r/min, sending coolant into the pressure vessel at a flow rate of 20,100 cubic meters per hour (Pintat and Chauvet 1985, 48–50). This design was considered superior to the one provided by Westinghouse (Dänzer-Kantof and Torres 2013, 173). On March 7, 1975, the Tihange Nuclear Power Station officially started to generate electricity and was connected to the grid, becoming the first nuclear power plant on the European continent to exceed 900 MW (Lamiral 1988, tome 1, 149–152; Pintat and Chauvet 1985, 51–52). The plant was the first true PWR power station designed and built by EDF and Framatome together, a representative of the apprenticeship of PWR technology in France before it achieved maturity.

During the construction of the Tihange Nuclear Power Station, France's energy circumstances underwent significant changes. Firstly, in 1969, due to cost and technical reasons, EDF officially announced the abandonment of the natural uranium graphite gas-cooled reactor route and instead adopted the light water reactor route for later nuclear energy development (Vichney 1969). Secondly, in 1973, the outbreak of the Middle East "Yom Kippur War" resulted in the implementation of an oil embargo by the Organization of the Petroleum Exporting Countries (OPEC), causing international crude oil prices to increase by 400 percent. The cost of importing oil to France surged from 15 billion francs in 1972 to 52 billion francs in 1974, which affected domestic industrial development and the trade balance, and severely hit the traditional electric power industry that relied on heavy oil. As the consumption of electricity in France continued to rise, the competitiveness of nuclear power greatly increased. The production cost of electricity generated by light water reactors dropped to 65% of that of traditional thermal power plants, and the construction cost of nuclear power plants decreased to 9.7 centimes/kWh, while that of heavy oil power plants was 13.3 centimes /kWh (Mentré 1978). On March 6, 1974, President George Pompidou, Charles de Gaulle's successor, convened an inter-ministerial committee and approved EDF's plan to invest in thirteen 900 MW nuclear power units to meet the expected annual power consumption of 420 TWh by 1985. By that time, 75% of France's electricity would be provided by nuclear power (Dänzer-Kantof and Torres 2013, 286–290). This meeting not only established France's pattern of relying on nuclear energy as its main means of power generation but also accelerated its absorption of PWR technology. France and Westinghouse entered into negotiations to transform Framatome from license holder to technology partner in 1982 and to acquire political, industrial, and commercial freedom. CEA purchased 30% of Westinghouse's stake in Framatome ("Evolution du capital" [1984] 1988, 205–206), and in November 1976, Framatome, CEA, and EDF signed a research and development agreement with Westinghouse to jointly promote innovation of PWR technology. The four parties planned to invest 100 million francs annually, and related work was carried out by different laboratories assisting each other (Coudray, Girard, and Mathias 1978; Lamiral 1988, tome 1, 267–268). Subsequently, new agreements were signed between 1981 and 1982, establishing a "communicative technology cross-licensing system" with the United States (Lamiral 1988, tome 1, 270–271). Westinghouse provided Framatome with all the required knowledge about PWR technology, and American experts went to the factories or construction sites to provide on-site guidance, participating in the testing and debugging of the reactors. Framatome's engineers were integrated into the Westinghouse design or construction teams for long-term training. In addition, with the approval of the US government, Framatome would be able to export PWR technology (Coudray, Girard, and Mathias 1978). These measures became the key to the comprehensive absorption and localization of PWR by France, building up its independent position in this technology.

During the construction of the Tihange Nuclear Power Station, France also made technical adjustments and developed the CPY technology. The new units were based on those at the North Anna 1 Power Station in the United States, and the two technologies were basically the same, using three cooling loops. However, the main pump flow of the former was increased, and the total generated power was 5% higher than that of the latter. France also adopted a dual-unit layout, with two reactors sharing a nuclear auxiliary building, with the turbo generator parallel to the reactor axis.[5] In

5 Internal document: Chinese Atomic Power Plant Technical Inspection Team, *Faguo yashuidui hedianzhan jishu* 法国压水堆核电站技术 [French PWR Technology], edited by the Science and Technology Intelligence Institute of the Ministry of Water Resources and Electric Power, August 1978, 1–4.

order to ensure the smooth progress of construction work, EDF innovatively proposed the concept of "standardization," that is, to reduce costs and improve quality through the series effect of equipment construction (Hug 2009, 23–24). EDF used the same technologies as much as possible to ensure delivery time and supply reliability while shortening construction time (Benat and Joly 1978). "The safety of nuclear power plants also benefited greatly from standardization and related concepts, because it allows time for analysis and thinking before introducing changes and develops safety rules in an orderly and consistent manner based on considering the actual consequences at the project level. It also enables operators to have a better understanding of the system, which is essential for daily safety" (Hug 2009, 24).[6] Large-scale PWR nuclear power plants construction in France was divided into several series: the first batch of 900 MW reactors was the prototype for this series, known as "Contrat de Programme n°0" (CP0); the tangentially-arranged eighteen reactors were designated as "Contrat de Programme n°1" (CP1); and the ten radially-arranged reactors were called "Contrat de Programme n°2" (CP2). They all used the same type of reactor and turbine unit. The CP1 and CP2 series were later referred to as CPY (Regroupe les Contrats de Programme n°1 et 2 des tranches nucléaires 900 MW). After improvements by Framatome, the 900 MW three cooling loop design M310 was established as a model to be exported, with better safety performance and economic value. In order to cope with the huge nuclear power plant construction plan, the French nuclear industry greatly increased in scale. Creusot invested in a new plant in 1976 to ensure an annual production of eighteen to twenty-four steam generators, eight boosters, and eight pressure vessels (Coudray, Girard, and Mathias 1978; Lamiral 1988, tome 1, 361–363). Alstom-Atlantic, established through merger, had become one of the world's largest turbine generator manufacturers by 1979, with a production capacity of 10 GW/year, next only to General Electric (20 GW/year) and Westinghouse (12 GW/year) (Chareyron and Fritsch 1978; Lamiral 1988, tome 1, 361–362).

The success of the "CP" series marked the accomplishment of France's absorption of US PWR technology and resulted in a significant increase in its nuclear equipment manufacturing capabilities. France was thus equipped to put products on the international market. It was also during this period that China began to contact France concerning nuclear power plant construction and the importing of relevant technology.

6 "De fait, la sûreté a tout à gagner à la standardisation et aux notions qui en découlent, car elle laisse le temps de l'analyse et de la réflexion avant l'introduction des changements et permet une évolution ordonnée et cohérente des règles de sûreté, appuyée sur l'examen des conséquences pratiques au niveau des projets. Elle donne en outre à l'exploitnt une bien meilleure connaissance des systèmes, facteur essentiel de la sûreté quotidienne."

2 Negotiations among China, France, and the United States on the introduction of French PWRs into China

Unlike regular scientific or industrial projects, the decision-making process for Sino-French nuclear cooperation was always led by the two governments, and thus evidently influenced by politics and diplomacy. The initial contact regarding this cooperation can be traced back to the Conférence Nucléaire Européenne held in Paris in April 1975. France attached great importance to the participation of the Chinese delegation, making clear its intention to cooperate with China in the field of nuclear power. For instance, prior to the conference, France had extended multiple invitations to China in the hope of gaining political support. Jacques René Chirac, the prime minister of France at the time, personally received the Chinese delegation, and during the reception, it received high-level treatment, with the head of the delegation invited to sit in the front row. During the conference, the delegation also visited French nuclear power plants, component manufacturing factories, pressure vessel workshops, steam generator workshops, and other facilities. France proactively offered to sell China natural uranium graphite gas-cooled reactor technology, but also mentioned that the direction of the research team would change within a year, making it difficult to purchase later.[7] This proposal did not receive a positive response from China. In fact, as mentioned earlier, France had abandoned graphite gas-cooled reactor technology as early as 1969, and China likely had obtained relevant intelligence about this (Liu 2019). Furthermore, during the conference, the Chinese delegation learned about the PWR technology imported by France from the United States and France's goal of generating over 70% of its national electricity by nuclear power by 1985. They also obtained technical information about PWRs.[8] It is thus evident that China could not accept the graphite gas-cooled reactor technology that had been phased out by France. Of course, the start of Sino-French nuclear power cooperation was also related to the support of national leaders. Deng Xiaoping attached great importance to the development of cutting-edge defense technology and consistently supported the development of the nuclear industry and nuclear power. Shortly after the Conférence Nucléaire Européenne in 1975, he was invited to visit France, marking the first official visit by a Chinese leader to a Western country. During his visit, he toured the Marcoule Atomic Energy Center, where the general manager and technical director introduced the

7 Observers Group Participating in the Conférence Nucléaire Européenne (参加欧洲核能会议观察员小组), "Outline of the Observers Group Participating in the Conférence Nucléaire Européenne" (参加欧洲核能会议观察员小组汇报提纲), June 11, 1975. B26-2-13, Shanghai Municipal Archives, Shanghai.

8 Observers Group Participating in the Conférence Nucléaire Européenne, "Outline of the Observers Group Participating in the Conférence Nucléaire Européenne," June 11, 1975. B26-2-13, Shanghai Municipal Archives, Shanghai.

advanced technologies of the center's nuclear reactors. This openness encouraged China to pursue international cooperation plans.

It took approximately five years for China and France to determine the appropriate technical solution for Chinese nuclear power plants, during which important issues such as US technology licenses and participation by British companies were resolved. China's in-depth contact with French PWRs occurred in 1978. In January 1978, French Prime Minister Raymond Barre visited China and formally proposed the sale of PWRs to China. The original intention behind this proposal was not to transfer the technology to China, but rather to reverse the declining trend of French trade with China through the sale of high-tech products.[9] Consequently, from February 1 to March 8 of that year, a Chinese delegation consisting of seventeen experts was invited by the French Ministry of Industry to conduct a technical investigation of atomic power plants. They inspected the research, design, manufacturing, construction, and operation of PWRs imported by France from the United States. During this trip, the Chinese delegation visited three PWRs, seven manufacturing plants, and one nuclear research center. They also held discussions with CEA, EDF, Framatome, and Alstom-Atlantic, obtaining a large amount of information on the design and production of major equipment, reactor safety research, waste treatment, as well as France's considerations in selecting plant sites. This investigation provided the delegation with a deeper understanding compared to their visit in 1975, and they concluded that France, relying on PWR technology patents acquired from Westinghouse, had rapidly developed nuclear power based on partial innovation. The construction of French PWR nuclear power plants had been carried out systematically, with standardized and serialized production of major equipment. This not only had reduced costs and shortened manufacturing cycles but also had improved operational reliability and safety. France's nuclear power development was characterized, they observed, by self-reliance and would soon free itself from the US and Soviet control over nuclear fuel, achieving self-sufficiency and the ability to export.[10] Although at that time, France's European Gaseous Diffusion Uranium Enrichment Consortium (Eurodif) enrichment plant had not yet been completed, it served as an important basis for demonstrating the integrity of its nuclear industry system to China and the possibility of cooperation in the field of nuclear fuel.[11] After returning to China, the delegation recommended importing two 900 MW nuclear

9 French Prime Minister Barre's Trip to China, January 13, 1978, E.O. 11652: XGDS-L, National Archives and Records Administration, in Access to Archival Databases (AAD).

10 Internal document: Chinese Atomic Power Plant Technical Inspection Team, *Faguo yashuidui hedianzhan jishu* 法国压水堆核电站技术 [French PWR Technology], edited by the Science and Technology Intelligence Institute of the Ministry of Water Resources and Electric Power, August 1978, 1–4.

11 Mission éventuelle en Chine de Cogema, le 27 aout 1981, 2882TOPO/2934, Les Archives du Ministère des Affaires étrangères (AMAE).

power units from France and constructing the Su'nan Nuclear Power Plant in Jiangyin, Jiangsu Province.

The news of the sale of nuclear power plants to China by France drew considerable attention from the United States. On the one hand, the United States held the patents for PWR technology, and prior to the new agreement between France and the United States on January 22, 1981, France still needed to submit applications to Westinghouse when conducting international trade in nuclear power plants.[12] On the other hand, even with the agreement in effect that PWR technology could be transferred even to China, the key issue was that China had not signed the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and had not joined the International Atomic Energy Agency (IAEA), and thus was not bound by relevant international systems. China also had laid down conditions for cooperation: it did not recognize the clauses proposed by the United States for the regular inspection of nuclear power plants, so it could not directly purchase the technology from Westinghouse. France also made the same request and hoped that the spent fuel would be handled by the French side, but China refused. The US government was concerned that China would use this technology for nuclear submarine development and increasing plutonium production. Therefore, there was no consensus on whether this plan could obtain a waiver from the Coordinating Committee for Multilateral Export Controls (COCOM).[13] However, the United States could not oppose the plan outright. Against the background of the easing of Sino-US relations and the Franco-American alliance, to do so might have a negative impact on bilateral relations, especially as it could lead to France cutting ties with Westinghouse and the United States, losing its "nuclear monitoring" of France. In addition, if this opportunity were managed properly, the United States would convey a positive attitude towards supporting China's modernization.[14] France also let the United States know that the nuclear power plant would be a "turnkey" implementation, thereby reducing the possibility of China obtaining sensitive technology.[15] After weighing the options, the US government agreed that it would not oppose the transaction, as long as China provided written assurances that the nuclear power plant would be used for peaceful purposes, and did not raise any objections during the COCOM review. On December 7, 1978, France submitted China's formal statement to the United States. The

12 Meeting with Guiringaud on French Sale of Nuclear Reactor to PRC, November 4, 1978, E.O. 11652: XGDS-1, in AAD; Vente de centrales nucléaires à la Chine, le 10 février 1981, 2882TOPO/2934, AMAE.

13 Prospective French Nuclear Reactor Sale to PRC, April 4, 1978, E.O. 11652: GDS, in AAD.

14 Prospective French Nuclear Reactor Sale to China, June 30, 1978, E.O. 11652: GDS, in AAD; Meeting with Guiringaud on French Sale of Nuclear Reactor to PRC, November 4, 1978, E.O. 11652: XGDS-1, in AAD.

15 Secretary's UNGA Bilateral with French: Nuclear Plants for China, October 3, 1978, E.O. 11652: GDS, in AAD.

statement read: "The two power plants, transferred equipment and materials will be used entirely for peaceful purposes, namely for power generation. The governments of both countries will ensure that their competent authorities take special protection measures within their respective areas of concern to ensure the physical safety of the transferred materials."[16] In the same month, Deng Xiaoping met with the French and agreed to purchase two units. Framatome and Alstom-Atlantic then submitted a large bid for the Su'nan Nuclear Power Plant project. By the end of the year, the technical negotiations between China and France were completed, and business negotiations were conducted in January 1979. However, due to China's economic restructuring in 1979 and the nuclear power plant accident in the United States, the plan was shelved.[17]

The demand for PWRs in Guangdong Province provided an opportunity for their introduction. As the power industry in the province had not been able to satisfy the needs of economic development for some time, Guangdong was very proactive in planning the development of nuclear power. In April 1980, China and France resumed discussions and shifted their focus to building nuclear power plants in Guangdong.[18] In October of the same year, French President Giscard d'Estaing visited China and negotiated the investment conditions for nuclear power plants with the Chinese government, formally agreeing to sell the plants. Guangdong Province proposed to sell part of the electricity to Hong Kong, which would not only help to solve the problem of the foreign exchange imbalance but also help to repay the foreign debt incurred for building the plants. Guangdong Power Company contacted China Light and Power Company (CLP) in Hong Kong, and the *Joint Feasibility Study Report for Cooperating on Nuclear Power Plants in Guangdong Province* (在广东省合营核电站可行性研究联合报告) was submitted for review in 1981 (Wang 2001).[19] This plan changed the model of state investment in major projects and instead brought about the introduction of a complete set of nuclear power plants through the method of "borrowing money to buy chickens,

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16 French Nuclear Sale to PRC, December 7, 1978, E.O.112065: GDS (SMITH, GERARDR), in AAD.

"LE GOUVERNEMENT CHINOIS CONFIRE QUE CES DEUX CENTRALES, LES EQUIPEMENTS AINSI QUE LES MATIERES TRANSFERES NE SERONT UTILISES QU'A DES FINS EXCLUSIVEMENT PACIFIQUES, PUR LA PRODUCTION D'ELECTRICITE.

LES DEUX GOUVERNMENTS VEILLERONT A CE QUE LEURS AUTORITES COMPETENTES PRENNENT, CHACUNE EN CE QUI LES CONCERNE, LES DISPOSITIONS SPECIALES DE PROTECTION, ASSURANT, AU NIVEAU APPROPRIE, LA SECURITY PHYSIQUE DES MATIERES TRANSFEREES."

17 Internal document: Jiangyin Power Supply Bureau Editorial Team (江阴市供电局修志组). 1990. *Jiangyin Shi dianli gongye zhi zhengqiu yijian gao* 江阴市电力工业志 征求意见稿 [The Draft of *Jiangyin Electric Power Industry Chronicle*], 1-18-19; Centrales nucléaires, le 2 mai 1983, 2882TOPO/2934, AMAE.

18 Centrales nucléaires, le 2 mai 1983, 2882TOPO/2934, AMAE.

19 Centrales nucléaires, le 2 mai 1983, 2882TOPO/2934, AMAE.

raising chickens to lay eggs, selling eggs to repay the debt" (Wang 2001).[20]

From 1982, China and France again entered into in-depth exchanges on the introduction of nuclear power plants. On August 19, a French nuclear delegation visited China.[21] From September 29 to October 20, a delegation from the Chinese Ministry of Nuclear Industry was invited to visit France. The Turbo-Generator Conference organized by Alstom-Atlantic was held in France from October 20 to 23, and representatives from China's Ministry of Nuclear Industry, relevant organizations in Guangdong Province and scientists who had established cooperation between China and France in the nuclear energy field were invited to attend, the international travel expenses being paid by France. These measures increased France's bargaining power in the Guangdong nuclear power project.[22] In December, China decided to build the Daya Bay NPP. After it was put into operation, in consideration of the loan repayment foreign exchange balance, 70% of the actual electricity generated would be sent to the Hong Kong grid and 30% to the Guangdong grid (Chen 1994, 15).

On February 4, 1983, Andre Caillault, the deputy head of the Nuclear Power Export Department of the Equipment Division in EDF, led a delegation to China to hold talks with the Chinese side on a number of issues, including preliminary research on the construction of nuclear power plants, personnel requirements and technical levels during the research period, nuclear power plant costs, research costs for technical services, the organization of the construction sites, the form of cooperation, and the type of contract envisioned.[23] In the March meeting, Alstom-Atlantic made it known that they could transfer technology for the conventional island equipment to China before the formal contract was signed.[24] During the visit of French President François Mitterrand to China in May, a memorandum of understanding was signed between China and France for nuclear power cooperation.[25] In June, China and France confirmed the purchase of four nuclear islands, two of which were to be built at the Daya Bay NPP. To make the conditions for technology transfer acceptable to China, Framatome agreed to the principle of joint production and maximum utilization of China's industrial technology and capabilities proposed by China, while reserving the right to intervene and refuse in case of non-compliance with specifications.[26]

An episode during this cooperation led to the supply of conventional island

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20 "借钱买鸡，养鸡生蛋，卖蛋还钱。" Centrales nucléaires, le 2 mai 1983, 2882TOPO/2934, AMAE.

21 Mission nucléaire, le 16 aout 1982, 2882TOPO/2934, AMAE.

22 TD, Pékin, no. 1362, le 22 septembre 1982, 2882TOPO/2934, AMAE.

23 Mission en Chine d'EDF, le 18 janvier 1983, 2882TOPO/2934, AMAE; Mission en Chine d'EDF, le 24 janvier 1983, 2882TOPO/2934, AMAE.

24 Mission en Chine de M.Desgeorges, P.D.G. d'Alsthom Atlantique, le 2 mars 1983, 2882TOPO/2934, AMAE.

25 Coopération nucléaire franco-chinoise, le 4 juillet 1983, 2882TOPO/2934, AMAE.

26 Mission en Chine de la Délégation Framatome, le 20 juin 1984, 2882TOPO/2934, AMAE.

equipment being obtained by the United Kingdom, resulting in China eventually signing three major contracts for equipment supply and engineering services with Framatome, General Electric Company PLC (GEC), and EDF. As mentioned earlier, the plan favored by France was to have all equipment supplied by France. However, the United Kingdom did everything it could to win the contract for the conventional island equipment for GEC, with Baroness Thatcher and the UK Foreign Secretary making demands that included the threat that Hong Kong would not purchase the electricity generated (Torres 2013, 41). In the end, after weighing various factors, China endorsed the proposal that the United Kingdom supply the conventional island equipment, in which the high-pressure cylinder of the turbine and the generator were "prototypes," and some auxiliary machines were also manufactured for the first time. Following these protracted negotiations, the construction of the Daya Bay NPP started in 1986.

3 The Daya Bay NPP: Led by French key technologies and implemented with Chinese cooperation

As the largest international cooperation project in China at the time, the engineering tasks and responsibilities for the Daya Bay NPP were divided between the participating Chinese and French entities from the beginning of the construction planning. Firstly, the design work was contracted to EDF, who assumed overall technical responsibility. This included the overall design of the nuclear power plant, coordinating the various equipment supply contracts, the procurement and design of all supporting facilities, and civil design for the nuclear island. Secondly, equipment procurement was divided into three parts: nuclear island equipment, conventional island equipment, and all supporting facilities. During the procurement process, EDF was responsible for drafting the procurement specifications for the first two parts, reviewing the technical documents for bidding, and participating in technical negotiations for the contracts. At the same time, EDF accepted agency offers for the procurement of all supporting facilities, including basic design, relevant bidding and technical documents, technical negotiations, and subsequent technical management, charging management fees proportionally. Thirdly, construction and installation were conducted through bidding. EDF was responsible for drafting the bidding specifications and could choose either domestic Chinese or foreign cooperation methods or hire foreign companies for technical support. In addition, EDF was entrusted with overall technical responsibility for commissioning and startup of the nuclear power station. During the commissioning activities, both the French and Chinese sides dispatched a number of professionals to form a commissioning team to work together. In order to develop the working capabilities of the Chinese commissioning team, the work of unit 1 was mainly carried out by personnel dispatched by EDF, while Chinese personnel were primarily responsible for unit 2 (Shen 1994, 19).

In terms of technology, compared to the Qinshan NPP, which was mainly constructed by the Chinese, the technology used in the Daya Bay NPP had been tested and improved, and was more advanced and mature. The design of the Daya Bay NPP took reference from the Gravelines NPP units 5 and 6, which belonged to the CP1 series of plants built in France in the mid-1980s, and incorporated improvements made after the Three Mile Island accident in the United States and the Chernobyl accident in the Soviet Union. As the project progressed, some technologies were adjusted, including the adoption of operational experience feedback from similar 900 MW nuclear power stations in France up to 1989. Overall, the Daya Bay NPP matched the international level of nuclear power technology in the 1980s (Chen 1994, "Preface").

Through international cooperation primarily with France and the United Kingdom, equipment for the Daya Bay NPP was imported and the construction was contracted to France. The nuclear island adopted the 3-loop million-kilowatt-class PWR technology developed by Framatome, which was an evolved version of the CPY. Specifically, the M310 model was modelled on the French improved 900 MW PWR and designed with reference to units 5 and 6 of the Gravelines of the CP1 series. Its nuclear steam supply system was all sourced from CPY. In order to make the unit cost more competitive, Framatome further increased the thermal power of the nuclear steam supply system from 2785 to 2905 MW using the main pump and steam generator developed for the 1300 MW units in France, and raised the outlet steam pressure from 5.77 to 6.71 MPa to improve the thermal efficiency of the turbine generator set. This improved type of nuclear steam supply system was known as the M310 model. Feasibility studies were completed by Framatome between 1982 and 1983, and in March 1984, approval from French security authorities was obtained. Final confirmation was provided in the nuclear island supply contract for the Daya Bay NPP signed in 1986 (Shen and Qian 1999).

The Daya Bay NPP underwent various improvements and adjustments in the determination of plans and technical parameters:

a. Due to the spread of "nuclear fear" caused by the Chernobyl accident, Deng Xiaoping stated in July 1986 that "the central leadership has not changed its position on building the Daya Bay NPP and will not change it. The central government will pay full attention to the safety issues of the plant" (Wang and Hu 2004, 228).[27] As a result, the safety of the Daya Bay NPP was further enhanced. It adopted safety systems specifically designed for the M310 model, including the injection system, containment spray system, and auxiliary feedwater system. The containment design used a single-layer prestressed containment with steel lining.

27 "中央领导对建大亚湾核电站没有改变，也不会改变，中央会充分注意核电站的安全问题。"

b. The plant used advanced high-power and high thermal efficiency steam turbines. Over several decades of development, the power of the steam turbines in PWR nuclear power stations had reached the million-kilowatt level, while efficiency had increased from the initial 80% to nearly 90%. The thermal system efficiency also had increased from less than 15% to over 45%. Metal consumption and costs had decreased continuously, while steam parameters continuously improved (Chen 1994, 539). The new steam supplied by the nuclear island was saturated steam, and the initial parameters of the main steam of the Daya Bay NPP fell into the medium range. To achieve high power output, a large flow rate was required (Chen 1994, 547). The steam turbine used was a prototype unit from GEC in the United Kingdom, consisting of a double-flow high-pressure cylinder and three double-flow, double-exhaust low-pressure cylinders. The rated speed of the turbine was 3000 rpm, with a rated output of 900 MW when the cooling water temperature reached a maximum of 33°C, and the maximum continuous power output was 928.9 MW. When the average cooling water temperature was 23°C, the maximum continuous power output was 983.8 MW (Chen 1994, 555–560).

c. The reactor adopted the French L106A control rod drive mechanism, with sixty-one control rod drive mechanism components on each reactor (Shen 1993, 430). The first cycle fuel components and the first reload components for unit 1 were produced by Framatome, while the reload components after 1995 were produced by Yibin Nuclear Fuel Element Plant (YFP).[28]

d. The steam flow generated by the nuclear island was 5800 t/h, and the temperature of the steam entering the turbine was 276.7°C.

e. As an important project during the installation of the nuclear island, the installation of the main pipelines was undertaken by Framatome-Spie Batignolles, and the welding work was carried out by the French.

In addition to the nuclear island and conventional island, a nuclear power plant also includes many auxiliary facilities called Balance of Plant (BOP). In the procurement plan for all the auxiliary systems and equipment of the Daya Bay NPP, the suppliers, Framatome and GE, being responsible for the nuclear island and conventional island, did not agree to supply all the required equipment. They only agreed to provide several important supporting facilities, while more than half of the systems and equipment needed to be purchased separately. Moreover, the two suppliers were not responsible for coordinating the connection of all the supporting facilities. Due to various factors, including unsuccessful negotiations with EDF for the overall contract, the final solution was to entrust EDF with purchasing all the supporting facilities. Therefore, the procurement of supporting facilities was no longer part of a "turnkey"

28 Before 1996, the fuel reloading design was undertaken by Framatome.

project. EDF was in full charge of the entire process, ranging from equipment bidding, design review, and civil engineering design to equipment manufacturing quality supervision. They also managed the coordination of technology, while the Chinese side had control over the supporting facilities, equipment quality, and project progress. The advantage of this outsourcing approach was that China could fully absorb the feedback and experience derived from French nuclear power projects, and technically mature and reliable equipment could be procured. However, in practice, French-made equipment was prioritized, even if there were better alternatives available. For example, the use of sulfur hexafluoride combined electrical equipment was rejected on the grounds of the lack of operational experience in other countries. Additionally, in this outsourcing approach, the opinions of the owner's technical personnel had to be approved by EDF technical personnel before being submitted to the suppliers, which affected direct communication between the two parties (Shen 1993, 18–26). In total, there were twenty-seven individual projects within the BOP. China International Water & Electric Corporation (CWE) and China Energy Engineering Group Northeast No. 1 Electric Power Construction (NEPC) jointly established the Northeast Nuclear Power Construction Company, which undertook twenty-two of these projects. Among these twenty-two projects, only the gas storage station equipment was supplied by the 719 Institute, two gantry cranes were provided by Tianjin Hoisting Machinery Factory, three freight elevators were supplied by Schindler (China) Elevator, and metalworking equipment was provided by China Wuhan Equipment Company. The rest of the equipment was designed and supplied by companies from France, the United Kingdom, and Japan, with an emphasis on French suppliers (Shen 1993, 31–38). Thus, China's involvement in the BOP was very limited, Chinese firms providing only a small amount of the equipment.

In terms of the construction of the Daya Bay NPP, China participated in a significant number of equipment installation projects, gaining valuable practical experience under the guidance of foreign experts. The installation projects were divided into 628 systems, with 310 for the nuclear island facilities, 202 for the conventional island facilities, and 116 for the supporting facilities. Framatome-Spie Batignolles was the main contractor for the nuclear island installation, with China Nuclear Industry No. 23 Construction Company as the subcontractor. The conventional island installation was contracted to Shandong Nuclear Power Construction Company with technical support from GEC. Northeast Nuclear Power Construction Company of China was the main contractor for the installation of auxiliary supporting facilities, with technical support from the US company the Bechtel Corporation.

Therefore, although the transfer of Westinghouse PWR technology to China was laid out in relevant agreements, when it came to the actual construction of the Daya Bay NPP, China could only passively adopt the "unhooking of technology and trade" approach, which involved procuring complete sets of French nuclear power technology without obtaining the technology transfer rights. China participated directly in construction, benefiting from the technology spillover effect and achieving significant progress in engineering management, the training of talent, and standardization. For China, which previously lacked ready-made construction models and standards for nuclear power, participating in the construction process of the Daya Bay NPP provided an important learning process in a number of areas:

1. Through small-scale civil engineering subcontracting projects, China began to learn efficient management and implementation methods for large-scale projects. This was one of the most important practical gains.
2. Throughout the period of construction, China achieved significant progress in the training of talent, construction management, and commissioning. In addition to Chinese engineering personnel involved in the civil engineering aspects, many other professionals, including experts, scholars, engineers, and graduate students nationwide, were hired, forming a highly capable team for the construction and management of the nuclear power plant.
3. As for the training of talent, under the contract EDF carried out training abroad for the operating personnel. Once Chinese personnel had passed classroom and on-the-job training and obtained graduation certificates, they returned to China.
4. During construction, international engineering management procedures became more standardized, and modern, rigorous management practices were strictly implemented. This had a profound impact on the participating construction companies and related industries. As a result, the importance of management as a productive force come to be fully recognized, encapsulated in the phrase that construction involved "three-tenths technology and seven-tenths management" (三分技术，七分管理), and also that managing a nuclear power plant depended on "doing things according to 'the law'" (以"法"办事). Through gradual conceptual changes, Chinese enterprises transformed from using traditional experiential management to modern management methods, resulting in significant improvements in engineering quality and efficiency.
5. Naturally, the commissioning work for such a large-scale nuclear power plant was also extremely complex, covering a wide range of activities from units system to plant performance testing, surpassing the scope of commissioning work in domestic French nuclear power plants. This commissioning was mainly carried out by French personnel, with Chinese personnel providing support (Chen 1994, 555–560).

Overall, the design, construction, equipment supply, and personnel training of the Daya Bay NPP were led by EDF through an engineering total package contract, the French company assuming overall responsibility and playing a decisive role in the entire project. Although China was only involved in a small amount of civil engineering work during construction, efforts were made to digest engineering management and professional technical training knowledge to fulfill the central government's directive at that time, which was to explore a development path for China's nuclear power industry and improve China's ability to construct nuclear power plants. In addition, the Daya Bay NPP effectively transformed China's management from a traditional experiential approach to a modern one. Modernized management involved document management, material management, and construction process management, all of which were carried out through the establishment of a planning management system for overall control. Engineering at the Daya Bay NPP was conducted following certain procedures, which was completely different from the concentrated approach adopted in "728 Project," and in general would not under normal circumstances rely on overtime work to shorten the construction period. With advanced management practices, based on scientific foundations and strict procedures (including procedures for installation, management, and working), the project transformed the previous experiential and closed approach to an open, innovative, and outward-looking style of management, resulting in a significant improvement in construction efficiency, economic benefits, and engineering quality.

4 From the "integration of technology and trade" to independent innovation—Ling'ao Phase I and II Nuclear Power Plants

After the successful construction of the Daya Bay NPP, China continued to introduce nuclear power technology. However, a different approach was adopted to that of countries like France and Japan, which had used the model of integrating technology and trade to form their own national technical standards. Starting from the "728 Project," the first thirty years of China's nuclear power development lacked such integration of technology and trade and went through a period of exploration. In the mid-1990s, Qinshan Phase II, Ling'ao Phase I, Qinshan Phase III, and Tianwan Phase I nuclear power projects were successively launched, marking the "small-batch development stage" (小批量发展阶段) of China's nuclear power from 1997 to 2003. The technologies introduced during this stage were mostly purchased as complete sets, involving little deep-level technology transfer and application. Instead, China's progress in nuclear power technology mainly relied on its own technological iteration and innovation. Among these projects, Qinshan Phase II NPP, a 600 MW-class PWR nuclear power station, was independently designed and constructed by China based on the self-reliance experience gained from Qinshan Phase I and referencing the Daya Bay NPP. Its focus was on enhancing self-reliance capabilities and realizing the construction of large commercial nuclear power plants.[29] It was not until the Ling'ao Phase I NPP (main construction for which started in May 1997 and commercial operation in January 2003) that the era of realizing the "integration of technology and trade" in nuclear power technology transfer truly began.

Technically speaking, Ling'ao Phase I was not a simple replica of the Daya Bay NPP; the mode and level of the cooperation involved in its construction underwent essential changes. Although the initial plan for Ling'ao Phase I took into consideration technological progress and international competition, ultimately cooperation was with France, following refusal by the United States, and the power plant was constructed by its contractors following the Daya Bay model. When France built the Daya Bay NPP, although it had agreed to conduct technology transfer during the negotiation period, in actual practice, there was an "unhooking of technology and trade," and the technology was largely not transferred. It should be acknowledged that there was a considerable gap between China's nuclear science and technology and manufacturing capabilities and those of the industrially advanced countries during the construction of the Daya Bay NPP. Up until Ling'ao Phase I, China had not produced equipment for million-kilowatt-level nuclear power units, and its equipment design and manufacturing capabilities were relatively weak. Therefore, to achieve the localization of the production of nuclear power equipment and the independent construction of nuclear power stations, it was necessary to take the route of "technology introduction." In the early negotiations for the Ling'ao NPP, a proposal was made to fully transfer the technology without charge in order to achieve China's localization goals. Eventually, an agreement was reached whereby some equipment would be subcontracted for domestic manufacture. Considering that the localization projects were limited, China decided to start with the manufacturing technology of equipment or components with high technological content, thus mastering key technologies (Zeng and Chu 2003, 5). The major parts of the unit 1 nuclear island and conventional island equipment were all manufactured in Europe ("Ling'ao hedian shebei" 2003), with only a small number of components and devices being part of the localization project. For unit 2, the manufacture of the steam generator, voltage regulator, reactor internals, control rods, turbine, generator, and other important equipment were localized (Zeng and Chu 2003, Appendix 1, 35–40). These locally-manufactured components strictly followed relevant French standards and specifications during development and achieved a level that was basically aligned with international standards. This was a significant contribution toward the localization of million-kilowatt-level nuclear power station design and equipment, and also promoted the completion of the nuclear power equipment base in Sichuan. The technology of Ling'ao Phase I also kept up with the times, combining

29 Originally planned as a million-kilowatt nuclear power plant, various factors led to its final construction as a 600 MW plant.

feedback from the ten-year major overhaul plan of French nuclear power plants (LOT93) and the operational experience of the Daya Bay NPP, adopting a series of improvements that reached the mid-1990s international level for nuclear power (China Nuclear Power Engineering Co., Ltd. 2013b, 32). Furthermore, by absorbing and utilizing successful experience and management models from foreign nuclear power construction projects and based on the experience of the Daya Bay NPP, Ling'ao Phase I further established a set of advanced management practices, achieving independence in project management and partial design, construction and management, and commissioning and production arrangements alongside the localization of partial main equipment manufacturing.

It is worth noting that in the Ling'ao Phase I project, Chinese technology and key equipment played a greater role than that in the Daya Bay NPP. Given the low level of Sino-French technological cooperation in the construction of the Daya Bay NPP, the Ling'ao project, through the model of subcontracting large-scale equipment manufacturing, implemented significant technological improvements based on the introduction and absorption of advanced foreign technology, successfully achieving independence in engineering management, construction and installation, commissioning, and production preparation, as well as the localization of the production of some equipment. This laid a solid foundation for the exploration and formation of an independent technology route for the production of million-kilowatt-level nuclear power. Through preferential technology transfer agreements signed with foreign companies, Chinese manufacturing plants obtained the technology for manufacturing equipment and related technologies required for subsequent development. Such locally-produced nuclear power equipment included steam generators, voltage regulators, reactor internals, control rod drive mechanisms, and several major components of the main pipelines (excluding pressure vessels and main pumps) conforming to RCC-M international standards and reaching international manufacturing levels. By promoting the manufacturing of nuclear power equipment, China further strengthened and improved its nuclear equipment manufacturing industry, driving the technological progress of domestic enterprises and leading to continuous technological breakthroughs. The Dongfang Boiler Factory was a typical example of this process, achieving a significant breakthrough in the manufacture of key equipment for unit 2 of the Ling'ao Phase I NPP, including boron injectors, safety injection boxes, voltage regulators, and steam generators.[30] However, although the construction of the Ling'ao Phase I project accelerated China's mastery of million-kilowatt-level PWR nuclear power plant technology, China did not yet fully possess the

30 Dongfang Boiler Factory later undertook the manufacturing of key equipment for million-kilowatt nuclear power units at Ling'ao Phase II, Qinshan Phase III, Hongheyan, Ningde, Yangjiang, and other nuclear power plants.

capability for independent design and manufacturing.

In early 2005, the guidelines for the development of China's nuclear power industry shifted from "moderate development" (适度发展) to "active advancement" (积极推进) (Editorial Committee 2007, 9). While adopting world-class advanced technology, it began to focus on promoting the mainstream technology (PWR) route. The Ling'ao Phase II project, which commenced construction in December of the same year, was the only nuclear power project initiated during the Tenth Five-Year Plan period. It also served as a demonstration project for China's independently developed CPR1000 nuclear power technology, shouldering the historical mission of fully realizing the independence of China's nuclear power construction. Ling'ao Phase II had been strategically planned in embryonic form as early as 1996, with a focus on the principle of "taking the lead in international cooperation and introducing technology to promote localization."[31] It was officially approved in 2003, and two million-kilowatt-class PWR nuclear power plants were independently developed. The achievement of independent design for Ling'ao Phase II relied on several domestic nuclear power design centers, including the Second Research and Design Institute of Nuclear Industry, Nuclear Power Institute of China, Guangdong Electric Power Design Institute, the Design Institute of China General Nuclear Power Corporation (CGN), as well as technical support from well-known foreign nuclear power enterprises such as EDF, AREVA, and Alstom (China Nuclear Power Engineering Co., Ltd. 2013a, 7). In terms of technology, Ling'ao Phase II adopted for the first time the independently developed CPR1000 scheme based on the technological foundation of Daya Bay and Ling'ao Phase I. This self-developed CPR1000 technology was based on the introduction and absorption of the M310 model, incorporating new international requirements for PWR technology development and regulation, and was formed through continuous improvement and innovation.[32] Ling'ao Phase II also implemented a "component procurement" strategy to promote the ability of domestic enterprises to master the technology for manufacturing million-kilowatt-level nuclear power equipment. Building upon Ling'ao Phase I and in conjunction with France's second ten-year major overhaul plan, Ling'ao Phase II took measures to prevent and mitigate serious accidents, and implemented over 300 technical improvements. These included the first application of a digital distributed control system (DCS), an advanced main control room, cutting-edge nuclear fuel assemblies, half-speed turbine generator sets, increased core thermal margin, optimized reactor pressure vessel design, standard operating procedure (SOP), and 44

31 "以我为主、中外合作、引进技术、推进国产化。"

32 CPR1000 has since undergone significant technological improvements and hundreds of technical upgrades, further enhancing its safety and economic performance, with its main technical and economic indicators reaching the highest level among similar nuclear power units in other countries, approaching the level of third-generation nuclear power technology worldwide. See China Nuclear Power Engineering Co., Ltd. (2013a, 32–33).

other significant technical improvements (China Nuclear Power Engineering Co., Ltd. 2013a, 5–6).

It is worth noting again that the CPR1000 is a million-kilowatt-level nuclear power technology independently developed by China, one that played a pivotal role in the independent development of nuclear power, and is currently the primary technology widely used in the construction of million-kilowatt-level nuclear power plants generation II+ in China. Overall, the comprehensive technological, safety, and economic

Table 1: The role of France and China in designing and constructing nuclear power plants mentioned in this paper

	Reactor type	The United States	France	China
Chooz NPP	Westinghouse type 312	Unilateral introduction of technology	Manufactured some of the equipment.	
Tihange NPP	Westinghouse type 312, modified by France	Introduction of technology	Participated in design and manufactured core equipment. Started to fully master PWR technology, and develop CPY technology and standardization.	
Daya Bay NPP	Framatome M310, export model based on CPY technology		Sold complete sets of nuclear power technology without licensing technology, and was responsible for all engineering design, construction and equipment supply except for the conventional island (for which the British were responsible).	The "unhooking of technology and trade" approach resulted in China's partially participating in construction and equipment installation, and the development of a modern management system.
Ling'ao Phase I	Framatome M310		All major parts of unit 1's nuclear and conventional island equipment were manufactured in Europe.	Introduction of technology through the "integration of technology and trade" approach; localization of a small number of components and devices for unit 1; localization of major equipment for unit 2 and a series of technological improvement measures.
Ling'ao Phase II	CPR1000, China's independent brand, which was based on the introduction and absorption of Framatome M310 technology			By and large, formed the ability of NPP self-reliant design and equipment manufacturing localization, while completing several major technological improvements.

indicators of Ling'ao Phase II reached a level comparable to similar international nuclear power plants. By constructing the Ling'ao Phase II project, China established its own brand of independent nuclear power plant design and acquired domestic equipment manufacturing capabilities. In addition, comprehensive mastery of the improved million-kilowatt-level nuclear power plant generation II technology was accelerated.

From the late 1990s to the early twenty-first century, from the purely imported M310, China's PWR technology has gone through the construction of multiple nuclear power plants, as well as the introduction of equipment, the absorption of advanced technology, and independent innovation, before gradually developing into CPR-1000. The nuclear power technology of China underwent intensive testing and highly-efficient accumulation of expertise, and achieved the goals set during the construction of the Daya Bay NPP—realizing the industrialization of internationally advanced million-kilowatt-level nuclear power technology and laying the technical foundations for the research and construction of China's generation III nuclear power technology.

5 Conclusion

Nuclear power projects in all countries have undergone a long and complex process of mutual influence, with technology accumulation, transfer, and innovation, inevitably affected by factors such as international politics, economic development, and the local ecology. The prerequisite for the large-scale development of nuclear power is to improve its economic viability, with the key being the localization of nuclear power and the implementation of standardized, serialized batch construction and production. France and China are typical cases of nuclear power localization and large-scale development, yet they exhibit significant differences.

The development of France's nuclear power had inherent advantages, owing to the country's accumulation of relevant basic science and technology and its manufacturing capacity as an industrial powerhouse. From a technological perspective, despite the abandonment of the natural uranium graphite gas-cooled reactor route in 1969, EDF, which early on led France's nuclear power research, had been involved in the Five-Year Nuclear Energy Plan since 1953 in cooperation with the CEA, accumulating a wealth of experience in the design and manufacturing of nuclear power plants. Moreover, Groupe Schneider and Alstom, both core players in the construction of French nuclear power plant equipment, were well-established heavy industry enterprises founded in 1836 and 1928, respectively. Therefore, even in the face of a change in technological route, the French nuclear power industry was able to quickly develop the capacity to manufacture a complete set of nuclear power plant equipment and, while meeting the country's critical technological needs, provide the knowledge, technology, and industrial foundation for improvements in the design, processes, and materials required for the Westinghouse PWR. For France, the acceptance of nuclear power technology transfer in the 1970s was achieved in a context similar to that of the United States in terms of knowledge system and industrial strength, facilitating subsequent innovation and advancement as well as new breakthroughs in management. Through the CPY series, France embarked on its own independent path in the field of nuclear power technology, actively exporting French-style PWR to other countries. On the one hand, it has continuously developed nuclear power technology, and on the other, it has exported nuclear power plant construction and operational technology, nuclear fuel, and related nuclear power services, maintaining its international position as an important exporter of nuclear power technology.

China's nuclear power industry was launched based on the unfinished projects left behind after the Soviet Union withdrew its aid to China. Thus, it had to be self-reliant, adopting the approach of "walking on two legs" (两条腿走路), and building the Qinshan and Daya Bay NPPs employing completely different technological routes. The technological level of the Qinshan Plant may have been markedly below international advanced levels at the time, but was self-reliant and had a complete suite of supporting facilities. The Daya Bay Plant, on the other hand, relied on the introduction of a complete suite of equipment from France. It had relatively new technology, but the key one was kept confidential by France, posing potential risks. In addition, although the equipment purchased for the plant was expensive, technology transfer did not occur, a different situation to that which had occurred when France gained control over the Westinghouse PWR technology through advantageous licensing in the 1970s. Therefore, while the accumulation of nuclear power technology at the Qinshan Plant had established a knowledge system by which China could interact with the French nuclear power, and was of benefit to the introduction of the Daya Bay project, China was still in a markedly unequal position with regard to technology transfer with France. Although both nuclear power projects had their shortcomings, they held special value for the accumulation of China's nuclear power technology and its evolution, laying an important foundation for independent nuclear power development. From the negotiations during preparatory period of the Daya Bay Plant to the purchase of advanced equipment, installation, commissioning, and operation, China gradually formed its own operational technology, and made certain innovations and accumulations of expertise, further supplementing the technical foundation for future cooperation with France. Therefore, based on the accumulated long-term experience gained from the Qinshan Plant, the Daya Bay Plant, and the construction of subsequent nuclear power projects, China gradually solved the problems of the localization of PWR technology. This process no longer relied on exploratory technological iterations of the construction of the Qinshan Plant, but was driven by the technological upgrades brought about by a large number of new technologies and standards. Subsequently, through independent innovation (such as in Qinshan Phase II) and the introduction and absorption of key technologies (such as in the Ling'ao Phase I and II projects), continuous innovation led to the realization of the independently developed CPR1000 brand. China ultimately accomplished the localization of million-kilowatt-level PWR nuclear power plants, leading to mass construction and exports, and developed generation III nuclear power, becoming a major nuclear power in the international community.

In conclusion, both France and China have become major nuclear powers by introducing generation II PWR technology and ultimately forming independently developed brands. Since the development of nuclear power technology and the construction of nuclear power plants are closely related to the historical background of the times, national scientific and technological foundations, industrial strength, the international political environment, and economic power, the inherently complex nature of technology transfer played a crucial role in nuclear power development in France and China, having a major impact. The intersection of various factors led to the two countries embarking on vastly different paths, each with its own characteristics, making them typical cases of technology transfer in the field of nuclear power. With the acquisition of more data in the future, it will be worthwhile to further explore these issues at different levels.

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