NUKLEARFORUM SCHWEIZ
FORUM NUCLÉAIRE SUISSE

Nuclear Developments in China

A report by GUO Wentao

December 2015

The Swiss Nuclear Forum is a non-governmental association with the purpose of fostering the peaceful use and further development of nuclear power in Switzerland. Since more than 50 years, it has been promoting a factual and objective debate. The Forum serves as a platform for the science-based dialogue on nuclear technology, primarily among experts in academia, industry and administration, and including politicians, the media and the general public.

Publisher:
Swiss Nuclear Forum, P.O.Box 1021, CH-3000 Berne 14
Switzerland
Phone: +41 31 560 36 50, fax +41 31 560 36 59
info@nuklearforum.ch
www.nuklearforum.ch

Cover photo: shutterstock/Anton Balazh

This report is online:
www.nuklearforum.ch/guo-china

Preface

China has a history of developing nuclear power for more than 20 years. In 2015, four years after the Fukushima nuclear accident, China restarted its nuclear power projects. Recently, considerable progress has been made in the country's nuclear industry. Now it has become the most dynamic country in developing nuclear power and attracted widespread attention. In this report, I attempt to give a brief introduction of the entire nuclear system in China and provide readers with a good insight of China's nuclear power field.

This report is composed of 10 chapters. Chapter 1 is written by Prof. Li Guanxing from the China Nuclear Power Corporation in Beijing and revised by me with the latest data. The other 9 chapters are written by me. In this report, I try to avoid difficult technical terms and equations. Concise graphs and charts are used to make the interpretation easier to understand. It is suitable for people from different educational background to read, especially for nuclear supporters who are interested in China's nuclear industry. I hope that anyone who goes through this report will find it interesting and worth reading. All constructive feedback is cordially invited.

This report was written during my internship at the Swiss Nuclear Forum in Berne, Switzerland, from July to October 2015, being part of my master studies of Nuclear Engineering at the Swiss Federal Institute of Technology of Zurich (ETHZ). Before I came to study in Switzerland, I studied Nuclear Engineering during my bachelor in China and in France from 2010 to 2014.

I am greatly indebted to Dr. Michael Schorer and Max Brugger of the staff of the Swiss Nuclear Forum for their guidance and help during my writing this report. Thanks are due to them and to Matthias Rey both for their careful reading of various drafts and for many helpful suggestions.

Guo Wentao
Berne, December 2015

About the author

Education:

2014-2016	Master's student of nuclear engineering at the Swiss Federal Institute of Technology, Lausanne and at the Swiss Federal Institute of Technology, Zurich, Switzerland
2013-2014	Bachelor degree of Nuclear Engineering at Phelma of INPG, Grenoble, France
2010-2013	Bachelor degree of Nuclear Engineering at the Harbin Institute of Technology, China

Achievements:

April 2012	Third prize at Energy-Saving and Emission Reduction Competition in China
Feb. 2011	Third prize at MCM (Mathematical Contest in Modeling) in the U.S.

Contact: wentao.guo@epfl.ch

Table of Contents

Tables and Figures

Executive Summary

Based on the analysis of China's nuclear industry, this report aims to describe and forecast the status and challenges of China's front-end nuclear fuel industry, its back-end nuclear fuel industry, the research and development situation of the advanced nuclear reactor types and the research on fusion. Some related background knowledge is introduced in the corresponding parts of this report as well as comparisons of China with other countries. China's international cooperation in the field of nuclear industry is also discussed.

This report starts in its first part with the introduction of China's front-end nuclear fuel cycle. By summarizing the current situation of uranium mining, conversion, enrichment and fuel assembly fabrication in China and abroad, the author gives corresponding measures to deal with the challenges identified at present.

The second chapter focuses on the four nuclear fuel corporations in China. Some corporations mentioned in the first chapter such as the China North Nuclear Fuel Company and CNNC Jianzhong Nuclear Fuel Co., Ltd are introduced in detail including their history, location, major business, output and contribution to China's nuclear industry.

The subject of the second part of this report is to introduce China's back-end fuel industry. In chapter 3, the author highlights the problems Chinese scientists are faced with while developing the weakest link of China's fuel cycle system – the nuclear fuel reprocessing. With the increasing amount of spent fuel, nuclear fuel reprocessing will become a big market waiting to be developed.

Furthermore, in the fourth chapter, the author focuses on the scheduled high level waste repository in Beishan in Gansu Province and presents the nuclear waste disposal technologies for low level and high level wastes. The necessity of building the high level waste repository is illustrated and the technologies to do that are promising. The author also points out that the construction of the high level waste repository is both time-consuming and costly.

The third part mainly deals with introducing the advanced reactor types that are developed in China at present. This includes three Generation IV reactors – the Molten Salt Reactor, the Sodium-cooled Fast Reactor and the High Temperature Gas-cooled Reactor as well as a popular and promising reactor type: the Small Modular Reactor.

In chapter 5, the author analyzes the advantages and the development of the Molten Salt Reactor in China. Moreover, it is the author's view that the future of the Molten Salt Reactor in China is promising because China has already mastered some key technologies and the thorium resources are abundant.

Chapter 6 provides an overview of the Sodium-cooled Fast Reactor development in China. It presents up-to-date information on the China Experimental Fast Reactor in Fangshan near Beijing. The development strategy of the Sodium-cooled Fast Reactor is also mentioned.

Chapter 7 not only introduces the Shidao Bay High Temperature Gas-cooled Reactor in Shandong Province, but also talks about the cooperation on the High Temperature Gas-cooled Reactor between China and other countries such as the United Arab Emirates, the Kingdom of Saudi Arabia and South Africa. China has self-owned intellectual property in this field and it is one of those advanced countries in developing the High Temperature Gas-cooled Reactor.

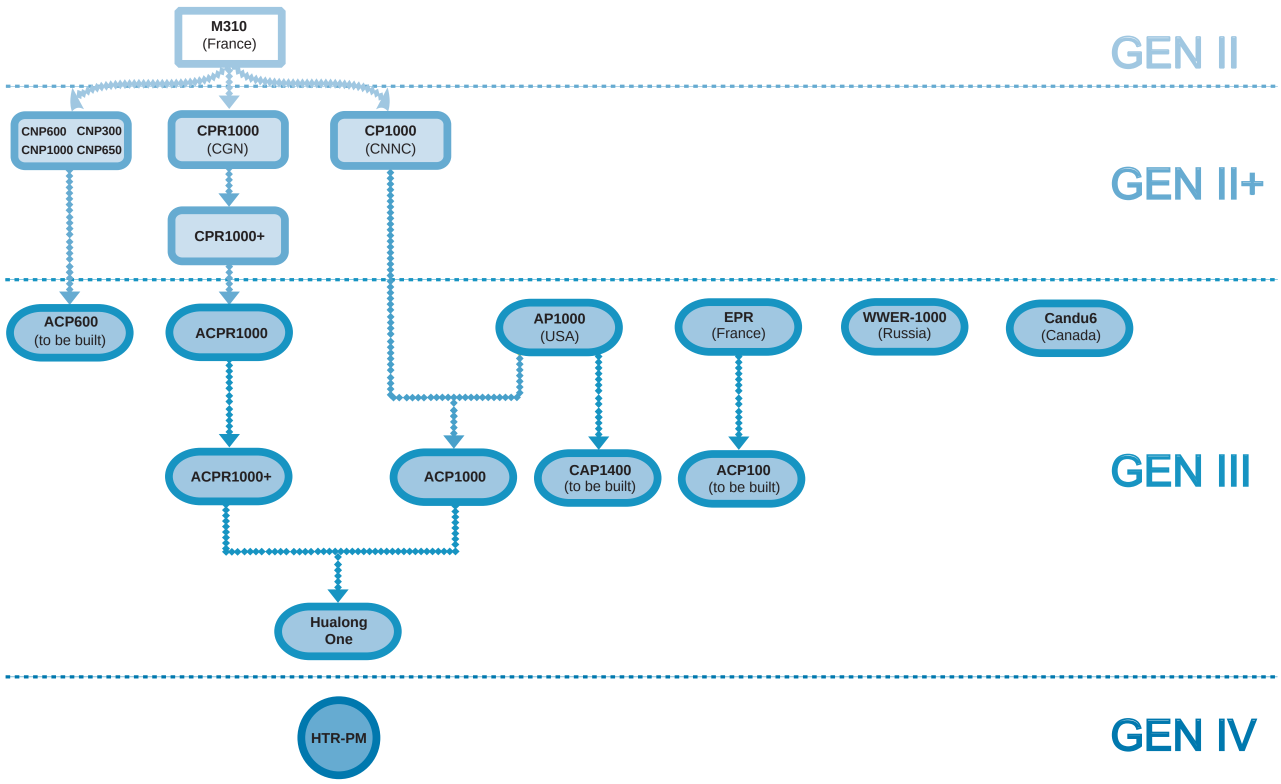
Chapter 8 reviews the characteristics and the application of the Small Modular Reactor. The author tries to summarize the safety, project schedule, challenges, difficulties and international cooperation on the China's Advanced 100 MWe Pressurized Water Reactor. Compared with the mature large-scale reactors, the Small Modular Reactor needs more time to achieve better commercial prospects.

In the last part, the author discusses the state of art in the fusion reaction development, including thermonuclear fusion and the so-called Low Energy Nuclear Reactions (LENR). The objective of chapter 9 is to outline the research and development situation of the ITER project and especially China's contribution to ITER. The most important contribution is the Experimental Advanced Superconducting Tokamak developed in the Institute of Plasma Physics, Chinese Academy of Sciences in Hefei. It is one of the world's most advanced devices in exploring controlled nuclear fusion.

The last chapter is a brief introduction of the LENR, also known as "cold fusion". The research was put forward in 1989, but the debate whether it is real has not yet come to a conclusion. The author describes the LENR development worldwide and China's major contribution to this field. China's attitude towards this unproven technology is also revealed at the end of this chapter.

Given the above information, the conclusion can be drawn that despite some drawbacks in the back-end fuel industry, China has by now formed a relatively complete nuclear industry system and actively participates in reactor research and development activities, including designs of fusion reactors. Some Chinese technologies are even in a leading position worldwide. As nuclear technologies become more and more mature in China, nuclear power will gradually increase its proportion in the gross electricity generation. Thus, it will occupy a major position in the future energy industry in China. As an affordable, reliable and clean energy source with high capacity, it is believed that the development prospect of nuclear power in China is promising.

Overview of the commercial nuclear reactor systems built and developed in China



Sources: Wikipedia, nuclearplanet.ch and chinese websites
Compiled in September 2015

Map of nuclear facilities in China

1

Status and Future of China's Front-End Nuclear Fuel Cycle Industry

By Prof. Li Guanxing, China Nuclear Power Corporation, Beijing*

The nuclear fuel cycle is the process of acquiring, using, reprocessing and recycling nuclear fuels. The cycle can be broken down into two parts: the front-end cycle and the back-end cycle. The front-end nuclear fuel cycle includes uranium mining, conversion, enrichment and fuel assembly fabrication [1].

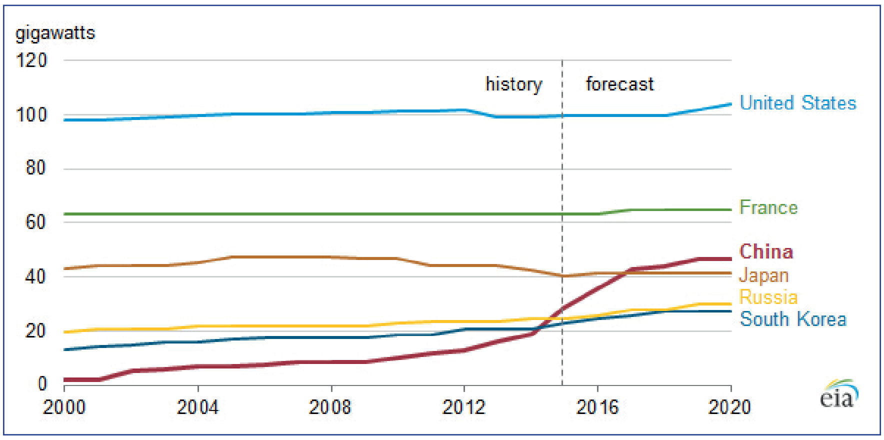


Fig. 1 – Nuclear generating capacity for the top six countries (2000–2020) [2]

1.1 Opportunity Opens to China's Nuclear Fuel Cycle Industry

The active promotion of nuclear power development in China has created unprecedented opportunities for the nuclear fuel cycle industry. Fig. 1 shows nuclear generating capacity for the top six countries (2000–2020).

Today the policy of actively promoting the development of nuclear power in China is well established. According to the "World Energy Outlook 2014", issued by the International Energy Agency, China is expected to build even more nuclear power plants over upcoming years.

Zhang Guobao, the vice president of the National Development and Research Center (NDRC) and also president of the country's National Energy Administration, has stated numerous times the need to readjust the medium and long term plan for China's nuclear industry, to strengthen the development of power plants in the coastal areas and to scientifically plan the development of nuclear power resources in inland China. He also announced a 5% target for nuclear power as a proportion of overall electricity production in China. Should China continue to actively promote the development of nuclear power, it is clear that the country is on its way to become the world's biggest producer of civil nuclear power. In step with this, the nuclear fuel cycle industry in China will see significant development opportunities, with the potential to grow into the largest nuclear fuel cycle market in the world. This is a basic fact one must keep in mind when analyzing and planning for the nuclear fuel industry, as it will also have a significant impact on the market structure of the nuclear fuel cycle industry.

However, along with the opportunities come tough challenges.

1.2 Supply of Natural Uranium

1.2.1 Natural Uranium Demand

As of June 1, 2015, there were 438 nuclear power plant units operating around the world. The total installed capacity amounted to 379 GWe [3]. The demand for uranium stood at 61 600 tons in 2012 [4]. In 2015, the Nuclear Energy Agency (NEA), a specialized agency within the Organization for Economic Co-operation and Development (OECD), published the "Red Book" titled "Uranium 2014 – Resources, Production and Demand". The Red Book estimated that 5.9 million tons of conventional uranium at a cost of under 130 US$/kg have been found, with speculative additional uranium reserves amounting to 13.54 million tons. Looking at unconventional uranium, it estimated that up to 21.39 million tons of uranium could be extracted from phosphate rock.

---

* Revised by Guo Wentao

1.2.2 Development and Utilization of Uranium Resources

According to the second National Uranium Resource Evaluation, which is currently ongoing, China has a significant quantity of uranium reserves – possibly over 2 million tons, while the proven resources of uranium could only fuel the reactors expected to be built by 2020.

According to the "Red Book 2014", China produced 1450 tons of uranium in 2012. It is generally recognized that ten years will be needed in geological prospecting of nuclear resources, including general exploration, specific exploration and official submission of the quantities of nuclear resources reserves. It takes four years to build a uranium mine. Meanwhile, the output volume of natural uranium still remains small. In order to meet the demand created by its nuclear power development, China will have to make significant efforts to secure the uranium supply.

At present, China has a number of overseas uranium exploration projects underway. The China Natural Nuclear Corporation has officially concluded four agreements with countries such as Niger, Namibia, etc., and signed multiple cooperation programs with Algeria, Kazakhstan and Jordan. The Chinese enterprises taking part in overseas uranium development are the China National Nuclear Corporation, Sinosteel Corp., the China Guangdong Nuclear Power Corporation, and PetroChina.

The China Nuclear Energy Industry Corporation has developed a stable international trade system to procure natural uranium. It is internationally competitive and has secured smooth uranium trade channels. At present, Chinese uranium development overseas is being conducted following the prescriptions of the China Medium and Long Term Development Plan for Nuclear Power (2005–2020). Uranium resources have been secured through domestic production, overseas exploration and the international uranium trade.

1.2.3 Challenges with the International Community

1.2.3.1 Challenges with Countries Holding Huge Uranium Resources

The countries holding the largest uranium resources are striving to shift from being natural uranium exporters to added-value uranium exporters. Kazakhstan is among these countries. Kazakhstan plans to secure 30% of the international market for uranium fuel by 2030. In July 2006, Kazakhstan and the Russian company Tenex signed an agreement to co-establish an international uranium enrichment center in Angarsk, Russia. In December 2006, Kazakhstan signed an agreement with China Guangdong Nuclear Power Corporation (CGNPC), whereby the uranium supplied must be processed into UO_2 in Kazakhstan before it is sent to China. Kazakhstan is actively building infrastructure to handle the front-end of the nuclear fuel cycle.

In May 2007, Kazakhstan and the Canadian company Cameco signed an agreement to co-establish an UF_6 enrichment plant with a capacity of 12 000 tons/year. In June 2007, Kazakhstan bought a 10% equity stake of Westinghouse in the USA. The Ulba Metallurgical Plant in Kazakhstan has built a nuclear fuel fabrication plant with the Toshiba-Westinghouse Consortium as its technical partner.

Other countries in the world are actively promoting their domestic uranium strategy in order to secure a greater share of the international market. Canada has demanded that uranium conversion be conducted in Canada before uranium is exported to other counties. Australia has established the nuclear fuel company NFAL. NFAL is to build a multinational uranium enrichment company in Australia and establish a uranium conversion plant using technology from the European nuclear fuel enrichment company Urenco.

1.2.3.2 Challenges with Countries with Surplus Nuclear Fuel Fabricating Capacities

China has been constantly challenged by countries that have surplus nuclear fuel fabricating capacity. Being the only company involved in all aspects of the nuclear fuel cycle and nuclear power plant construction, and in order to continue leading the global nuclear industry, the French company Areva has made significant investments developing its capabilities in the front-end of the nuclear fuel cycle, including nuclear mine exploration, processing, conversion, enrichment and fuel fabrication. In 2010, Areva had a 30% share of the world nuclear fuel market and sufficient uranium reserves. On November 11, 2007, Areva and China Guangdong Nuclear Power Corporation (CGNPC) signed the EPR project agreement, whereby Areva will provide nuclear fuel and fuel assembly services to CGNPC over the next 15 years.

Upon the restructuring of its nuclear industry, Russia established State-controlled Atom Energo Prom. Russia had a 17% share of the global nuclear fuel market in 2010. Meanwhile, Russia has ambitious plans to increase this market share.

Russia has large uranium reserves. In January 2006, President Vladimir Putin raised the idea of establishing an international uranium enrichment center. In July 2006, the Russian Atomic Energy Agency announced the establishment of the first international nuclear enrichment center in Angarsk.

China's Tianwan nuclear power plant was constructed with technologies imported from Russia, which provided the first fuel load and the fuels for the first three reloads. It goes without saying that China's nuclear fuel cycle market is targeted by countries rich in uranium resources and in nuclear fuel fabrication capacity. The shortage of natural uranium domestically is the weak spot in China's nuclear power development scheme. China should be wary of the impact foreign nuclear powers might have on its domestic nuclear fuel market.

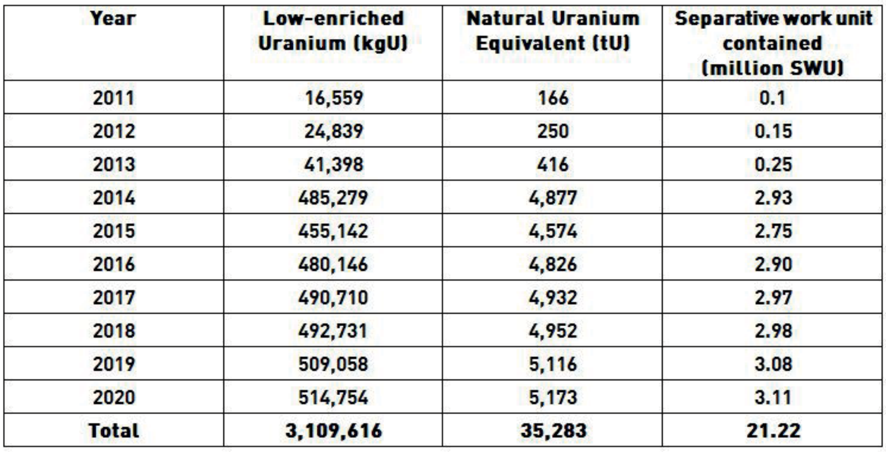
1.2.4 Two Conclusions

(1) According to the analysis above, the global natural uranium market today would appear to be a buyer's market.

(2) China should protect and promote its domestic nuclear fuel industry, to ensure it grows bigger and stronger, and strengthen the awareness of protection.

People generally have a one-sided understanding of the market economy and international standards. In fact, every country has means in place to protect the domestic market. For example, Europe and the U.S. have long prevented Russian low-enriched uranium from entering their markets. The U.S feels that its domestic nuclear fuel industry could be endangered with imports of Russian fuel. An agreement that effectively suspends fuel imports from Russia into the U.S. was concluded in 1993 and expired in 2013 only. According to the agreement, the U.S. government would charge a 112% tariff on low-enriched uranium imported from Russia.

Russia and the U.S. signed a new trade agreement on February 1, 2008 that allows Russian shipments of uranium to the U.S. starting from 2014. The amount of low-enriched uranium from Russia cannot exceed 20% of the total amount imported. Based on the draft agreement the U.S Department of Energy issued in December 2007, the limits on uranium shipments from Russia to the U.S. are shown in Table 1.



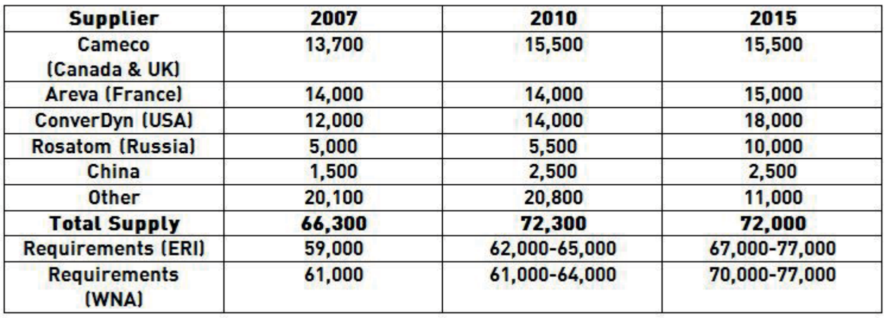
Year	Low-enriched Uranium (kgU)	Natural Uranium Equivalent (tU)	Separative work unit contained (million SWU)
2011	16,559	166	0.1
2012	24,839	250	0.15
2013	41,398	416	0.25
2014	485,279	4,877	2.93
2015	455,142	4,574	2.75
2016	480,146	4,826	2.90
2017	490,710	4,932	2.97
2018	492,731	4,952	2.98
2019	509,058	5,116	3.08
2020	514,754	5,173	3.11
Total	**3,109,616**	**35,283**	**21.22**

Table 1 – Limits of nuclear fuel shipments from Russia to the USA (source: U.S. Department of Energy)

1.3 Uranium Conversion and Enrichment

1.3.1 Supply and Demand of Global Uranium Conversion

The process of changing U_3O_8 or "yellow cake" into UF_6 is called uranium conversion. Table 2 shows the supply and demand of global nuclear fuel conversion. It can be seen that the production capacity is smaller than the demand if the already converted uranium inventory is not considered. For example in 2007, the demand of converted uranium was 59 000 MTU and the production capacity was 46 200 MTU. The U.S needed 20 000 MTU converted uranium annually but the production capacity was only 12 000 MTU. All the countries are increasing the capacity to convert uranium. The figures in Table 2 are given by the World Nuclear Association (WNA). In 2007 the China nuclear conversion plants produced 1500 t of uranium. China should increase its capacity to convert more uranium to meet the domestic demand.



Supplier	2007	2010	2015
Cameco (Canada & UK)	13,700	15,500	15,500
Areva (France)	14,000	14,000	15,000
ConverDyn (USA)	12,000	14,000	18,000
Rosatom (Russia)	5,000	5,500	10,000
China	1,500	2,500	2,500
Other	20,100	20,800	11,000
Total Supply	**66,300**	**72,300**	**72,000**
Requirements (ERI)	59,000	62,000-65,000	67,000-77,000
Requirements (WNA)	61,000	61,000-64,000	70,000-77,000

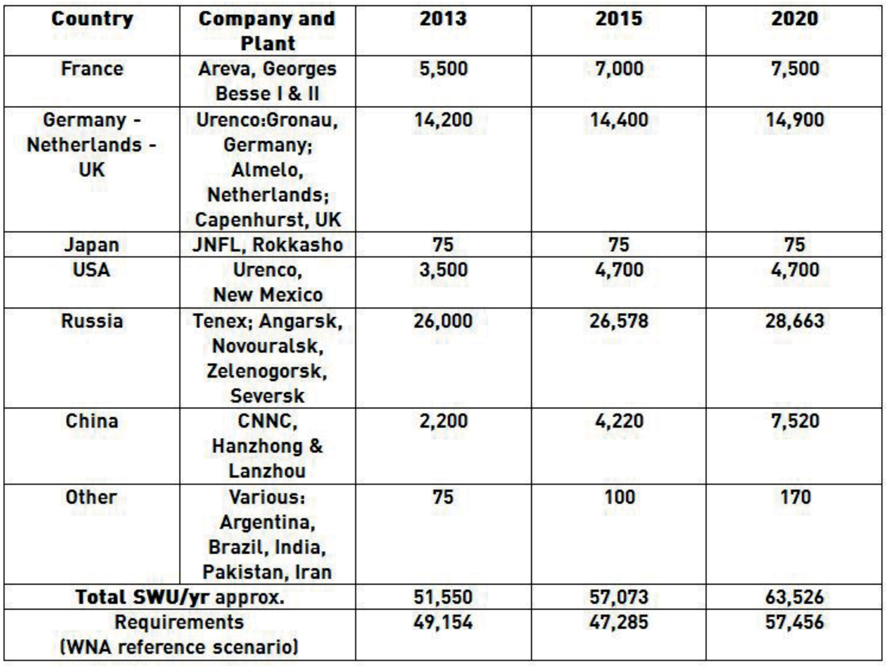
Table 2 – Supply and demand of uranium conversion worldwide, in metric tons (data for 2010 and 2015 are projections) [5]

1.3.2 Supply and Demand of Enriched Uranium in the World

At present, there are four uranium enrichment service providers in the world: Areva, Urenco, USEC Inc. and the Russian Techsnabexport (Tenex). The large-scale commercial operating uranium enrichment plants are in France, Germany, the Netherlands, the United Kingdom, the U.S and Russia. In addition, there are many small uranium enrichment plants worldwide. France and the U.S are constructing new centrifuge uranium plants. Table 3 shows the supply and demand of uranium enrichment in the world. In 2015, the supply and demand situation was balanced. In 2007 diffusion method accounted for 25%, centrifuge method accounted for 65%. Now the diffusion method is no longer used.

1.3.3 Uranium Enrichment Industry in China

China's uranium enrichment technology has transferred from diffusion to centrifuge. Being the only nuclear fuel provider in China, the China National Nuclear Corporation followed the strategy of "increasing speed of nuclear fuel made in China and actively promoting imported fuel from abroad". Up to 2020, it is planned that every year there will be new fuel production lines under construction and also new production lines put into use. This enhances China's uranium enrichment capacity rapidly and makes it possible for China to export nuclear fuel after meeting its own demand in nuclear fuel supply. China is looking forward to becoming the uranium enrichment center of Asia.



Country	Company and Plant	2013	2015	2020
France	Areva, Georges Besse I & II	5,500	7,000	7,500
Germany - Netherlands - UK	Urenco:Gronau, Germany; Almelo, Netherlands; Capenhurst, UK	14,200	14,400	14,900
Japan	JNFL, Rokkasho	75	75	75
USA	Urenco, New Mexico	3,500	4,700	4,700
Russia	Tenex; Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	26,578	28,663
China	CNNC, Hanzhong & Lanzhou	2,200	4,220	7,520
Other	Various: Argentina, Brazil, India, Pakistan, Iran	75	100	170
Total SWU/yr approx.		51,550	57,073	63,526
Requirements (WNA reference scenario)		49,154	47,285	57,456

Table 3 – World enrichment capacity – operational and planned (thousand SWU/a) [6]

1.4 Nuclear Fuel Fabrication

1.4.1 Analysis of Nuclear Fuel Fabrication Capacity

1.4.1.1 Analysis of Nuclear Fuel Fabrication Capacity in the World

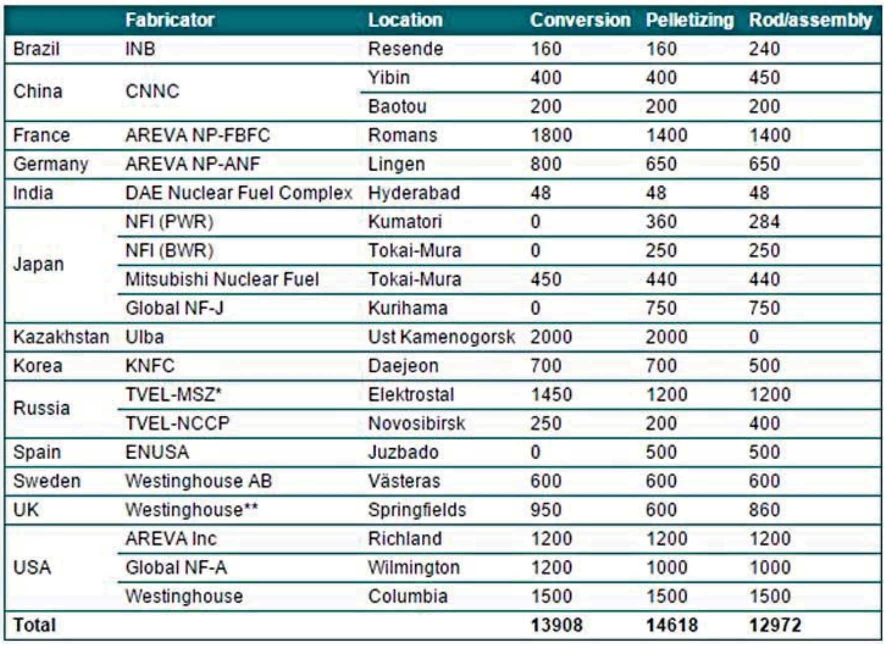
Table 4 shows that there are 13 countries in the world having fuel fabrication plants for light water reactors. The fuel fabrication capacity in the world is 12972 MTU/a [7]. Areva, Global Nuclear Fuel (GNF) and the Westinghouse Electric Company (WEC) are the three largest international fuel producers in the world. GNF mainly fabricates fuels for boiling water reactors.

1.4.1.2 Forecast of China's Nuclear Fuel Fabrication Capacity

In 2020, the demand of fuel fabrication capacity will be 1273.2 tons annually. The number is close to the production capacity of the Westinghouse plant in Columbia, South Carolina, which is 1350 MTU. In 2030, the production demand will be 2231.2 tons, in 2040, 3191.2 tons, and in 2050, 4151.2 tons. Thus, China will become the country with the biggest fuel fabrication capacity for light water reactors in the world.

1.4.2 Nuclear Fuel Components in Operating Reactors

Several types of nuclear fuel components, manufactured through technology import and independent research and development, are already in use in Chinese operating reactors. The 15×15 nuclear fuel assemblies, indigenously developed by the China Jianzhong Nuclear Fuel Company, had designed burn-ups of 25 GWd/tU, but have now reached 33 GWd/tU through upgrading. These CQS 300 fuel assemblies have



	Fabricator	Location	Conversion	Pelletizing	Rod/assembly
Brazil	INB	Resende	160	160	240
China	CNNC	Yibin	400	400	450
		Baotou	200	200	200
France	AREVA NP-FBFC	Romans	1800	1400	1400
Germany	AREVA NP-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
Japan	NFI (PWR)	Kumatori	0	360	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global NF-J	Kurihama	0	750	750
Kazakhstan	Ulba	Ust Kamenogorsk	2000	2000	0
Korea	KNFC	Daejeon	700	700	500
Russia	TVEL-MSZ*	Elektrostal	1450	1200	1200
	TVEL-NCCP	Novosibirsk	250	200	400
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	600	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	AREVA Inc	Richland	1200	1200	1200
	Global NF-A	Wilmington	1200	1000	1000
	Westinghouse	Columbia	1500	1500	1500
Total			**13908**	**14618**	**12972**

Table 4 – World light water reactor fuel fabrication capacity (MTU/a) [7]

never sustained any broken fuel rods. This demonstrates the success of China's indigenous research and development in this area of nuclear fuel assemblies.

The Daya Bay units 1 and 2 adopted the AFA-2G type nuclear fuel technology from France. The designed burn-up of this type of fuel assembly is 33 GWD/tU. The fuel assemblies for the initial loading were provided by a French company. In 1991, the China Jianzhong Nuclear Fuel Company imported the technology from France to produce AFA-2G nuclear fuel assemblies and in 1994 it delivered the first batch to unit 2 of Daya Bay. From 1996 to 2002, it manufactured 13 batches of 772 AFA-2G nuclear fuel assemblies and secured the supply of nuclear fuel for Daya Bay. These best quality fuel assemblies gave the Daya Bay reactors safe operation for seven years with no fuel leakage and no deformed, broken or abnormal fuel rods.

In order to improve the fuel efficiency in Daya Bay, the China Jianzhong Nuclear Fuel Company imported the AFA-3G nuclear fuel manufacturing technology from France in December 1998, which improved fuel burn-up rates to 54 GWD/tU. This technology prolonged the fuel reloading period from 12 months to 18 months. In February 2002, the first batch of AFA-3G manufactured by China Jianzhong Nuclear Fuel Company was loaded into the reactor core of Daya Bay unit 2. In April 2002, AFA-3G type nuclear fuel was loaded into the reactor core of unit 1. Up until September 2005, when unit 2 started its refueling outage, the first batch of 52 fuel rods had been through three fuel reloading periods and no fuel rod was reported broken.

The nearby two units at Ling-ao nuclear power plant were synchronized to the grid and started to generate electricity in May 2002 and January 2003 respectively. The two units were loaded with AFA-2G fuel assemblies initially and later changed to AFA-3G fuel assemblies in 2003. To further improve the fuel efficiency, China Jianzhong Nuclear Fuel Company imported the M5-AFA-3G fuel manufacturing technology from France. This technology is based on the AFA-3G and has the advantage of high fuel efficiency. With the M5-AFA-3G technology fully adopted, a quarter of the nuclear fuel assemblies only will be required to be changed during each fuel reloading. In February 2007, all the fuel assemblies in Ling-ao nuclear power reactors were Chinese manufactured M5-AFA-3G assemblies.

The two units of phase two of Qinshan nuclear power plant were connected to the grid and started electricity generation in April 2002 and May 2004 respectively. Initially AFA-2G type nuclear fuel was loaded and in 2004 AFA-3G nuclear fuel was adopted.

The two units at Tianwan nuclear power plant were connected to the grid and started power generation in May 2007 and August 2007 respectively. Russian VVER-1000 nuclear fuel technology was adopted. Fuel assemblies for the initial core and the subsequent three fuel reloading periods were provided by Russian companies. China Jianzhong Nuclear Fuel Company began to supply nuclear fuels to Tianwan nuclear power plant from the fourth fuel reloading. The fuel assemblies, which can be used in all AES-91 pressurized reactors, were manufactured with technology imported from Russia. The VVER-1000 nuclear fuel production line was installed and tested in mid-August 2008. It began to produce fuel assemblies in 2009 and supplied fuel for the fourth fuel reloading in 2010.

In order to supply CANDU-6 fuel assemblies domestically, in December 1998 the China North Nuclear Fuel Company (CNNC 202 Factory) began to import CANDU-6 fuel technology from ZPI, a Canadian company. Construction of the fuel manufacturing plant began in April 1999. In 2002, the plant began to manufacture fuel assemblies which were loaded into reactor cores in March 2003. By the end of September 2003, 38 743 CANDU-6 type fuel assemblies had been loaded into the reactor and 30 659 unloaded. This indicates that the fuel assemblies had been in stable operation and the quality had reached international standards.

To sum up, the fuel assemblies for China's operational pressurized water reactors were AFA, VVER and CQS 300, which were Chinese designed and manufactured. Up to 2015, the six reactors in Daya Bay nuclear power plant, Ling-ao phase one and Qinshan phase two all used AFA-3G 17 × 17 square arrangement fuel assemblies. The extension projects of Qinshan phase two, Ling-ao phase two and the upcoming Fuqing, Fangjiashan, Hongyanhe, Ningde and Yangjiang etc. also use AFA-3G fuel assemblies. The Tianwan nuclear power plant is using VVER fuel.

1.4.3 Nuclear Fuels for the Third Generation Pressurized Water Reactors

The four AP1000 nuclear reactors under construction in Sanmen and Haiyang will have AP1000 fuel assemblies for initial core loading provided by Westinghouse. China will provide AP1000 fuel assemblies for the first and subsequent fuel reloadings.

The State Nuclear Power Technology Corporation (SNPTC) is responsible for importing AP1000 nuclear fuel technology from Westinghouse. The China North Nuclear Fuel Company, SNPTC and China Jianzhong Nuclear Fuel Company co-established the China Baotou Nuclear Fuel Company which has started to develop and manufacture AP1000 nuclear fuels in 2013.

Areva and the China Guangdong Nuclear Power Company (CGNPC) signed a project agreement, affirming Areva will provide nuclear fuel and fuel assemblies for the two EPR at Taishan nuclear power plant for 15 years. Nevertheless, CGNPC imported fuel fabrication technology together with the EPR reactors.

1.4.4 China's Fuel Manufacturing Ability

China has two nuclear fuel manufacturing bases which are China Jianzhong Nuclear Fuel Company (in Sichuan Province) and China North Nuclear Fuel Company (Inner Mongolia). The China Jianzhong Nuclear Fuel Company had an 800 tU/a fuel manufacturing capacity for pressurized water reactors in 2014.

China North Nuclear Fuel Company at present has a fuel rod manufacturing capacity of 200 tU/a for CANDU-6 reactors and 800 tU/a for AFA-3G nuclear fuel assemblies.

Detailed introduction about nuclear fuel companies in China can be found in the second chapter.

1.4.4.1 Zirconium Alloy for Nuclear Fuel Fabrication

Zirconium alloy is a critical material in manufacturing nuclear fuel assemblies. The fuel assemblies for phase one of Qinshan nuclear power plant used Zr-Sn alloy cladding material, which was domestically designed and manufactured in China in the 1980s. No cladding tubes have been found broken since the Qinshan reactor was connected to the grid on December 15, 1991, which demonstrated that the quality of zirconium alloy is in line with international advanced standards. The low-tin Zr-4 alloy, a modified Zr-4 alloy, can be used to make nuclear fuels with a burn-up of less than 40-45GWd/t.

The AFA-3G fuel assemblies used the M5 alloy from France. M5 alloy is a Zr-Nb alloy developed by a French company. It was used to manufacture cladding tubes for AFA-3G assemblies whose designed burn-up is 55-60GWd/t. The M5 alloy has been used in eight operating reactors in Europe and one in the US. Its corrosion, irradiation growth and deformation are less than the low-tin alloy Zr-4. Although China began to import the M5 cladding tube manufacturing technique from France, the technology transfer has not yet been completed. Until 2015, most of M5 alloy cladding tubes and materials needed in China have been imported from abroad.

The E110 (99%Zr-1%Nb) alloy was adopted in manufacturing VVER-1000 fuel assemblies. The E110 alloy cladding tube manufacturing technology was imported from Russia for the Tianwan nuclear power project. In the plant's fourth fuel reload, domestically manufactured E110 alloy was used in the fuel assemblies.

The CANDU-6 type fuel assemblies adopted Zr-4 alloy. China imported technologies from the Canadian company ZPI for manufacturing cladding tubes and a variety of plates, rods and wires. The technology transfer process is almost finished, but the Chinese manufacturing has not yet begun. Right now, all the zirconium tubes China needs are from ZPI.

The AP1000 fuel assemblies have used Zirlo alloy, developed by Westinghouse in the 1970s. The Zirlo alloy (97% Zr, 1.0% Nb, 1.0% Sn, 1.0% Fe) combines advantages of both Zr-Sn and Zr-Nb. The burn-up rate of fuel assemblies with Zirlo alloy was 55GWd/t in 1992. In 1995, Zirlo alloy was in industrial scale use.

1.4.4.2 Construction of the Production Chain of Nuclear Grade Zirconium

While importing the AP1000 nuclear fuel manufacturing technology, China is also importing the zirconium production chain from Westinghouse including zirconium sponge, alloy, materials and tubing. Under the agreement with Westinghouse, China is going to use domestically manufactured zirconium materials in the first fuel reload to see if the technology transfer is successful. The State Nuclear Baoti Zirconium Industry Company, a joint venture between the State Nuclear Power Technology Corporation and the Baoti Group, will receive the manufacturing technology for zirconium materials from Westinghouse. When the technology transfer is finished, a complete zirconium production chain will exist in China.

1.4.5 Progress in China's Nuclear Fuel Manufacturing Technology

China began to import nuclear fuel manufacturing technology in 1991. In 2014, China finished the construction of the first AP1000 nuclear fuel element production line.

In these past 25 years, China has imported the nuclear power technology, including the M310 reactor from France, the VVER-1000 from Russia and the CANDU-600 from Canada. Now, the third generation nuclear technology is being imported: AP1000 from Westinghouse in the United States and the EPR from Areva in France. China also imported the related fuel manufacturing technologies. China has imported AFA-2G, AFA-3G and M5 AFA-3G (three fuel technologies from France), the VVER-1000 fuel technology from Russia and the CANDU-600 technology from Canada. All these fuel technologies are now made in China.

The diversity of nuclear technologies in use in China brings diversity in fuel manufacturing technologies and also serious technical barriers. Nuclear fuel manufacturing is different from the other fuel cycle industries. The natural uranium, conversed or enriched, is universal and has characteristics of original materials. However, fuel assemblies are critical parts of reactors and involve very complicated manufacturing procedures with detailed design and stringent assessment. One type of fuel technology can only fit into one type of reactor. This must be given enough recognition. For example, the AFA series fuel cannot fit into VVER reactors nor into AP1000 reactors and vice versa (at least not now).

1.5 Challenges and Policies

1.5.1 Challenges in China's Nuclear Fuel Cycle Industry

According to the report of Prof. Li Guanxing presented here, China's nuclear fuel cycle industry is faced with many challenges. The scale of the front-end of China's nuclear fuel industry is small. The equipment and technology levels are behind that of developed countries. All this makes it impossible for China's nuclear fuel industry to meet the demands of its nuclear industry. How should China secure its nuclear power industry, expand capacity and improve the production level according to the situation of the nuclear fuel industry?

The nuclear fuel cycle industry is a market-oriented international industry. Countries with surplus production capacities are looking to enter the nuclear fuel cycle market of China. The question facing China is how to plan its quick development in the context of the world's open market.

The nuclear fuel cycle industry is the basis of the entire nuclear industry. It is of national safety concern and very sensitive. All the leading nuclear powers are very protective of their native nuclear fuel industries. However, "openness" and "protection" are contradictory. China should create appropriate policies and implement them to protect its nuclear fuel industry.

The development of the nuclear fuel industry will have a huge impact on the old system. China should adjust the nuclear fuel system to avoid disordered competition.

1.5.2 Research on Countermeasures

China must recognize the situation and think differently to catch up with all the big changes taking place, one of which is that China will have the largest fleet of nuclear power plants. Correspondingly, China's nuclear fuel industry must have the largest scale too. To achieve this is an important mission for contemporary nuclear engineers.

The nuclear fuel cycle should be of concern for everyone working in the nuclear industry. The administrative leadership and coordination must be strengthened and modern enterprise systems must be promoted. Actions that put personal interest in front of national interest should be avoided. All this can contribute towards a healthy development of China's nuclear fuel industry.

References

[1] Li Guanxing. The Challenges and Opportunities of the Nuclear Fuel Cycle Industry in China, Uranium Geology [J]. V24 No.5, Sept. 2008: 258.

[2] U.S. Energy Information Administration: China will soon surpass South Korea, Russia and Japan in nuclear generating capacity: *http://www.eia.gov/todayinenergy/detail.cfm?id=22132*

[3] European Nuclear Society: Nuclear Power Plants, Worldwide: *https://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-world-wide.htm*

[4] Uranium 2014: Resources, Production and Demand, A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency.

[5] WNA. Uranium Enrichment [J]. October 2007.

[6] WNA. Uranium Enrichment [J]. September 2015.

[7] WNA. Market Report 2013.

2

Introduction of the China Nuclear Fuel Corporation (CNFC) and its Member Corporations

The China Nuclear Fuel Corporation (CNFC) is affiliated with the China National Nuclear Corporation (CNNC). It is one of the important industry pillars in this group company. On April 12, 2013, according to the requirement of the group company and the demand of industrial development, China Nuclear Fuel Corporation was officially incorporated [1].

The business scope of this company covers nuclear fuel production, transportation, sales, construction of associated works, technology research and development, technology transfer, technical services and international cooperation. It is the only nuclear fuel manufacturer, supplier, and service provider in China. CNFC and its affiliated units provide high-class nuclear fuels to all the nuclear power plants in operation in China.

CNFC has thirteen affiliated units in Beijing, Tianjin, Shanghai, Gansu, Sichuan, Shaanxi, Inner Mongolia, Guangdong and Shanxi. Among these thirteen units, there are four fabrication factories which are CNNC 202 Factory, CNNC Jianzhong Nuclear Fuel Co., Ltd (CJNF), CNNC Lanzhou Uranium Enrichment Co., Ltd (LUEC) and CNNC Shaanxi Uranium Enrichment Co., Ltd (SUEC). Here is a brief introduction of these four factories.

2.1 The China National Nuclear Corporation 202 Factory

The CNNC 202 Factory, the first scientific research and production-oriented enterprise for nuclear fuels and materials in China, is located in Qingshan district, Baotou City, Inner Mongolia [2].

With the fast development of China's nuclear power, the CNNC 202 Factory built the fuel element production line for the first CANDU nuclear power plant in China. In December 2002, the CANDU fuel element factory went into production officially. It has provided qualified fuel assemblies to the Qinshan Phase III heavy water reactor since

Fig. 2 – The CNNC 202 Factory in Baotou City, Qingshan District, Inner Mongolia [3]

2003. In 2012, 100 000 rod clusters were produced, the quality of which reached the international advanced level.

For the past few years, the fuel element production tasks of the CNNC 202 Factory followed one by one. The pressurized water reactor (PWR) fuel element production line was completed in 2010, which has the ability to handle 200 t of metallic uranium per year. Besides, the production of the fuel for the Generation III AP1000 PWRs reached 800 t. In 2014, it provided the Sanmen and Haiyang nuclear power plants with fuel elements for the first time.

After the completion of the High Temperature Gas-Cooled Reactor (HTGR) fuel element production line, it will be capable to produce 300 000 pebble fuel elements per year, marking that China masters the HTGR fuel element technology after Germany, the USA and Japan.

Meanwhile, in order to meet the demand of developing nuclear power in a massive scale, the CNNC 202 Factory will extend the construction of the AFA3G PWR fuel element production line. At the appointed time, the CNNC 202 Factory will become the industrial base for all types of fuel elements in China. The factory was also built with ministerial key laboratories and the National Physical and Chemical Testing Center as well as a research institute and one postdoctoral scientific research station [3].

The CNNC 202 Factory is not only the biggest fuel element production base of China, but also the research and development center of fuel elements. All types of fuel elements in test reactors, research reactors and engineering reactors in China are researched, developed and fabricated there.

The safety of nuclear power plants is related to the quality of fuel elements. After entering the PWR fuel element production area, all the materials are completely sealed in closed containers and pipelines, which means that people and materials do not get in contact with each other. There are two sealing barriers: One is the processing equipment and the pipelines, the other are the peripheral barrier and its exhaust system. The whole plant has a negative pressure system in the production area. Air can only flow from the outside to the inside, which prevents radioactive substances from diffusing into the environment.

The CNNC 202 Factory fuel element production lines have high automation levels. Workers use touch screens to operate them. They can only operate following preset programs and have no authority to change the operation in order to avoid misoperation [4].

Although the radioactivity of uranium during fuel element operation is low, the "three wastes" (waste gas, waste water and waste residues) disposal is very strict. The CNNC 202 Factory has special uranium and fluorine-bearing wastewater treatment facilities. They can recycle uranium from the wastewater and implement wastewater defluoridation. All of the treated water is recycled and reused.

The CNNC 202 Factory has also built advanced waste gas treatment facilities. With the help of air filtration, absorbing and washing facilities, the air inside the workshop passes through multistage purification, which reduces waste gas production to a minimum. The exhaust gas purification efficiency of fuel element factories in China is 99.97%. CNNC 202 Factory reached 99.99%.

In order to prevent and control the pollution of exhaust gases, the inlet and outlet of the waste gas treatment facilities are equipped with monitoring instruments or sampling ports to have real-time monitoring. Meanwhile, environmental monitoring sites are set up around the factory. The monitoring data will be reported to the local environmental protection agency and the supervision department. The research result from many years' monitoring data shows that nuclear facilities in China have very little impact on the surrounding environment.

From construction, operation to retirement of nuclear facilities, natural conditions such as geology, hydrology and weather must be evaluated carefully. Although the CNNC 202 Factory is not far away from mountains, it is not on geological fault zones. Moreover, the building standards of the factory are high. The anti-seismic grade of the factory is 8 and the seismic fortification level is 9. All the radioactive working places are airtight workshops. Even if a leakage of substances would happen, radioactive substances could be controlled within the factory and emissions to the environment are reduced thanks to the outer barriers.

U_3O_8 powder and UO_2 pellets are a very stable solid. UF_6 is solid under normal pressure and temperature. It is stored in airtight steel vessels. The operation and processing of UF_6 is within the airtight pipelines, equipment and containers, which avoid releases to the environment. Because UF_6 is chemically active, in the case of a leakage, UF_6 will react with moisture in the air and most of it will form UO_2F_2 and deposit inside the factory. HF will be confined inside the factory. The formed UO_2F_2 can also be recycled.

Besides, U_3O_8 and other forms of pure uranium are weak radioactive matter. Even if the factory building collapses because of a violent earthquake, flood or other extreme disasters, as long as we can reclaim the material, the consequences of the accident are mainly controlled within the factory.

Since the CNNC 202 Factory was built, it suffered earthquakes greater than magnitude six and other disasters, but none of these caused damage to the production facilities. Up to now, the CNNC 202 Factory has never caused any measurable harmful effects to the surrounding environment. The safety level of this fuel element factory is very high.

Fig. 3 – Design sketch of the CJNF “2015 Project” in Yibin, Sichuan Province (source: *http://news.huaxi100.com*)

2.2 The CNNC Jianzhong Nuclear Fuel Co., Ltd

Along with the strategic adjustment of the National Nuclear Development Plan, China ushered in the era of nuclear energy development. The first safety barrier of a nuclear power plant is the fuel elements itself. China is now actively establishing a world class fuel element manufacturing base [5].

The biggest pressurized water reactor (PWR) fuel element manufacturing base in China is CJNF. It was built in 1965 and belongs to CNNC. It is located in Yibin, Sichuan Province. It provides fuel assemblies to all the existing PWR plants and those under construction in China and has achieved “zero breakage” for many years. After forty years of development, it has become a large state-owned enterprise being the industry leader of fuel element fabrication and the civil industry of perfume and lithium batteries. Manufacturing, scientific research, domestic and foreign trade have become an organic whole [6].

From the Qinshan Nuclear Power Plant unit 1, to Daya Bay to Qinshan unit 2, Ling-ao unit 1, and Ling-ao unit 2, CJNF has provided the existing PWRs in China and the Chashma NPP in Pakistan with more than nine thousand fuel assemblies and around two million fuel rods. They passed long-term safe operation and no assembly was damaged because of mistakes in manufacturing.

After entering the 21th century, with the implementation of the National Nuclear Long-and-medium Term Development Plan, nuclear fuel demand grows with every day because of the rapid development of nuclear power. The gap between the demand and the insufficient production capacity is growing gradually. In 2006, the uranium production capacity was 200 tons per year, which could not meet the demand of fuel elements in the NPPs from 2008 to 2010. So it was decided to enlarge the capacity of the fuel element production line.

On July 17, 2014, the technical innovation and expansion projects of the CJNF 400 ton fuel element production line was put into operation, realizing a leap of uranium annual output from 400 tons to 800 tons. The production capacity is among the highest in the world, which can meet the refueling needs of thirty 1000 MWe PWR nuclear power units [7].

The “2015 Project” is a major project carried out by CNNC in order to meet the demand of nuclear energy development in China, making the fuel element manufacturing industry stronger and better, upgrading the production capacity and ensuring the safe and reliable fuel element supply. It is also one of the fifty major projects in Sichuan Province [8].

On December 26, 2014, the commencement ceremony of the CJNF “2015 Project” was held in Gaojie Industrial Park in Yibin, marking that the fuel element manufacturing base covering an area of 667 000 square meters with an investment of CHF 800 million started construction. After completion, the annual value of production is estimated to be CHF 1600 million.

The construction of the “2015 Project” marks the beginning of the CJNF fuel element manufacturing capacity promotion and technical equipment upgrade. It is also an important symbol of cooperation between CJNF and Yibin which can not only improve the CJNF fuel element manufacturing level and reinforce its core competitiveness, but also promote the local economic development.

2.3 The CNNC Lanzhou Uranium Enrichment Corporation, Ltd

The CNNC Lanzhou Uranium Enrichment Co., Ltd. (LUEC) is a key Science and Technology Industry of National Defense enterprise in China. It is an important fuel element manufacturing base. Since reform and opening up (1978), LUEC never stopped exploiting the civilian market and using nuclear energy peacefully. It completed the mission of providing Qinshan and Daya Bay NPP with initial core loadings and normal refueling successfully and moved to a new level in serving the Science and Technology Industry of National Defense and the national economy. While ensuring the stable production of fuel elements, it actively adjusted its product structures and developed non-nuclear civilian activities. It has so far developed packaging products, fine chemical products, aluminum-plastic products, mechanical processing products, pressure vessels, nuclear electronic instruments, industrial gases and so on [9].

LUEC is located in suburban Lanzhou, Gansu Province, covering an area of 7.67 square kilometers. It has an international advanced technology production system and provided the first NPP in China with qualified fuel elements.

The next ten years will be another golden age for the nuclear industry development in China. The nuclear fuel industry will step into a track of fast development and LUEC also shows a bright future. According to the development planning of the corporation, up to 2020, the scale of nuclear fuel production will increase significantly. Then LUEC will become a first-rate nuclear fuel base with high technology, new mechanisms, high standard team, strict management, large scale and good economic returns.

2.4 CNNC Shaanxi Uranium Enrichment Co., Ltd

SUEC was built in October, 1969, located in Hanzhong, Shaanxi Province. It is a large-scale mainstay enterprise belonging to CNNC. It has 2000 employees and covers an area of two square kilometers. In 1992, after the permission of the State Council, it imported packaged production technology and equipment from abroad to work on advanced uranium enrichment production. It became the first enterprise to use centrifugal processes to produce enriched uranium in China [10].

SUEC’s 405 technical innovation project was included in the national key construction projects during the “Eighth Five-Year Plan” and Ninth Five-Year Plan” period (from 1991 to 2000). In December, 2002, it finished the completion acceptance, marking that China realized promotion of production capacity and technical level in this key link of the nuclear fuel cycle as well as it gained experience, cultivated talents and trained teams for the further development of China’s nuclear fuel industry [11].

Under the leadership of CNNC, SUEC continuously imported foreign uranium enrichment technology and signed a commercial contract for a uranium enrichment production project. In 2011, this project was completed and put into operation. This promoted SUEC’s scale of production and economic benefits dramatically and exerted a positive influence on China’s nuclear power development. On this basis, in order to meet the further requirements of nuclear fuel, SUEC is actively planning and striving for bigger engineering projects to expand production scale and enhance competitiveness. At present, all the projects have achieved primary progress, marking that SUEC is on an expressway of development.

References

[1] *http://www.cnncnf.com.cn*

[2] *http://news.ifeng.com/gundong*

[3] *http://baike.baidu.com/*

[4] *http://military.china.com/important*

[5] *http://news.xinhuanet.com/politics*

[6] *http://baike.baidu.com*

[7] h*ttp://www.guancha.cn/Industry*

[8] h*ttp://www.wccdaily.com.cn*

[9] *http://baike.baidu.com*

[10] *http://baike.baidu.com*

[11] *http://baike.baidu.com*

3

Introduction of Fuel Reprocessing - Recycling in China

3.1 Introduction

Nuclear energy is one kind of clean energy which has high energy density and low carbon emission. It plays an important role in ensuring energy safety, easing pressure on the environment in order to achieve economic and social sustainability in China. In the "Twelfth Five-year Plan" (from 2011 to 2015) of China, safety and high efficiency are emphasized on nuclear energy, which makes a clear way for the development of nuclear power [1].

The fuel cycle is like a "main artery" in the nuclear energy system. In order to make sure the sustainable development of nuclear energy in China, a technology (and possibly resource) independent, complete and advanced nuclear fuel cycle system must be established. Making full use of nuclear resources, achieving minimal nuclear waste and safe disposal are the basic requirements for sustainable development. Fast reactors and a closed fuel cycle can meet these requirements.

Compared to developed countries, the development of nuclear energy in China started late. China falls behind in fuel cycling technology. It established industrial production capacity in the front end of fuel recycling, which can meet the demand in the near future. But the scale of production and the technological level need to be enlarged and improved. The industrial capacity of the back end of the fuel cycle is still not been well developed, which is the weakest link in nuclear industry system. The back end of the fuel cycle includes thermal reactor spent fuel reprocessing, manufacturing of fast reactor fuel, fast reactor spent fuel reprocessing, and disposal of high level waste. In this article we focus on core issues of the fuel cycle system in China, that is the technical problems of spent fuel reprocessing/recycling.

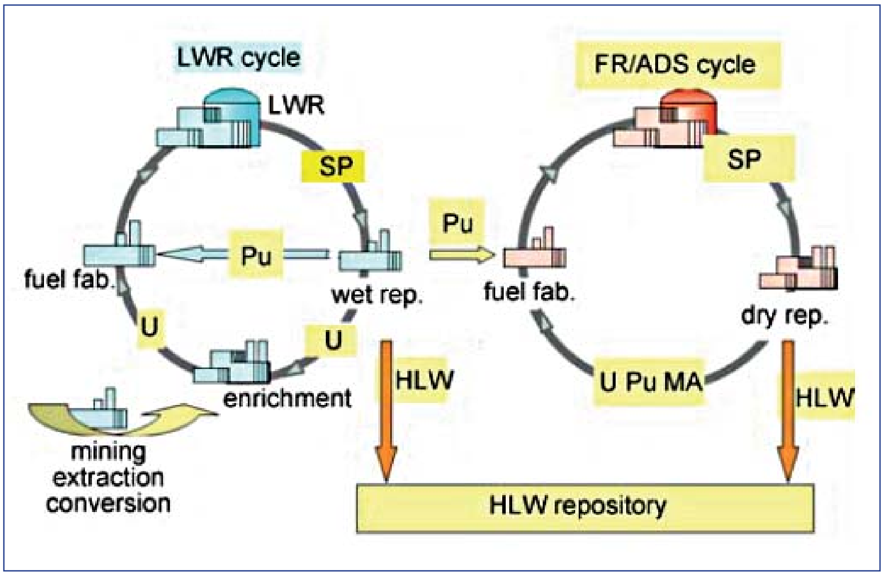


Fig. 4 – Schematic illustration of a closed fuel cycle [1]

3.2 The Concept of Fuel Cycle

The fuel cycle of nuclear energy systems (such as the U-Pu cycle) means a series of industrial processes from Uranium mining to the final disposal of nuclear waste. It is divided into two parts: the front end and the back end by setting the reactor as a boundary. There are two categories of fuel cycles: the closed fuel cycle and the once-through cycle. There are no differences between the two ways in the front end of fuel cycle, which all include uranium mining, milling, conversion, enrichment and fuel assembly fabrication.

The differences between the two ways exist in the back end. The closed fuel cycle includes interim storage of spent fuel, spent fuel reprocessing, Pu and U recycling, disposal of radioactive waste. The recovered fuel can be recycled in thermal reactors or in fast reactors. In Fig. 4, the left side shows the closed fuel cycle of thermal reactors (mainly light water reactors) and the right side shows the closed fuel cycle of fast reactors or accelerator driven sub-critical systems (ADS). As for the once-through cycle, direct geological disposal will start after the spent fuel is removed from the reactor core and interim storage.

3.3 The Current Situation of Nuclear Fuel Reprocessing/Recycling Technology in China

In the middle of the 1960s, China successfully developed reprocessing technology for military use and built reprocessing factories. The separation technology was very close to the world standard at that time. But after 1980s, with the shutting down of military reprocessing factories, the research and development funding for reprocessing got extremely insufficient, leading to the reprocessing technology becoming the weakest link of the nuclear energy system in China.

Even in this relatively difficult conditions, Chinese scientists and engineers achieved some good results in reprocessing R&D and constructing the China National Nuclear Corporation (CNNC) 404 pilot plant in Lanzhou, Gansu Province.

In the field of reprocessing technology research, the China institute of Atomic Energy did research and development of advanced reprocessing process since 1990s. The focus is on applying a salt-free reagent, aiming to reduce radioactive waste, simplify the technology process and control the moving of key nuclides. The researched salt-free reagent is divided into two categories: reductant and complexant. The former includes hydroxylamine and its derivatives, hydrazine and its derivatives, aldehydes, aldoximes and hydoxyureas etc. The latter is mainly the short-chain hydroxamic acid. The features of the advanced double loop PUREX process with salt-free reagent are using dimethylhydroxylamine-monomethyl hydrazine to reduce and extract Pu during the U/Pu separation part and Pu purification cycle as well as using acethydroxamic acid during uranium purification cycle and separating Pu and Np from uranium.

According to the twelfth five year plan, a laboratory scale hot test should be done on the advanced salt-free double loop PUREX process during 2011–2015. If the hot test succeeds, verification tests will be carried out step by step in the CNNC 404 pilot plant. In order to provide the required conditions for the hot test, research will be focused on confirming the properties of the process and optimizing the technological parameters, including the conditions of Pu passivation cycle in non-reflux extraction, Pu unsalted conditioning technology, purification performance of the process to fragments, chemical and irradiation stability of salt-free reagents as well as treatment of salt-free reagents and their reaction products in the following process. Besides, developing new types of salt-free reagent is still proceeding. In order to improve the level of experimental technology, they developed mixer-settlers, a centrifugal extractor, feed pump and other experimental equipment and systems. Furthermore, they will carry out some research on materials of experimental devices and automatic control in order to make enough preparation for the hot test.

In the field of high level waste separation, the Institute of Nuclear and New Energy Technology, Tsinghua University in Beijing, proposed and developed the TRPO (Trialkyl Phosphine Oxide) extraction process of actinides in the end of the 1970s. From 1992 to 1993, they cooperated with the Institute for Transuranium Elements (ITU) in Karlsruhe, Germany, and finished thermal verification tests of the TRPO extraction process. From 1996 to 2000, they cooperated with the CNNC 404 Pilot Plant and did research on auxiliary technics of full separation process, mud washing tests and proposed advise on non-α of mud. Besides, research on extraction equipment and pre-feasibility of projects is also done by these institutes. They also came up with the CYANEX 301 extraction method.

Based on the above research achievements, Tsinghua University finished a miniature bench thermal verification experiment which lasted for more than 120 hours in 2009. It showed that the decontamination factor of α-emitting nuclides reached above 3×10^3. For nuclides with high heat release rate like Sr-90 and Cs-137, the decontamination factor can be more than 10^4 which can meet the technical requirements of making high level waste non-α and turning high level waste into low or medium level waste.

In terms of researching and developing non-aqueous reprocessing of nuclear fuel, China studied fluoride volatility methods for reprocessing in the 1970s. But it stopped because of serious equipment erosion. In the 1990s, cooperating with fast reactor projects, they did a few researches. In recent years, some preliminary studies of non-aqueous reprocessing are arranged in some projects like ADS, nuclear fuel cycle and nuclear safety which are supported by the Ministry of Science and Technology of the People’s Republic of China. But the R&D of non-aqueous reprocessing has not been included into the National Plan for the Development of Reprocessing.

The CNNC 404 pilot plant is designed and developed independently by China for reprocessing. They completed researches on water test, acid test and cold uranium test. In 2010, hot tests were successfully finished. After a long time of research and development, several technical problems were solved related to devices. For example, stable control of air-lift equipment, the engineering application of an air-purge set of liquid level non-contact measurement[1], or a reliability study of decanter and the development of a shearing machine. The successfully debugging and operating of the CNNC 404 pilot plant will provide important reference for designing and constructing large nuclear fuel reprocessing factories.

Although China made some progress in the development of reprocessing technology, great gaps still exist between China's technology and advanced international levels in respect of reprocessing devices, automatic control and remote maintenance.

3.4 The Development Strategy of Fuel Reprocessing/Recycling in China

After the restart in China in the wake of the Fukushima disaster, nuclear construction is progressing smoothly and steadily. The large-scale development trend becomes obvious day by day. It not only provides wide space for industrial development of reprocessing, but also gives serious challenges of the reprocessing abilities. Because of the complexity of the technology in the back-end of the fuel cycle, its development has fallen behind compared to other fields in nuclear energy and gets wide attention in both industry and society.

After operating nuclear power plants for more than 20 years, a large amount of spent fuel has been produced. Until 2020, more than 1000 tons of spent fuel will be generated from nuclear power plants per year, based on the nuclear development planning. At that time, the accumulated spent fuel production in China will be around 10 000 tons. Such massive amounts of spent fuel will bring serious challenges to their safety management. Accelerating the development of reprocessing allows no delay.

In recent times, people in the nuclear industry organized a series of discussions on China's current situation of reprocessing development. After summarizing comments from different parties, three aspects are focused:

1. Accelerating the industrialization process of spent fuel reprocessing is eagerly demanded according to the current situation of development;
2. Before achieving a closed fuel cycle, some contingency plan or phased transition options must become new projects.
3. The opportunity for promoting an industrial capacity of reprocessing in China is ready and the journey has already started.

A closed fuel cycle and spent fuel reprocessing, which can improve the utilization ratio of uranium effectively and decrease the volume of high level waste, are the set policy as well as strategic choices for the long-term strategic development of the nuclear energy in China. Moreover, the overall strategy of nuclear energy development in China is "thermal reactor – fast reactor – fusion reactor" (three-step strategy), and spent fuel reprocessing is the key point for moving towards the second step. Compared to the strategic planning process of fast reactors, the time and tasks of reprocessing development are becoming extremely urgent.

The reprocessing development is forced by the "three-step strategy". In the "three-step strategy", the multiple loop system of "reprocessing + fast reactor" is the second step of nuclear development in China. According to the development plan for the fast reactors, up to 2035 fast reactors will be put into commercial operation step by step.

Reprocessing projects should be started as soon as possible because of its complex technology and long construction period. Experts point out that in order to achieve large scale nuclear development, spending 15 years on completing commercialization of spent fuel reprocessing, 20 years on completing the study on fast reactors and demonstration projects of the fast reactor fuel cycle should be considered. In the time scale, the tasks and demands of these researches are quite urgent. So from now on, the harmony and coherence between the development of the reprocessing industry and the project construction schedule should be well handled [2].

---

[1] The air-purge set of liquid level non-contact measurement is one of the non-contact measuring methods. It transfers the measurement of liquid level to the measurement of pressure differentials. Using this method can measure the level, density and interface of the medium inside the equipment.

3.5 Key Technical Problems of Reprocessing/Recycling in China

3.5.1 Thermal Reactor Spent Fuel Reprocessing

The research objectives of the aqueous HYDRO process in China are as follows: enhancing researches on advanced reprocessing process flows to make it economic, safe and minimizing waste while separating U, Pu, minor actinides (MA) and low level fission products (LLFP) which can provide technical support for commercial reprocessing factories.

According to their reprocessing technology basis and the practice in most countries, the development of an advanced reprocessing technology will be based on the proven PUREX procedure. An improved PUREX process and the separation of the minor actinides from high level waste will be developed in order to apply the research achievements of reprocessing to the process flow design of reprocessing factories.

The improvement research of the reprocessing process is focused on simplification of the separation process (reducing cycle times) and using new types of salt-free reagents. As for the development of high level waste separation, its connection to the reprocessing main process and the connection between separated MA and transmutation will be studied. Besides process flows, reprocessing technology development also includes studies of special processing equipment and its material (especially for spent fuel cut-off machines and dissolvers), analysis and testing technology, criticality safety etc.

In conclusion, in China, R&D aimed at a commercial reprocessing factory construction will make full use of the research results accumulated over many years and the operation experience of the CNNC 404 pilot plant. Meanwhile, China will learn and import advanced and proven technique and equipment – like key process equipment, remote maintenance equipment and automatic control systems – from other countries. They will try to form a self-possession property right technology based on digesting and absorbing foreign technologies in order to obtain the initiative in the international cooperation and competition.

3.5.2 Fast Reactor Spent Fuel Reprocessing

3.5.2.1 Fast Reactor Spent Fuel HYDRO Process

For the fast reactor mixed oxide (MOX) spent fuel reprocessing, research on the HYDRO process has never been stopped in the world. So China will not give up its research on the HYDRO process of fast reactor MOX spent fuel reprocessing. In order to avoid detours and mistakes, enough investigation will be done in the start stage. Experts will be organized to discuss and evaluate in order to put forward reasonable research plans.

3.5.2.2 Fast Reactor Spent Fuel Non-aqueous Reprocessing

In recent years, non-aqueous reprocessing of spent fuel has become a hot research area in the world. China will conduct a wide range of investigations and master the entirely new progress in this area. It will have an in-depth discussion on the road of R&D in non-aqueous reprocessing, put forward its own R&D roadmap and carry out related feasibility studies. Meanwhile, international cooperation will be implemented actively in order to use research results in foreign countries and to promote the own R&D.

3.6 The CNNC 404 Pilot Plant and Reprocessing Factory Project

The China National Nuclear Corporation has mastered the key technology issues of spent fuel reprocessing and built China's first spent fuel reprocessing pilot plant: the CNNC 404 Pilot Plant. It has been developed and built for more than 20 years. From 2004 to 2008, water tests, acid tests and cold uranium linkage debugging were completed successfully. The hot tests started in March 2010. It achieved success on December 21, 2010, after finishing radioactive hot tests and producing qualified products, meaning that the goal of a closed fuel cycle is realized. It effectively promoted the development of the nuclear fuel

Fig. 5 – The hot test of the CNNC 404 Pilot Plant [4]

industry and nuclear power as well as providing an important research-experiment platform for developing advanced reprocessing engineering technology. It marked that China had mastered the spent fuel reprocessing technology [3].

After the successful hot test, China is still facing a series of tasks in reprocessing:

1. Operation of the CNNC 404 Pilot Plant and gaining empirical data;
2. Design and construction of thermal reactor spent fuel commercial reprocessing factories;
3. Research, development, design and construction of fast reactor spent fuel reprocessing factories [4].

The preparatory work for big commercial reprocessing factories was carried out according to the "we take the initiative, combination of Chinese and foreign" principle. In 2013, CNNC and Areva signed a letter of intent to cooperate on the reprocessing factory project. This factory will be built using international advanced reprocessing/recycling technology and will be able to reprocess 800 tons of spent fuel per year.

In March 2014, CNNC and Areva signed the memorandum of understanding in France on a reprocessing/recycling long term cooperation. By the end of 2013, China and France had cleared their scope of work and responsibility and finished the negotiations of the technical content. At present, they are following the technical negotiation minutes and implementing the technical content of the contract. In the next stage, the focus of the negotiation work will be turned to business negotiations [5].

3.7 Conclusion

Nuclear fuel reprocessing/recycling based on the U-Pu-cycle is the key problem of the fast reactor fuel cycle system, which is also the weakest link of China's fuel cycle system. Reprocessing/recycling is related to the thermal reactor spent fuel reprocessing, the fast reactor fuel fabrication, the fast reactor spent fuel reprocessing etc. It is complex systematic engineering, and a top level design must be done under the unified state plan and the overall layout in order to make sure that each link is developed in coordination with the others.

It may take 25 to 35 years for China to make technical breakthroughs in the main issues in order to achieve the industrialization of a fast reactor nuclear energy system and solve the worries of nuclear power sustainability in China.

References

[1] Gu Zhongmao, Chai Zhifang, 2011. Some thinking of nuclear fuel reprocessing/recycling in China. Process in Chemistry.

[2] *http://www.chinapower.com.cn/newsarticle/1230/new1230145.asp*

[3] *http://www.chinanews.com/ny/2010/12-28/2751155.shtml*

[4] *http://paper.people.com.cn/zgnyb/html/2011-03/14/content_767971.htm*

[5] *http://www.chinapower.com.cn/newsarticle/1210/new1210083.asp*

4

Nuclear Waste Disposal in China

4.1 Properties of Nuclear Wastes and Disposal Concepts

High level nuclear wastes are plutonium and other radioactive materials generated from nuclear power plant operation and nuclear weapon manufacturing and dismantling. They are highly radioactive and the half-life period can be thousands, tens of thousands or even hundreds of thousands of years. This means that after hundreds of thousands of years, these wastes can still cause harm to humans and the environment. So how to dispose nuclear wastes safely and permanently is an important subject for scientists [1].

4.1.1 Properties of Nuclear Waste

From a technical perspective, nuclear wastes fall into three categories: high level wastes, medium level wastes and low level wastes. High level wastes include spent fuels and their treatments after using them to generate electricity. Medium and low level wastes include contaminated equipment, checkout equipment, hydration systems under operation, exchange resin, wastewater, waste liquid and labor protection appliance like gloves, which account for 99% of all nuclear wastes. Medium and low nuclear wastes are less harmful, whereas high level wastes contain many highly radioactive elements which are extremely harmful to human health. So the disposal methods for different nuclear wastes are not the same. The following particular properties of nuclear wastes make it troublesome for disposal.

- Radioactivity: The radioactivity of nuclear wastes cannot be eliminated by physical, chemical or biological methods in a general way. It can only be reduced by the radioactive decay itself.
- Radiation hazards: When the rays emitted from nuclear wastes pass through matter, ionization and excitation will happen, causing radiation damage to living bodies.
- Thermal release: In nuclear wastes, radionuclides release energy by decay. When radioactive nuclides are highly concentrated, the released heat will lead to the increase of the waste temperature, as far as to boil if it is in liquid form and melt if solid.

4.1.2 Disposal of Nuclear Wastes

The International Atomic Energy Agency (IAEA) has issued requirements on nuclear waste disposal and requires every country to follow them. When disposing, all the countries must accept international supervision.

For medium and low radioactive wastes disposal, IAEA requires that – no matter if solid or liquid nuclear wastes are handled – they should have a conditioning and then be put into a sealed container and a shallow land repository.

As for high level wastes, there are two treatment methods worldwide. One is regarding spent fuel as nuclear waste. After treatment, the fuel is put into canisters and ultimately buried deep underground. At present, countries such as the USA, Russia, Canada, Switzerland, Sweden and Finland are using this direct disposal. It is the most safe nuclear waste disposal method and is internationally recognized.

The other method is to reprocess the fuel to regain the uranium and the plutonium and to store in the deep geological repository the remaining fission products and minor actinides only.

4.2 Current Situation of Nuclear Waste Disposal and its Future

In the past thirty years of operation, China's nuclear industry stored up to tens of thousands of cubic meters of medium and low level solid wastes. At present, 150 tons of high-level wastes are generated per year. Besides, experts speculate that the pressure on nuclear waste storage space will appear around 2030. At that time, the high level wastes generated by the NPP alone will reach up to 3200 tons.

Up to now, China has built two medium & low level waste repositories and plans to build two more. The two completed repositories are in Beilong which is close to Daya Bay in Guangdong Province, and in Yumen, Gansu Province. But there are no high level waste repositories in China yet.

4.2.1 Low and Medium Level Waste Repositories

The Beilong repository covers an area of 210 000 square meters. The total design handling capacity is 80 000 cubic meters. It is five kilometers away from Daya Bay NPP and four kilometers away from Ling-ao NPP. Medium and low level solid wastes generated from the NPP in Guangdong and in areas close to Guangdong are sent here for perma-

Fig. 6 – Exploring the site for a high level waste deposit: a scientist is checking a drill hole in Beishan, Gansu Province [3]

nent disposal. It took a 10-year period from the site selection and exploration in 1991 to temporarily store the contaminated guide cylinders from Daya Bay in November 2001.

As a kind of relatively simple civil nuclear treatment facility, the Beilong repository is designed with 70 disposal units within 130 000 square meters. Every disposal unit is a 17m×17m×7m shielded box made of ferroconcrete. When a disposal unit is full of waste packages, the gaps between the waste packages are filled with cement paste in order to immobilize them and strengthen the shielding. Then the disposal units will be capped by ferroconcrete. Even if an earthquake happens, it is still a whole cement block and cannot be broken down easily.

The other low and medium level repository is the North West repository in Yumen, Gansu Province. It is located 10 to 20 meters below the surface. Dozens of square kilometers around the repository are closed to the public. A medium and low level waste repository needs an isolation period of 300 to 500 years.

Compared to the impulsion of fighting for nuclear power projects in various regions, regional governments have quite a backlash on building repositories locally. The site selection of the East China repository has not been decided yet because of this reason. Authorities believe that it should be built in Zhejiang Province, because the construction of NPP's in Zhejiang was the first in time and largest in quantity.

According to calculations, building a low and medium level waste repository now needs around CHF 30 million. According to the plan, in addition to the two repositories which have been built in the northwest and south part of China, two more regional low level waste repositories will be built in Southwest and East China [2].

4.2.2 High Level Waste Repositories

In order to avoid harmful effects on environment, high level wastes must go through strict conditioning processes. First, the nuclear wastes must be transformed into a vitrified solid and then put into canisters that can shield the radiation. Finally, they have to be placed in repositories that are 500 to 1000 meters underground. Because the half-life period of these nuclear wastes range from tens of thousands of years to one hundred thousand years, when choosing the repository site, the geological conditions must guarantee the safety of the repositories at least for that time.

In the first half of 2015, the State Commission of Science and Technology for National Defense Industry ran a seminar about disposing high level wastes and started planning for medium and long term nuclear waste disposal. The final goal is to build a permanent high level waste repository in China. The canisters' design lifetime would be 10 000 years.

After the safety is assured by the geology. the repository's capacity should be able to store the high level nuclear wastes generated during 100 to 200 years in China. When full, it will be permanently sealed. This means that at least within the next 100 years, there will be a second permanent high level waste repository in Chinese Mainland.

According to the nuclear power development plan, China will determine the site of the first permanent high level nuclear waste repository between 2015 and 2020. At present, there are six regions chosen for site reconnaissance nationwide. They are East China, the southern part of China, South West China, Inner Mongolia Province, Xinjiang Province and Gansu Province.

In East China, the site selection was once considered at the junction of Jiangsu, Zhejiang and Anhui Provinces. The geology and lithology there are relatively good. But taking the future economic development of this region into consideration, no more investigation work was done in the end.

The site in Beishan in Gansu Province is often assumed to be the first underground high level nuclear waste repository in the Chinese Mainland. Its code name is "Beishan Number One". But its exact name is "Pre-selected Site of High Level Waste Geological Disposal Repository in Beishan, Gansu Province". It is 25 kilometers away to the southeast of Mo Kao Grotto at Dunhuang. It is in the Gobi desert which has the same area as Hainan Province. Human beings are few and far dispersed in this zone. The population in the entire region is less than twelve thousand. The economic development in Beishan is relatively backward. There are no mineral resources around. Therefore, building nuclear waste repositories would have little negative influence on the economic development.

The climate conditions are also ideal. The average annual rainfall is only 70 millimeters while the evaporation capacity reaches 3000 millimeters. So the underground water level is very low and reduces the risk of radioactive elements diffusing with underground water. Besides, Beishan has convenient transportation facilities. The repository site is only 70 to 80 kilometers away from the railway. And the geological conditions of Beishan are excellent. It is located in a stable region within the crustal movements. The repository site has a complete granite body which is a good "protection suit" to deal with radiation. After conducting a field study, experts from the International Atomic Energy Agency (IAEA) declared that Beishan is one of the best-suited nuclear waste repository sites in the world.

Previously, the State Commission of Science and Technology of the National Defense Industry has planned three stages for the research and development (R&D) and engineering construction of high level repositories:

(1) underground lab R&D and site selection of repositories (2006–2020)
(2) underground testing (2021–2040)
(3) repository prototype verification and repository construction (2041–2050).

But the current progress is so slow that it is scarcely possible to finish the underground lab construction before 2020 [3].

Since the start of drilling in Beishan-1 in 2000, the project has now entered into Beishan-6. Nineteen holes were drilled in total and eight of them are shallow boreholes. Compared with the international situation, the data acquisition for such a large area like Beishan is far from being enough. Some repositories in other countries had thousands of boreholes, which is not only time-consuming but also expensive. The average cost of drilling is CHF 180 000 per hole. The expenditure of drilling holes alone is an enormous figure. The accumulated input of USA's Yucca Mountain Project has reached USD 40 000 million in 2010.

4.3 The Necessity of Constructing High Level Waste Repositories

Before the completion of nuclear waste repositories, the high level wastes in China can only be temporarily stored in Boron pools on site in the NPPs. If the construction of the repository cannot be completed timely, the Chinese nuclear industry will be faced with the fact that the nuclear wastes can be stored nowhere.

In this respect, the USA (and other countries) had to learn some painful lessons. Their original plan was to complete the construction of a high level waste repository in 1998. Although the US Government put heavy financial resources and manpower into research, there is still no high level repository in operation.

China has not yet completed any commercial spent fuel reprocessing plants. But high level solid wastes will be produced ultimately regardless of the preferred fuel handling method. This will either be high-level vitrified wastes generated by reprocessing plants or spent fuel from NPPs for once-through direct disposal. Finally, they all need to be put into high-level waste repositories. At present, the storage situation is a little bit stressful. There is only little storing space in NPPs. It has come to the point of having to build repositories quickly to store high-level wastes.

4.4 Conclusions

Scientists in China are studying on how to dispose nuclear wastes. For medium and low-level wastes, China is able to dispose them safely by means of landfill. For disposing of high-level wastes, countries such as Sweden and Finland have achieved some progress in order to meet the safety standards after treatment. In China, the high-level waste repository is planned to be completed between 2030 and 2040, which is quite urgent. Its capacity should be enough to hold all high-level wastes generated by China's nuclear industry in the next 100 to 200 years. The repository will confine the nuclear wastes in deep underground forever. However, the high-level waste repository is a costly project. According to the future size of China's nuclear power fleet, the high-level waste repository will cost around CHF 10 000 million. Only if this issue can be dealt well with, nuclear power is really a promising technology for China.

References

[1] China.com: Chinese Interpretation 31st Issue: *http://news.china.com/jiedu/20140724/*
[2] Tiexue Internet Forum: *http://bbs.tiexue.net/post_6961832_1.html*
[3] Southern Weekly: *http://www.infzm.com/content/101619*

5
Development of the Molten Salt Reactor (MSR) in China

5.1 Introduction of the MSR

The MSR is a fission type reactor. Its primary coolant is a salt-mixture in a molten state. It can be operated at high temperatures (with higher thermal efficiency) while keeping a low vapor pressure in order to decrease mechanical stress and to improve safety. And it has lower chemical activity than a molten sodium coolant [1]. The nuclear fuel can be solid fuel rods or can be dissolved in the coolant. So there is no need to fabricate fuel rods. The reactor structure is simplified and the burn-up is homogeneous. On-site nuclear fuel reprocessing is feasible.

The liquid fluoride thorium reactor (LFTR) is the most famous MSR type. In many designing schemes, nuclear fuel dissolves in molten Villiaumite coolant and forms UF_4 and other compounds (Villiaumite is a mineral composed of sodium fluoride). In the reactor core, graphite is used as moderator and liquid molten salt reaches criticality therein. The design of liquid fuel reactors has a significantly different focal point of safety compared with solid fuel reactors: It is less likely to have reactor accidents (such as LOCA, reactivity addition, heat removal from the reactor primary circuit). But the likelihood of operating accidents increases.

Recent research is focused on the real advantages of high-temperature, low-pressure main cooling circuits. Many modern design schemes use ceramic fuels uniformly distributed in a graphite matrix and molten salt to provide cooling in a low pressure and high temperature environment. Molten salt can remove heat from reactor cores very effectively in order to reduce requirements from pumps, pipelines and core size. The dimension of these components can be reduced.

5.2 Some Advantages of MSRs

Being the only liquid fuel reactor among the six Generation IV reactor type candidates, the MSR has many advantages such as a simple structure, operable at normal pressure etc. The reactor can be built compactly. It can be operated for several decades after putting a certain amount of nuclear fuel into it. After sufficient burning, theoretically the nuclear wastes generated by MSRs will be only one thousandth of the existing technology [2].

The operation of traditional nuclear reactors is accompanied by the production of Plutonium. Therefore, the peaceful use of nuclear energy is accompanied by the nuclear proliferation risk. But burning Th-232 will generate U-233 along with some U-232 and its strongly radioactive decay products as impurities. So the Th-U nuclear fuel is unsuited for developing nuclear weapons, which is internationally recognized.

A MSR is operated under normal pressure rather than at high pressure like traditional light water reactors, what makes the operation safe and simple. If the core temperature would rise above the safe value, the frozen plug at the bot-

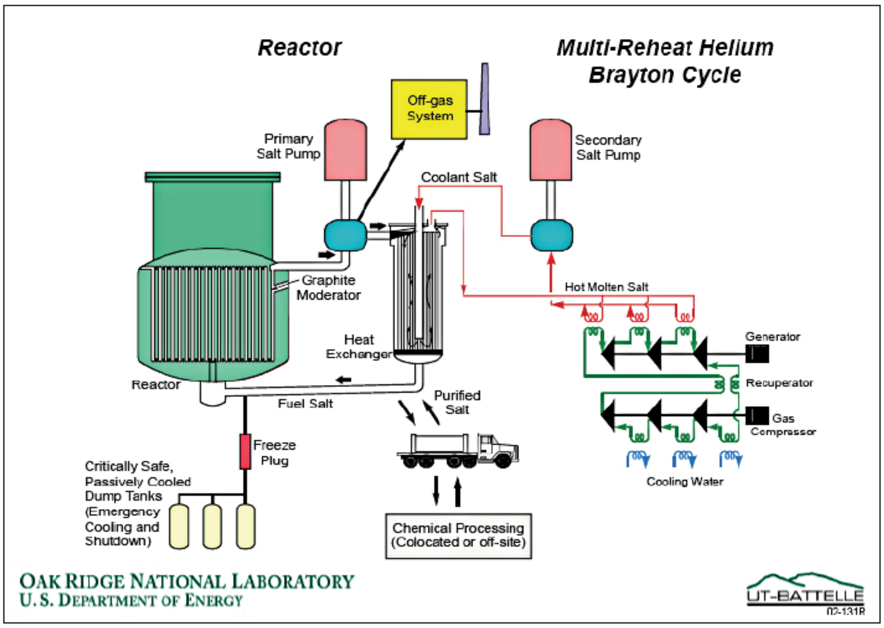


Fig. 7 – Overall structure of a Molten Salt Reactor

tom will fuse automatically. The molten salt with the nuclear fuel will flow completely into emergency storage tanks and the nuclear reactions will stop. Because the coolant is fluoride salt (carrying the nuclear fuel), it will become solid after cooling. So the nuclear fuel is very unlikely to leak or dissolve into groundwater and cause ecological disasters. This gives more freedom for the site selection of a MSR. In addition, it can be built tens of meters underground, which does not only isolate the radiation completely, but also prevents attacks. It can be built in big cities as well as in the wilderness to provide long-lasting power to remote villages.

5.3 The Situation of MSR Development in China

5.3.1 Energy Background

Fossil fuels will be depleted one day. Solar energy and wind energy are not stable. Hydropower development has already reached the limit. Nuclear energy seems to be a reliable choice for China's mainstay energy in the future. It has a high energy density, low carbon emissions and the potential for sustainable development.

Striving to develop nuclear energy has become the key point of China's medium and long-term energy development plan. At present (December 2015), China has 30 in-service nuclear power units. The installed generation capacity is 26.67 GWe and 2% of the total electricity is produced by nuclear power.

According to the development plan from the National Development and Reform Commission (NDRC), there will be 70 nuclear power units in operation in 2020. It is estimated that in 2030, the proportion of nuclear power in China will reach 10% of its electricity generation, and in 2050 the installed generation capacity will be over 400 GWe, which exceeds the present total installed generation capacity in the world. However, most of the operating nuclear reactors in the world are thermal reactors, that is to say, using thermal neutrons to induce fission. The main nuclear fuel consumed by the thermal reactor is U-235. Its reserves in the nature are only 0.71% of the total uranium. Most of the rest, 99.02% is U-238. Therefore, China's and also the world's rapid development of nuclear energy will be faced with the severe challenge of a stable nuclear fuel supply in the future.

In 2005, China's total GDP was CHF 2 800 000 million. The total consumption of primary energy is 2230 million standard tons of coal. Nowadays, China has become a top greenhouse gas emitter. In another thirty or forty years, China's total GDP might reach CHF 18 000 000 million. The corresponding energy demand will increase enormously. Meanwhile, the greenhouse gas emissions should be reduced rather than increased. This seems impossible without using nuclear energy. In terms of existing nuclear power technology, 1 kg uranium can release 82 million Megajoule thermal energy while 1 kg standard coal can only give 29 Megajoule.

Therefore, in the face of global climate change, the need for energy conservation, emission reduction and the low carbon economy are prompting the revival of nuclear energy in China.

5.3.2 History of Development

As a matter of fact, the first reactor type developed in China was a thorium reactor. Most of the researchers were older generation elite scientists who had studied in the USA. In the late 1960s, the Shanghai Institute of Nuclear Research (now Shanghai Institute of Applied Physics, Chinese Academy of Sciences) carried out research on U-233 purification processes. Since the 1970s, under the leadership of Zhang Jiahua, the Shanghai Institute of Nuclear Research studied uranium-thorium nuclear fuel circulation for twenty years. China's first nuclear power plant, Qinshan NPP in Zhejiang Province, was even prepared to use molten salt reactors. But the outcome of the debate in that time was to adopt the pressurized water reactor (PWR) which already had some experience in submarines. This led the research on thorium-based reactors to a standstill [3].

After entering the 21st century, the Chinese Academy of Sciences (CAS) restarted the study on MSRs. Recently the government of China announced plans to appropriate CHF 385 million as special project research fund looking forward to building a 2 MWe test reactor as soon as possible. This will make the MSR, along with the High Temperature Gas-cooled Reactor (HTGR), built by Tsinghua University in Beijing, and the Sodium-cooled Fast Reactor (SFR) built by the China Institute of Atomic Energy (CIAE) the most important three types of Generation IV reactors in China.

5.3.3 Development Plan

On January 25, 2011, in the "Innovation 2020" press conference held during the CAS 2011 annual work meeting, CAS announced that the thorium-based Molten Salt Reactor (TMSR) nuclear project started implementation.

The aim of the TMSR project: doing the research and development for a TMSR Generation IV fission reactor nuclear system within 20 years. All the technologies meet pilot level and with independent intellectual property rights. Cultivate a TMSR technology team with more than one thousand talents, a wide range of disciplines and techniques, reasonable age distribution, international leading level and industrial capacity. Complete a world-class TMSR study base.

The TMSR project gives consideration to scientific research, technological development and engineering construction. It starts from the basic scientific problems of thorium MSRs and looks into the laws of physics. It will begin with the engineering and construction of a small reactor and gradually enlarge the scale. Related key techniques will be developed and finally all the key TMSR techniques will be mastered and achieve industrialization. Here is the roadmap:

(1) Preliminary stage from 2011 to 2015: Establish a perfect research platform. Learn and master the existing technology. Carry out research into key science and technology problems. The goal of the project is to build a 2 MWe thorium based molten salt experimental reactor and reach criticality at zero power level. Unfortunately, the time table for the end of this year will not be met. According to the new plan, the construction of the 2 MWe MSR will start in 2017.

(2) Developing stage from 2016 to 2020: Complete the thorium based MSR pilot system. Fully solve the related scientific and technical problems. Reach the international advanced level in the field. The project goal is to build a 10 MWe thorium MSR and reach criticality.

(3) Breakthrough stage from 2020 to 2030: Build an industrial-size thorium-based demonstration MSR nuclear power system and solve related scientific problems. Develop and master all the key technologies. Realize the industrialization of small modular MSRs. The project goal is to complete a 100 MWe thorium-based demonstration MSR nuclear power system and reach criticality.

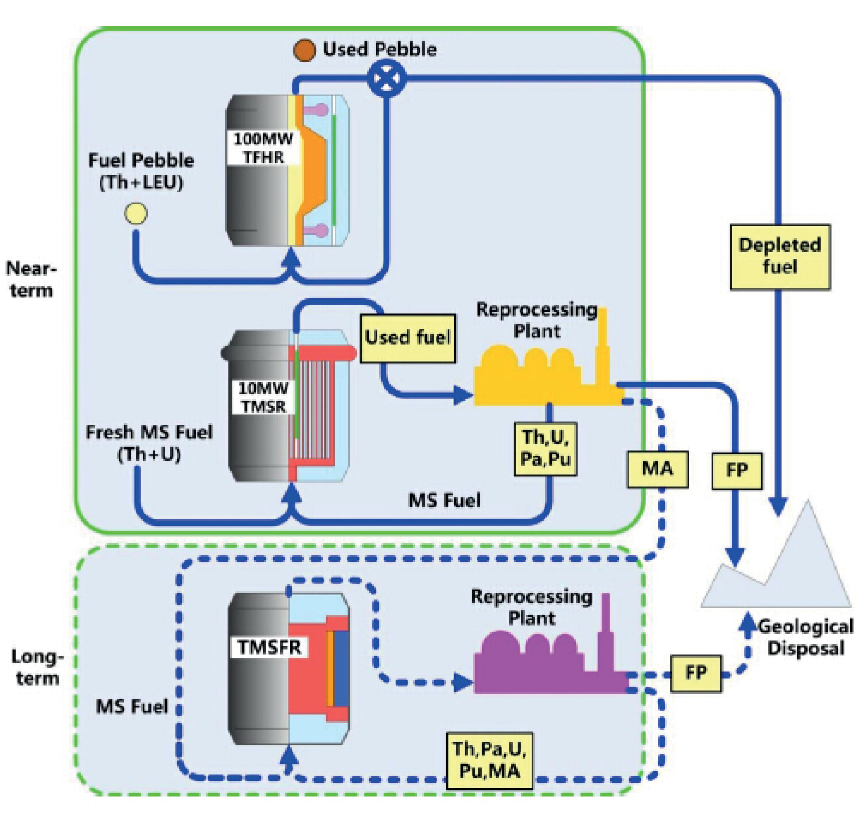


Fig. 8 – Nuclear fuel cycle of a Molten Salt Reactor (graph provided by the Shanghai Institute of Applied Physics)

On August 16, 2006, the North American Energy Corporation announced that they were ready to develop thorium-based nuclear power generation facilities and thorium batteries. But because the global next-generation nuclear reactors are still in research and development, China is likely to get all the intellectual property rights if they develop a thorium-based MSR independently. This will enable China to firmly grasp the lifeline of energy in its own hands.

Although the prospects are exciting for scientists, many difficulties need to be mastered. It took nearly 20 years from the first successful test of the first reactor in the world to the commercial promotion of NPPs. And from that time on until the maturity of the current mainstream NPP technology was another 20 years of development. It may also need 20 to 30 years before MSRs are achieving widespread application.

5.3.4 Achievements in Scientific Research

China has already obtained many important achievements in the research of thorium nuclear reactors. Research and technological innovation capability has reached the advanced world-class level [4].

5.3.4.1 Successful Commissioning of a HTS Molten Salt Loop

On January 17, 2012, the first HTS (a mixture composed of 40% $NaNO_2$, 7% $NaNO_3$, 53% KNO_3) molten salt thermal test loop of the TMSR project achieved successful commissioning in the Shanghai Institute of Applied Physics, Chinese Academy of Sciences [5].

In this nuclear power system, the cooling medium assumes the transmission of the thermal energy generated by the reactor. Its thermal-hydraulic design is related to the thermal energy and thermal safety of the reactor and is the key technology of this nuclear energy system. But the molten salt coolant used in the MSR also bears the function of the nuclear fuel carrier at the same time. So the circulation circuit and thermal-hydraulic design of a MSR are decisive factors for safety, stability and reliable operation.

The TMSR project is in accord with the principle of "from small to large" and "from the easier to the more advanced". Scientists plan to construct four large molten salt test circuits within five years in order to study the thermal hydraulic characteristics of the molten salt, master the design and operation of the molten salt loop, test the loop structure materials and key equipment and in the end finish the thorium-based MSR design and construction tasks.

The HTS molten salt thermal test loop with nitrate as working medium is the first test loop of the TMSR project. The HTS test loop is a system with complete preheating and feeding, heating, recycling and cooling functions. It uses Inconel™ (an austenite nickel-chromium-based superalloy) and a centralized network control system based on an Experimental Physics and Industrial Control System (EPICS). This loop was constructed since the middle of October 2011. On January 13, 2012, equipment installation and debugging of parts were completed.

The overall testing and adjusting work started with loading the molten salt on January 14. After three consecutive days of testing and adjusting, in the afternoon of January 16, the loop circulation ran successfully, followed by isothermal operation testing and adjusting under different temperatures and the testing and adjusting of small temperature differences. In the morning of January 17, large temperature difference operation testing and adjusting at 400 degrees centigrade was completed.

The success of the loop testing and adjusting marks that the TMSR project has now an initial capacity for molten salt thermal hydraulic tests. Thermal hydraulic parameters of the molten salt medium under different conditions as well as high temperature molten salt loop equipment can be measured and tested. Thus, experience for future design, construction and operation of loops is gathered.

5.3.4.2 GH3535 Alloy

The ultimate mission of the TMSR project is to solve the looming energy crisis and develop a new generation of nuclear technology which is safer and has lower cost and higher fuel efficiency. This project is led by the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. The Institute of Metal Research, Chinese Academy of Science in Liaoning Province is responsible for the metal alloy preparation for this system [6].

The task undertaken by the Institute of Metal Research seems insignificant, but it is the most important part of the entire system. In the design of the Generation IV rector systems, the liquid MSR is considered to be an ideal reactor type for thorium resource utilization. But most of the materials used in a MSR need to be strong in multiple extreme environments such as high temperature, extreme corrosion and neutron radiation. This makes the most stringent requirements for the materials. Dr. Dong Jiasheng and Dr. Han Weixin from the Institute of Metal Research led the team to undertake this task and developed qualified structural metal materials for the MSR.

The choice of the metals, on the one hand, is related to nuclear radiation safety of the surrounding personnel and environment. On the other hand, their performance affects the service life of the thorium-based MSR as well as its costs and benefits. By design and optimization of alloy composition, they eventually developed the GH3535 alloy, which can meet the requirements, with independent intellectual property rights.

Furthermore, the researchers made breakthroughs in rolling and precision shaping of the GH3535 alloy. This material will be processed into plates, pipes and welding wires etc. which are needed for MSRs. They also prepared vessel samples and loop piping components for the 2 MWe MSR, meeting the needs of alloys used in small power MSRs.

At present, the GH3535 alloy they have developed can withstand temperatures up to 650 degrees centigrade and harsh molten salt corrosion. With the in-depth research in the future, materials which can meet the operating requirements at 700 or even 800 degrees centigrade are expected to be developed. However, although the Institute of Metal Research made breakthroughs in a series of GH3535 key technologies, the long-term stability of the material is still subjected to the test of practice.

5.3.5 International Cooperation

The US Department of Energy (DOE) plans to sign a 10-year cooperation agreement with the Chinese government, assisting China to build at least one MSR in this period. The United States intends to develop the MSR which can be built in the United States eventually through a large-scale cooperation between the DOE and the Chinese Academy of Sciences [7].

China will implement this work and share information with the US. The US will also send experts to provide support for China. China has a shorter period of time in developing MSRs and needs technical support. They may benefit from the DOE's help. If they can finish the project and build an experimental reactor, they can provide scientists in this field with a lot of useful information. Based on this 10-year cooperative research and development agreement, the DOE and the Chinese government signed a small scale memorandum of understanding at the end of 2011. The content is to cooperate on MSR technology. According to the new plan, China will provide a lot of money.

In the initial phase, the two sides will not focus on copying Alvin Martin Weinberg's famous experimental reactor in Oak Ridge, Tennessee, in 1967. Weinberg used liquid fuel: he mixed uranium and molten salt. This mixture was both reactor fuel and coolant in the reactor. The DOE will focus on helping China to develop a cobblestone-shaped solid fuel reactor using molten salt as the coolant.

China also plans to build a liquid fuel MSR eventually. In this respect, the cooperation with the DOE can also help. To promote efficiency, China plans to use thorium fuel instead of uranium.

5.4 Conclusion

The MSR is the only liquid fuel reactor among the six Generation IV reactors. It has huge advantages over other reactors in inherent safety, economy, sustainable development with regard to nuclear resources and nuclear nonproliferation. At present, China has been moving towards the world leading level in the development of MSR and gradually developed many key technologies with independent intellectual property rights. In addition, China has natural advantages in the development of MSR. Abundant thorium resources in Inner Mongolia can guarantee that China will not be beset by problems of the MSR's fuel supply. The development of HTGRs with MSR would be a revolutionary change in China's energy industry. China will likely become one of the world's energy powers and achieve greater advantages in development in the 21st century.

References

[1] Baidu baike: Molten Salt Reactor: *http://baike.baidu.com/*

[2] Shanghai Institute of Applied Physics, Chinese Academy of Sciences: *http://www.sinap.cas.cn/xwzx/cmsm/201209/t20120910_3640782.html*

[3] Douban: *http://www.douban.com/note/168411688/*

[4] Tiexue BBS: *http://bbs.tiexue.net/post_6673616_1.html*

[5] Shanghai Institute of Applied Physics, Chinese Academy of Sciences: *http://www.sinap.cas.cn/kxyj/kyxm/201209/t20120905_3639171.html*

[6] Phoenix New Media: *http://news.ifeng.com/a/20140814/41575311_0.shtml*

[7] Phoenix New Media: *http://finance.ifeng.com/a/20150206/13486567_0.shtml*

6

Development of the Sodium-cooled Fast Reactor (SFR) in China

6.1 Basic Principles of the Sodium-cooled Fast Reactor

The sodium-cooled fast reactor (SFR) is a Generation IV reactor in which liquid metallic sodium is used as the sole coolant, carrying heat from the core. “Fast reactor” is the short term for fast breeder reactor. It is a type of reactor in which nuclear fission is mainly caused by fast neutrons with an average energy above 0.1 MeV. Its most important characteristic is that while consuming the nuclear fuel, it can breed more fissile fuel than it consumes. The more you burn, the more nuclear fuel and less nuclear waste you will have [1].

Currently, there are more than 400 nuclear power plants all over the world, most of which are light water reactors. Pressurized water reactors and boiling water reactors are two types of light water reactors. Fission reactions are mainly caused by thermal neutrons. So they are also known as thermal reactors. U-235 is the main nuclear fuel consumed by thermal reactors.

There are three natural uranium isotopes: U-234, U-235 and U-238. Nuclear fission of U-234 will not occur. U-238 is not fissionable by thermal neutrons. Only materials like U-235 can be made into nuclear fuels because they can allow nuclear fission easily.

However, the nature reserve of U-235 is only 0.72% of all uranium. Most of the rest is U-238. It accounts for 99.27%. To ensure the normal nuclear reaction, light water reactors usually use U-235 which has an enrichment of 3-4%. That is to say, only 3-4% of the nuclear materials are involved in the nuclear reaction. Almost all of the rest is uranium-238.

In the early times of studying nuclear reactions, researchers found that when participating in fission, U-238 absorbs a small amount of the fast neutrons and becomes U-239. But U-239 is very unstable and quickly decays into Pu-239. Pu-239 is again a fissile material similar to U-235. Based on this property, in the late 1960s, French scientists produced the first fast reactor by increasing the fast neutron production. The U-238 in the fuel is continuously converted into Pu-239 by fast neutrons. Since the production is greater than the consumption, the initial fuel is breeding continuously fissile Pu-239 out of not fissile U-238.

6.2 The Significance of Developing the SFR in China

Many developing countries attach great importance to the development of nuclear power. In Asia, China amazes the world by its large number of nuclear power plant construction programs. According to these plans, China will build 58 new 1000-Mega-class nuclear power units by 2020, which is equivalent to the total number of nuclear power units in France at present. But the large-scale nuclear power construction program is in contradiction of the increasingly depleted uranium resources. It is predicted that by 2030, 80% of the world’s low-cost and easy exploitation uranium resources will be consumed. So the awkward situation may appear that the NPPs in China will not have enough nuclear fuel in the near future.

Fast breeder reactors can solve this problem. U-238 can be saved from nuclear wastes and turned into nuclear fuel so the utilization ratio of uranium ores increases from 1% to more than 70%. Besides, it can transmute long-lived radioactive wastes produced from light water reactors and minimize the amount of radioactive wastes [2]. Furthermore, fast reactors, which are recognized as optimizing reactors in Generation IV advanced nuclear energy systems, show high safety and reliability [3]. Development and promotion of fast reactor technology is of great significance in enhancing the sustainable development of China’s nuclear power and establishing an advanced fuel cycle system.

6.3 The China Experimental Fast Reactor (CEFR)

The CEFR, located in Fangshan near Beijing, is the first fast reactor in China. Its thermal power is 65 MWth and electric power is 20 MWe. It uses a “sodium-sodium-water” three circuit design. The primary circuit is an integrative pool type reactor structure. The core inlet temperature is 360 °C. The outlet temperature is 530 °C. The steam temperature is 480 °C. The pressure is 14 MPa. The decay heat removal system is passive, directly cooling the sodium in the reactor core.

Fig. 9 – The China Experimental Fast Reactor (CEFR) of the China Institute of Atomic Energy (CIAE) in Fangshan near Beijing [1]

6.3.1 Outstanding Features

The CEFR is the first step of the fast reactor development in China. It's one of the few high power experimental fast reactors with power generation function in the world. Its main system settings and parameter selections are the same as other large fast reactors in the world. The CEFR has advantages in inherent safety and uses a variety of passive safety technologies. It uses an advanced pool type reactor structure. In this structure, even if the circulation pumps fail or if a sodium loss caused by pipeline rupture or blockage of sodium influx occurs, the core is still in a large pool of sodium. The large amount of sodium in the pool has enough heat capacity to absorb the decay heat and has the ability of natural convection. It can prevent a loss of coolant accident (LOCA). In this respect the pool type reactor structure is superior in safety to the loop type reactor structure. Its safety meets the requirements of a Generation IV nuclear system.

6.3.2 History of Development

China's fast reactor research began in 1965 and embodied painstaking efforts from generations of people. It went through a fundamental study stage (1965–1987) and an applied basic research stage (1987–1993). Now it is in the experimental design validation stage (since 1995). In the late 1960s, Premier Zhou Enlai personally approved 50 kg of enriched uranium for a fast reactor zero power construction. At that time the research was focused on fast reactor neutronics, engineering thermodynamics, sodium processes, materials and other fundamental aspects. By 1987, China had built 12 sets of test devices and sodium loop devices, including a fast zero-power device. It reached criticality at the end of June, 1970.

In 1987, the fast reactor technology was listed as one topic of the 863 Program (National High-tech Research and Development Program). This accelerated the fast reactor research. At that time, elite fast reactor researchers throughout the country converged on the Ministry of Nuclear Industry and the government allocated special funds to establish a special fast reactor research laboratory. In 1992, it was officially named Fast Reactor Research Center and started basic research for application aiming at a 65 MWth CEFR.

It successfully carried out research work on 9 topics and 60 sub-topics, acquiring a large number of scientific achievements. Around fifty calculation programs were developed and designed in the fields of physics, thermo hydraulics, fuels, mechanics and safety, basically meeting the needs of software in a fast reactor design. It had built multi-functional purification sodium test beds and medium scale sodium purification equipment. Practical sodium purification technology was successfully developed and a high temperature sodium boiling test loop was established, providing the analytical basis for the safety design of the fuel elements. The scientists also successfully developed fast reactor fuel cladding and core structure materials, making overall technology preparations to provide the CEFR with homemade materials.

6.3.3 Process of Construction

The CEFR has 15 sub-items and 219 systems. At the end of 1995, this project was approved by the relevant department. In 1997, the preliminary design of the reactor was completed. On May 30, 2000, the first pot of concrete was poured. On July 18, 2000, Chinese President Jiang Zemin and Russian President Vladimir Putin attended the signing ceremony of "Chinese and Russian governments for the construction and operation of an experimental fast neutron reactor in China cooperation agreement", pushing the fast reactor technology cooper-

Fig. 10 – On August 15, 2002, the CEFR nuclear main building was officially capped [1]

ation between the two countries to the new height of national level. In August, 2002, the nuclear island main building was capped.

On August 11, 2005, the first large parts were hauled into the reactor hall for installation [4].

At 9:50 on July 21, 2010, China’s first fast reactor which was developed and researched independently by CIAE reached criticality for the first time. This is a major independent innovation achievement in the field of nuclear power in China, meaning that China achieved a great breakthrough in the technology development of Generation IV advanced nuclear energy systems. Thus, China has become one of the few countries mastering fast reactor technology. At 10:00 on July 21, 2011, the CEFR was connected to the grid successfully for the first time.

In November, 2012, the CEFR project passed expert acceptance of the Science and Technology Organization. Experts believe that the completion of the CEFR marks a significant breakthrough in the key second step of the nuclear energy three-step development strategy: “Pressurized Water Reactor (PWR) – Fast Reactor – Fusion Reactor”. This breakthrough also marks China’s entry into the international advanced level in the Generation IV nuclear power technology research and development.

At 17:00 on December 15, 2014, the CEFR reached 100% power for the first time. At 17:00 on December 18, it achieved stable operation at full power for 72 hours. Main technological parameters and safety performance indicators met the design requirements. This indicates that China has fully mastered the core technology of fast reactor design, construction, commissioning and operation. The realization of 72 hours full power operation laid a solid foundation for the subsequent development of fast reactor technology, industrialization application and nuclear fuel cycle technology. Subsequent performance verification tests will be done in order to realize industrialization as soon as possible.

Fig. 11 – The on-site situation of the CEFR at full power operation [3]

Up to 10:00 on December 19, 2014, the CEFR had been in grid-connected operation for 438 hours. The electric energy production was more than 3 million kWh. The on-grid energy was over 1.8 million kWh. Materials and fuel irradiation test experiments were also carried out at the same time. Follow-up tests such as full power scram tests, reactor core natural circulation tests, argon gas leakage rate tests and other concomitant tests were finished in the first half of 2015.

6.3.4 Development Planning

Fast reactors occupy a very important position in China's nuclear energy strategic layout. According to the plan, the fast reactor development in China is divided into three steps:

(1) The CEFR is the first step of development. Its main purpose is to accumulate design, construction and operation experience and to test and irradiate fuels, materials and equipment.
(2) The second step is to design, construct and operate a Chinese 600 MWe prototype or demonstration fast reactor. This goal has been included in the 2006–2020 Medium and Long Term Science and Technology Plan. Design preparation has begun. The reactor named CFR600 will be put into operation in 2020.
(3) The third step is to build 1000-1500 MWe high breeding commercial fast reactor nuclear power plants. The expected completion is in 2025 and mass construction and promotion will be from 2030 to 2035.

In this way, only 250 000 to 300 000 tons of natural uranium are needed to support the joint development of PWRs and fast reactors. The grand national goal of 240 GWe or more nuclear power capacity by 2050 can be achieved. The SFR will make significant contributions to China's sustainable nuclear energy development and national energy supply security.

6.4 Conclusion

The fast reactor is the front running reactor type in the world's Generation IV advanced nuclear energy systems. Technically, a fast reactor is much more difficult to build than a light water reactor (LWR). But it has unique advantages. Therefore, France and the EU, Japan, Russia, India and other countries are actively developing fast reactors [5]. China is the eighth country in the world which has completed the construction of a fast reactor following the USA, Russia, France, Britain, Japan, India and Germany [6].

Although China is behind some developed countries in the development of fast reactors, it makes improvements on the basis of learning from foreign technologies. Both management and safety have improved. After more than 20 years of experimental fast reactor research and development, the Chinese scientists have mastered the fast reactor technology and made a large number of independent innovation achievements and patents and achieved independent research, independent design, independent construction, autonomous operation and self-management. They have formed complete research and development capabilities as well as cultivated a batch of excellent technical personnel.

Due to the requirements of China's economic development and reduction of greenhouse gas emission, a variety of clean energies will make contributions adjusted to local conditions. Nuclear power as a type of clean energy will be developed in a large scale. SFRs which can use nuclear resources effectively as well as incinerate and transmute high level wastes (HLW) will follow a three-step development strategy and will see rapid development, realizing the sustainable development of China's nuclear power. Currently, the design of a 600 MWe demonstration fast reactor has already begun. It will draw the experience from the CEFR safety design and lay the foundations for the development of high-power SFR's, further development of passive safety systems and ensuring China's full realization of Generation IV nuclear system requirements for high-power fast reactors [7].

References

[1] Sina blog: CEFR Project: *http://blog.sina.com.cn/s/blog_5a53af350100d7oy.html*
[2] Baidu baike: CEFR: *http://baike.baidu.com/*
[3] Guancha Syndicate: China's First SFR Achieved Full Power Operation for 72 Hours: *http://www.guancha.cn/Science/2014_12_19_303835.shtml*
[4] Baidu baike: CEFR Project: *http://baike.baidu.com/*
[5] Baidu baike: Fast Neutron Reactor: *http://baike.baidu.com/*
[6] China Energy News: Accelerate the Construction of Nuclear Fuel Cycle System in China: *http://paper.people.com.cn/zgnyb/html/2011-03/14/content_767971.htm*
[7] Xu Mi, Safety of Sodium-cooled Fast Reactors. Chinese Journal of Nature Vol. 35, No.2.

7

Development of the High Temperature Gas-cooled Reactor (HTGR) in China

7.1 Introduction of the HTGR

Recent developments in High Temperature Gas-cooled Reactors (HTGRs) attracted widespread attention. China, Japan, South Africa, USA, Russia and France are all actively initiating the development work of HTGRs. Some developing countries expressed great interest in this type of reactor [1].

The HTGR is one of the six Generation IV reactors put forward by the Generation IV International Forum (GIF) in 2002. This type of reactor has a high outlet temperature. It uses Helium as coolant and graphite as moderator. Pebble fuel and a ceramic reactor core are adopted. At the center of each poppy seed-size fuel particle is a uranium kernel. Layers of carbon and silicon carbide contain the radioactive material [2]. Fig. 12 shows the overall structure of the HTR-10 MW Test Module constructed by the Institute of Nuclear and New Energy Technology at Tsinghua University. Fig. 14 shows the pebble fuel element structure of HTGR.

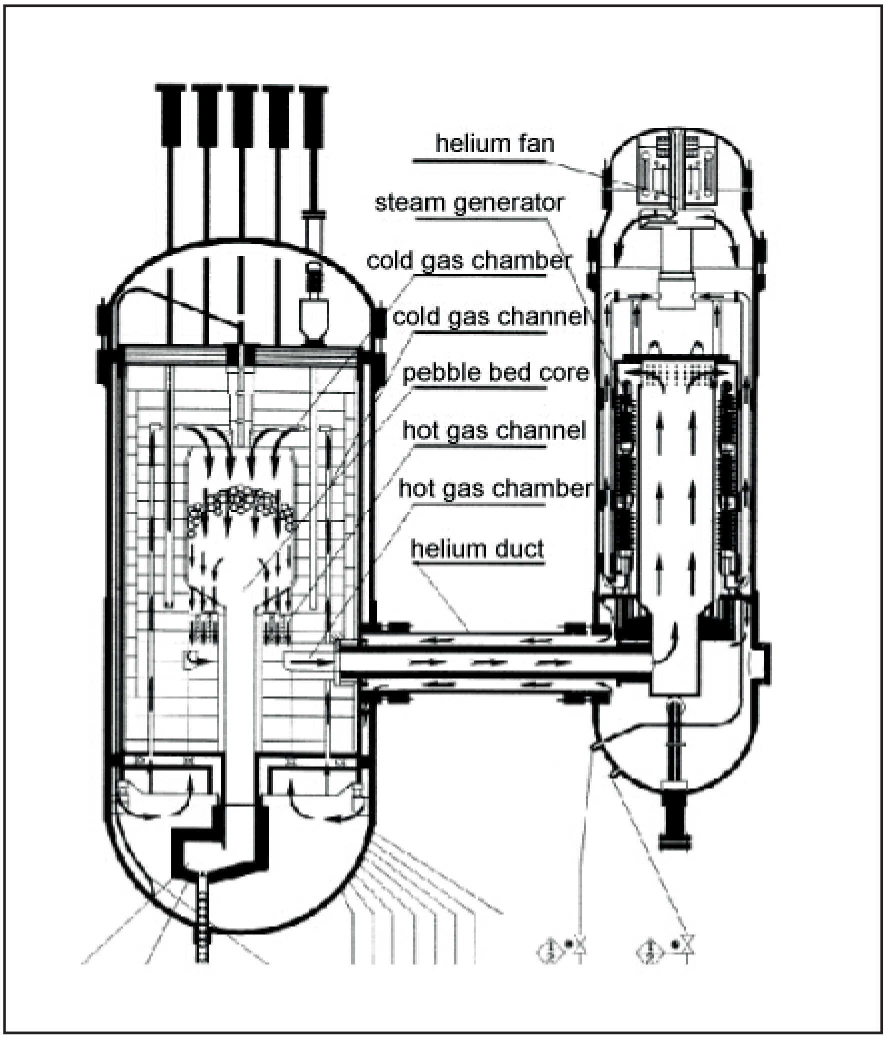


Fig. 12 – The 10 MWt High Temperature Gas-cooled Rector (HTGR) [7]

The most important feature of modular high temperature gas cooled reactors is that under any accident conditions, including a large loss of coolant accident (LLOCA), the reactor can be kept in a safe state without any human or machine intervention.

The modular HTGR also has other advantages such as:

1. High generating efficiency: Its efficiency is 25% higher than PWR nuclear power plants because of the high outlet temperature.
2. Short construction period: the HTGR adopts a modular construction approach. The construction period can be reduced to two years. Compared to PWR power plants which have 5 to 6 years of construction, the interest payment during construction is reduced and the construction investment can be reduced by 20%.
3. Simple system: The HTGR has passive safety features which greatly simplify the system. Engineering safety facilities like emergency core cooling system and full grade containment don't need to be installed, which can reduce the construction investment.

7.2 The Development History of China's HTR and its Current Situation

The HTGR research and development work in China started in the 1970s. By implementing the National High-Technology Project (863), the Tsinghua University designed and built a HTR-10 MW Test Module under the support of the China National Nuclear Corporation (CNNC). It realized the first power generation on January 7, 2003 [3].

In 2006, the Tsinghua University in Beijing, the China Nuclear Engineering Group Corporation (CNEC) and the China Huaneng Group co-financed the construction of the HTR demonstration project, after which a complete industrial chain will be formed. In this system, the Institute of Nuclear and New Energy Technology, Tsinghua University is the liability subject in charge of technology R&D and providing design and technical support; CNEC is the major special project implementation body, responsible for designing, purchasing and constructing the demonstration project of the nuclear island and its auxiliary systems; Huaneng Shandong Shidao Bay Nuclear Power Co., Ltd. takes charge of the investment operations of the demonstration project [4].

Fig. 13 – The construction of the Shidao Bay HTGR conventional island was finished on June 27, 2015 (photo credit: Shidao Bay NPP)

The High Temperature Reactor-Pebble-bed Modules (HTR-PM) under construction has two reactors (2x100 MWe) and one turbine. On December 9, 2012, the construction of the Shandong Rongcheng Shidao Bay HTR demonstration project started. Up to April 20, 2015, civil construction of the basements came to an end and turned to the intensive equipment installation stage. The key point for construction was shifted from civil construction to installation construction. On June 24, after two months of arduous struggle, the Shidao Bay Nuclear Power Project completed the pouring task of the reactor building walls for the first modular High Temperature Gas-cooled Demonstration Reactor in the world [5]. The reactor building walls were poured to 41.30 meters, marking the HTGR project meeting the requirement of heavy equipment lifting. On June 27, by capping of the Shidao Bay HTGR conventional island was finished [6]. This is another major step after the end of the pouring task. The project will be completed and put into operation at the end of 2017.

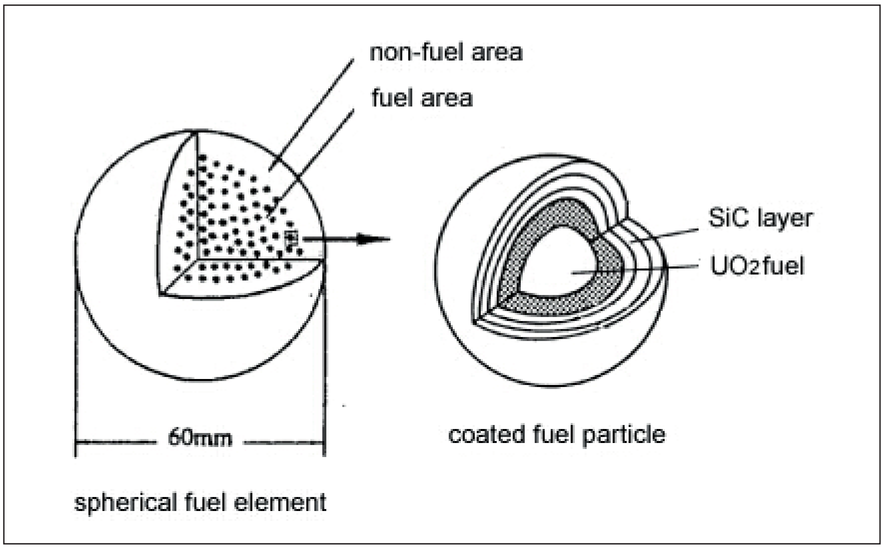


Fig. 14 – The pebble fuel element of the HTGR [7]

7.3 Future Expectations of HTGRs in China

The HTGR industrialization has shifted from research toward commercial applications. CNEC announced that the feasibility study report of the 600 MWe commercial high temperature reactor project (6x100 MWe) in Ruijin, Jiangxi Province, has passed the experts auditing and promises to be the first commercial Generation IV nuclear power plant in the world. At present, China has mastered all the technology of HTGR systematically and takes the lead in the world. The home manufacture can be realized for 95% of the equipment.

As next step, CNEC and Jiangxi Province will combine together and submit the project proposals to the National Development and Reform Commission (NDRC), applying to list the project into the National Nuclear Long and Medium Term Development Planning. After receiving the permit, the feasibility study of the project will be carried out. Land requisition, “Five-Outlet-one-Dish”[1] and the construction of the auxiliary facilities will be carried out at the same time. After getting the approval from the NDRC and obtaining building permits from the National Nuclear Safety Administration (NNSA), the commencement of work for the two units in the first-stage project is planned in 2017 and they will be connected to the grid around 2021.

7.4 HTGR Cooperation between China and Other Countries

By the way of multi-module combination, the installed capacity of the HTGR nuclear power plants can be 200 MWe (2x100 MWe), 400 MWe, 600 MWe, 800 MWe and 1000 MWe. These power plants can be operated with flexibility to suit the market and meet the need of different power grids. It is suitable for being constructed close to load centers as well as in countries and regions with small or middle power grids.

Many countries in Southeast Asia, the Middle East and Europe, including some potential users in China, express a keen interest in the application of HTGRs in nuclear electric power generation, sea water desalination, petrochemical industry and coal chemical industry. The related business cooperations are under way.

At present, CNEC starts working on the HTGR preliminary work in Jiangxi, Hunan, Guangdong, Fujian, Shandong, Hubei and Zhejiang Province successively. Meanwhile, CNEC signed the memorandum of understanding (MOU) on cooperation with Dubai’s Nuclear Energy Committee and provides King Abdulaziz City for Science and Technology (KACST) with the design scheme of a HTGR for seawater desalination. They have also reached a consensus on signing the memorandum of understanding on cooperation with Saudi Energy City. On April 21, 2015, they signed the MOU with the South African Nuclear Energy Corporation (NECSA). CNEC is jointly with other organizations responsible to provide nuclear fuels, spent fuel reclamation, nuclear power plant operation, technical support, personnel training and other integration services to the international market.

7.5 Conclusion

Generation IV nuclear power systems are advanced systems which stand for a major revolution in economy, safety, waste treatment and nuclear nonproliferation. The HTGR is considered to be the most possibly actualized and the most promising advanced reactor type in the near future by the international nuclear community [7].

Under the support of the National High-Technology Project, the Institute of Nuclear and New Energy Technology, Tsinghua University, built the HTR-10 MW Test Module successfully, and achieved joining the national power grid with full power. Long-term operation and safety tests verified the intrinsic safety of the HTGR and proved its technical feasibility. The success of the HTR-10 MW Test Module construction and operation marks that China has made a breakthrough in the R&D of HTGRs. China has been included among those advanced countries in the development of HTGR technology.

In early 2006, the large pressurized water reactors and HTGRs were included in the 16 major scientific and technological projects by “China’s national policy for medium and long-term scientific development” in which they are striving to make breakthroughs in 15 years. Actualizing the major scientific and technological project of HTGRs marks that the HTGR technology, in which China has self-owned intellectual property, takes a crucial step towards industrialization.

References

[1] Wu Zongxin, February 2000. Development of China’s High Temperature Gas-cooled Reactor. Nuclear Power Engineering.

[2] *http://baike.baidu.com/*

[3] *http://military.china.com/news/568/20150421/19562626.html*

[4] *http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2014-11/01/content_282325.htm?div=-1*

[5] *http://www.cet.com.cn/nypd/*hn/1576726.shtml

[6] *http://paper.people.com.cn/zgnyb/html/2015-07/06/content_1585012.htm*

[7] Fu Xiaoming, Wangjie, October 2006. Summary of HTGR Development in China. Modern Electric Power

---

[1] Five-Outlet-one-Dish: In order to construct efficiently and orderly, some on-site first-phase preparations have to be made, such as electrifying, communication, road access, water access, gas access and land smoothing.

8

Development of Small Modular Reactors (SMR) in China

8.1 Introduction of Small Modular Reactors

Nowadays the development of clean energy has become the theme of the times. Besides large-scale nuclear power plants being deployed at large scales in many countries, the development and utilization of small modular reactors (SMRs) is becoming an important scenery in the international markets [1]. Small nuclear reactors are defined by the International Atomic Energy Agency (IAEA) as reactors with electricity power less than 300 MWe. Small nuclear reactors with modular design, modular equipment system prefabrication and on-site modular assembly are called small modular reactors [2].

With the development of global nuclear power, more and more countries begin to pay close attention to the application of SMRs. IAEA said they would encourage the development and use of safe, reliable and economically viable SMRs. In fact, SMRs received international attention and centralizing research in the early years of this century. But in the 1950s and 1960s already, the use of small and medium-sized reactors had begun. In the meantime, in addition to the early experimental reactors and standard nuclear power plants, hundreds of SMRs for ship propulsion were also built. We can say that the development and construction of SMRs have accumulated a lot of experience in engineering and technology.

According to IAEA's latest statistics, currently there are 132 small and medium-sized reactors in the world in operation, of which 106 are medium sized reactors and 26 are SMRs [2]. There are also 13 SMRs under construction. 28 countries have small or medium-sized reactors. The total capacity of all these small and medium-sized reactors is 57 GWe. The cumulative operating experience is 5082 reactor-years.

8.1.1 Characteristics of SMRs

After analyzing the developed SMRs and those under development in different countries, IAEA evaluated the characteristics of this type of reactor. IAEA believes SMRs have great advantages in safety, economy, nuclear non-proliferation and no need of on-site refueling. The biggest market advantage of SMRs is their flexibility. Capacity can be added in small steps according to the users' requirements. They can be built in regions or countries with small grid systems that cannot support large-scale nuclear power plants. Furthermore, compared to large reactors, the emergency planning zone of an SMR is greatly reduced. Sites close to cities and close to users become possible[3].

8.1.2 Application of SMRs

In addition to generating electricity, SMRs have a number of interesting features. They can be comprehensively utilized in heating, water desalination, refrigeration and providing industrial heat. They will be the ideal source for Combined Cooling Heating and Power (CCHP) which is already the industry consensus. Moreover, SMRs providing power for icebreakers, ships and rockets are also one of the focuses in the industry. Furthermore, research and development of nuclear energy for space technology is going on. To realize manned Mars exploration in 2017, nuclear power must be used, relevant experts in the field of nuclear energy have pointed out [2].

8.2 The Significance of Developing SMRs in China

The majority of China's inland areas and remote areas are affected by constraints in location, geology, climate, cooling water, transportation, grid capacity and financing capacity. Therefore, the application of large nuclear power equipment is greatly constrained while SMRs could satisfy the power demand of these areas. Furthermore, China's urban heating energy demand is the highest in the world. The development of nuclear energy heating and replacing coal power plants with SMRs is an effective way to solve the problem of air pollution and carbon dioxide emissions. Meanwhile, China is also a country with serious shortage of water resources. Using SMRs for desalination is a practical solution.

8.3 Introduction of China's Advanced 100 MWe Pressurized Water Reactor (ACP100)

The ACP100 is a small reactor type launched by the China National Nuclear Corporation (CNNC). It is a modular pressurized water reactor suitable for distributed generation [4]. The ACP100 is substantially retrenched by CNNC from the three-loop design originally launched by Areva in France. The reactor consists of 57 fuel rods which are 2.15 meters long. The module also includes a 287 °C steam generator and a complete steam supply system. The thermal design power is 310 MWth and the electric power is 100 MWe. The design life is 60 years and the refueling cycle lasts for 24 months [5].

In addition to be used as a conventional nuclear power plant, the ACP100 can also be placed on ships as a floating power station. It can provide rapid power supply for offshore platforms and overseas harbor activities of enterprises. The process is quite easy. Just put the floating power plant into electrical connection. In case of emergency or wars, it can be quickly removed.

Fig. 15 – Model of China's advanced Small Modular Reactor ACP100 [5]

CNNC's main market is in China and the company has signed a development agreement with Fujian, Zhejiang, Jiangxi, Hunan, Heilongjiang and Jilin Provinces. The ACP100 design was finalized by the end of 2013. The first two ACP100 are planned to be constructed in Putian, Fujian Province. The construction period will be 36 to 40 months. The Putian reactors will take multiple tasks such as power generation, desalination, community heating etc.

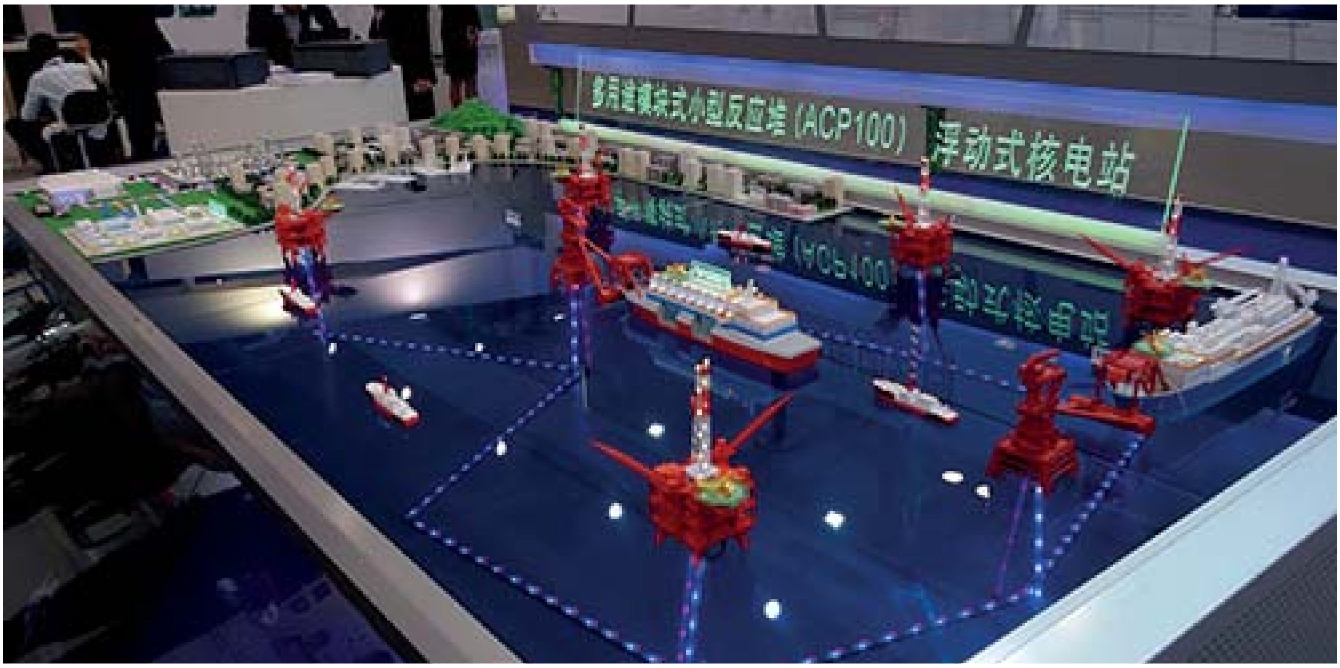


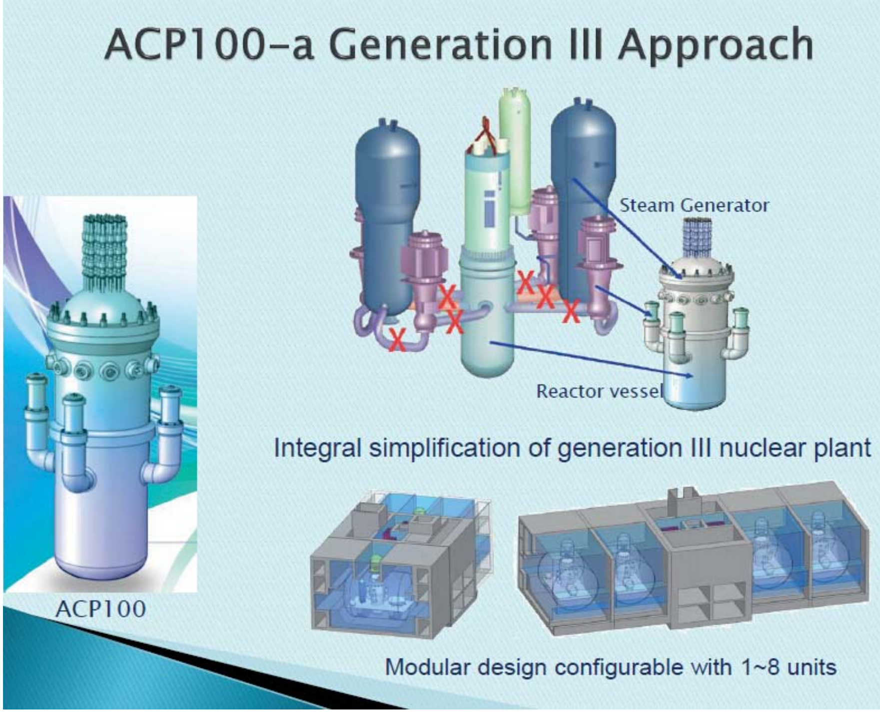
Fig. 16 – Model of the ACP100 Floating Boat Power Plant [3]

8.3.1 Safety

Compared with large NPP reactors, the ACP100 has higher operational flexibility and safety. The emergency planning zone of an ACP100 is greatly reduced. The required evacuation radius is only 300 meters and the radius of the power plant is also 300 meters. The area involved in the emergency plan can be greatly simplified, making it possible to build this reactor close to cities and users. It uses the same passive core cooling system as the ACP1000 and the Hualong-One-Reactor. It can operate safely for 14 days without outside interference under the worst multiple external small probability accident. This can buy enough time for emergency response. It is a highly advanced technology in the field of worldwide nuclear energy.

On the plant construction level, the SMR adopts the way of basement settings. All parts are built underground, which of course is different from the large traditional NPPs. The natural barrier of the surrounding rock is reinforced by concrete around the facility. The rock also becomes an infinite containment structure.

On April 16, 2015, an agreement on the ACP100 was signed by the IAEA. The ACP100 reactor safety review by IAEA experts started in July. The program will last for 7 months. After passing the review, the ACP100 will obtain a certification from IAEA.



ACP100–a Generation III Approach

Integral simplification of generation III nuclear plant

Modular design configurable with 1~8 units

Fig. 17 – The structure of ACP100 (graph provided by the Institute of Nuclear Energy Technology, Tsinghua University, Beijing)

8.3.2 Project Schedule

In June, 2010, the ACP100 was set up as the major scientific and technological project of CNNC. Soon afterwards, the Nuclear Power Institute of China (NPIC) and the China Nuclear Power Engineering Co., Ltd. set up a research and development team and immediately started independent research and design work. By the end of 2010, the top-layer design of the ACP100 was completed.

In 2011, the program design was completed and China's SMR demonstration project was listed in the Energy Development "Twelfth Five Year Plan" (from 2011 to 2015) and in the Energy Science and Technology "Twelfth Five Year Plan". This project did not stay on paper only. The support of the country is reflected in a multi-sector action. The National Nuclear Safety Administration (NNSA), the State Administration of Science & Technology and Industry for National Defense (SASTIND) and the National Energy Board (NEB) joined hands in support of China's first SMR-ACP100 research and development by CNNC. They provided strong support in financial security, key technology research, supporting research of demonstration projects and other aspects. By the end of 2012, the standardized design was completed.

In the seventh EXPO Central China in 2012, CNNC and the Hunan Provincial Government signed a strategic cooperation agreement. It planned to select six sites in the inland Hunan Province. The total installed capacity is about 6000 MWe. During the "Twelfth Five Year Plan", the first inland SMR project is trying to be completed. The expected aim will be reached at the end of the "Fourteenth Five Year Plan" (from 2021 to 2025) [6].

In July, 2013, the County of Ningdu, in Jiangxi Province signed a formal contract with CNNC on a "small multipurpose modular reactor (ACP100)". The project construction period is 36 months with a total investment of 2.46 billion CHF. This signing ceremony marked that the project is now in the substantive phase. By the end of December, 2013, the preliminary design of the ACP100 demonstration project in Putian, Fujian Province was finished by parties organized by China Nuclear Power Engineering Co., Ltd.

In 2014, CNNC further introduced the ACP100S. The aim is to research and develop a floating SMR which can operate offshore on the basis of the previous ACP100 on land. The installed capacity is also 100 MWe [7]. The development speed of the ACP100 in China is astonishing. But behind this surprising speed is not "weaken the pursuit of domestic innovative technology". On the contrary, relying on 20 years of research on the basis of key technologies, each design keeps improving.

8.3.3 Challenges and Difficulties

Being one of seven major ACP100 tests, the cold test of the control rod drive line is an important test to verify the drive mechanism and other equipment. It provides the experimental basis for the drive line setting, design optimization and safety review by measuring the control rod drop data. In fact, cold tests of the control rod drive line have been carried out many times by the Nuclear Power Institute of China (NPIC). But because of the different reactor structure, the test specimens of the ACP100 are quite different from other NPPs. Therefore, the design, manufacture and installation of the test specimens have to start again, which is a new challenge.

One of the challenges is that the test specimens are the longest ever used in previous similar tests. Due to the SMRs integrated design, the drive rod alone is already 8 meters long. The entire test specimen is up to 14 meters. The second challenge is the complex structure of the test specimen. One set of drive lines in the reactor used for the test contains fuel assemblies, guide assemblies, drive mechanism control rod assemblies and other drive line components. The machining precision and installation requirements are the same as for the prototype. When simulating the prototype structure, several parameter measurement problems also need to be considered at the same time.

Design of the new drive line, test specimens and test scheme are almost simultaneous. The test related personnel learned at the beginning of the project a lot about the test requirements, structures of the drive line components and interfaces between the components in order to combine the test specimens and the test scheme.

It is necessary to not only consider the feasibility of the testing methods as well as the test site installation conditions, but also to try not to change the structure of the drive line and the operating environment. In order to ensure that the design is practicable, every measurement scheme is formulated after historical data research, group discussion, manufacturers' consultation, communication and assessment with task parties, field investigation and many other links.

The cold test of the control rod drive line was required to be completed in June 2013. Otherwise it would have affected the progress of the follow-up test. In order to guarantee the test schedule, the staffs of the task team all went out to do experiments. Ultimately, after months of remarkable efforts, they finished all test contents on schedule.

On July 25, 2014, the ACP100 control rod drive line successfully completed qualification tests. Its live test and seismic test results met the design requirements. It marks that now the ACP100 control rod drive line has a foundation of engineering application [8].

8.3.4 International Cooperation and Exchanges in ACP100

In June, 2014, CNNC was invited to attend the International Small Modular Reactor Development Forum (ISMRDF) in Washington D.C. They comprehensively and systematically introduced the development status, market demands and future prospects of the ACP100. This forum was organized by the American Nuclear Society. More than one hundred experts and scholars in the United States, Russia, Britain, France, Canada, Japan, Korea, Indonesia. Vietnam and other countries attended the meeting. After this forum, the ACP100 formally entered the international SMR family and will be written into the SMR family tree by IAEA.

Internationally, China's SMR, especially the ACP100, is regarded as a potential partner and competitor by nuclear powers such as France, Russia, and the USA. Canada and many countries in the Middle East are very optimistic about the economy and maturity of the ACP100. They have already offered an olive branch to CNNC [9].

8.4 Conclusion

Currently, the development boom of SMRs set off once again in the global nuclear industry. The development of SMRs has also been focused by many countries and large nuclear industries as a new type of commercial interest. In March 2010, Steven Chu, the minister of the United States Department of Energy recommended the SMRs and said it was one of the most promising fields in the future of nuclear power.

At present the world's leading nuclear powers and engineering enterprises are all researching and developing SMRs. International enthusiasm for SMR research and development also let people see that the differential development strategy made by CNNC, which is a roadmap of developing large-scale reactors and accelerating the development of ACP100 at the same time, is correct.

Meanwhile, the safety design concepts and technology proposed by the ACP100 is in line with the international development trends. China's ACP100 is partly transformed from the military application (such as nuclear submarines etc.) by NPIC. The development of military nuclear technology in China is very mature. The technology gap between China and the international level in SMRs is not large. But to achieve better commercial prospects and safety performance, they also need to explore the technology further.

References

[1] CLP Exhibition Website: CNNC Promotes ACP100 Independent Research Work: *http://www.365zhanlan.com/*

[2] Polaris Power Grid: SMR Open a New Era of Nuclear Energy: *http://news.bjx.com.cn/html/20130410/427741.shtml*

[3] China.com: China Launched Floating ACP100 SMR Directed at Marine Development: *http://military.china.com/news/568/20140619/18573534.html*

[4] Wikipedia: ACP100: *https://zh.wikipedia.org/wiki/ACP100*

[5] Super Camp Military Forum: ACP100 Compact Reactor:*http://lt.cjdby.net/thread-1743542-1-1.html*

[6] Polaris Power Grid: SMR Projects Are Favored Gradually: *http://news.bjx.com.cn/html/20130704/443672.shtml*

[7] Polaris Power Grid: Chinese SMR Accelerate to Go Overseas: *http://news.bjx.com.cn/html/20140416/503954.shtml*

[8] SOHO: ZHEFU Holding Group Co.,Ltd ACP100 SMR Control Rod Drive Line Qualification Tests Have Been Completed: *http://business.sohu.com/20140813/n403411458.shtml*

[9] State Administration of Science, Technology and Industry for National Defense, PRC: China's ACP100 Officially Enters the International SMR Community: *http://www.sastind.gov.cn/*

9

Introduction of Fusion Development and the International Thermonuclear Experimental Reactor (ITER) Project in China

9.1 Basic Principles of Nuclear Fusion

The fission energy released from heavy nuclei under neutron bombardment is the source of conventional nuclear power plants [1]. The energy emitted by fusion reaction of two hydrogen nuclei is the energy source of the stars. Mankind has been able to control and use nuclear fission energy. But because it is difficult to overcome the Coulomb barrier and get two positively charged light nuclei close to each other to have fusion reactions, control and utilization of nuclear fusion require a long and difficult research and development process. Among all possible nuclear fusion reactions, nuclear fusion of hydrogen isotopes – deuterium and tritium – seems to be the most promising way to implement.

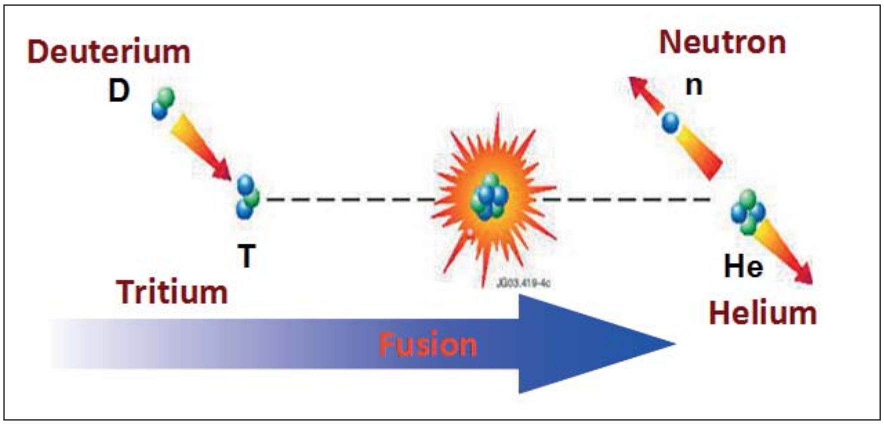


Fig. 18 – Fusion reaction using deuterium and tritium (source: Baidu wenku)

Taking into account the conditions of deuterium and tritium fusion reactions, if we want a deuterium and tritium gas mixture to produce a large number of nuclear fusions, the gas temperature must be above 100 million degrees centigrade. At such temperatures, the negatively charged electrons and the positively charged nuclei are completely disengaged. Their movement is independent. This high temperature gas is called plasma, consisting of charged particles that are completely free. Therefore, the first problem to be solved to realize controlled thermonuclear fusion is to heat the gas to millions, tens of millions and hundreds of millions of degrees centigrade. However, such a plasma cannot be constrained by containers made from any material. Therefore, the hot plasma has to be kept away from the reactor walls. In addition, ways must be found to prevent the escape of the plasma. A magnetic field with closed field lines is the most likely choice. Research on plasma motion behavior and escape prevention in the different designs of the "magnetic cage" becomes a second difficulty for controlled thermonuclear fusion. If we want fusion reactions to continue, the plasma with hundreds of millions of degrees centigrade must be maintained for a long time. Improving the ability of the magnetic cage to confine plasma over long time is the third major difficulty to achieve the feasibility of magnetic confinement fusion.

Since the late 1940s, many countries have developed different types of magnetic cages. But since the 1970s, the "tokamak" approach invented by Soviet scientists showed unique advantages and became the mainstream of fusion energy research in the 1980s (the other type of fusion reactor in an advanced state is the stellarator developed in Greifswald, Germany). The tokamak device is a magnetic cage composed of closed annular magnetic fields. By putting different sizes of tokamaks into operation and doing experiments in different countries, the tokamaks showed a bright prospect: The plasma reached several million degrees centigrade and plasma confinement also had a good performance. Scientists realized that by expanding the scale of such devices it is possible to get plasmas with conditions close to fusion.

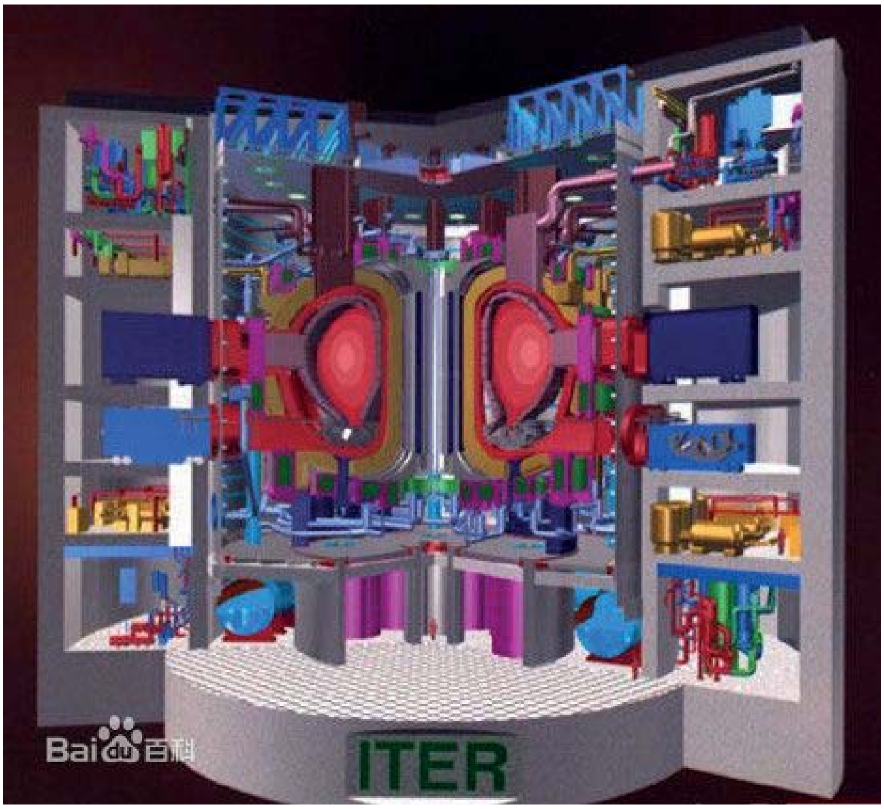


Fig. 19 – The structure of ITER [1]

9.2 The Advantages of Nuclear Fusion

The deuterium–tritium fusion reaction can release an enormous amount of energy. Deuterium is abundant in sea water. Extracted from one liter of water , it can release the same amount of energy as 300 liters of gasoline combustion. Tritium can be generated from lithium in the reactor and lithium, too, is abundant in the crust of the earth and in seawater. The product of the deuterium–tritium reaction – helium gas – is not radioactive. The neutron activation of the reactor structure materials only produces a small amount of short-lived radioactive substances that are relatively easy to handle. Fusion reactors don't produce noxious gases or greenhouse gases. Taking into account the inherent safety of fusion reactors, it can be said that fusion energy is pollution-free, without long-lived radioactive nuclear waste and with infinite resources. Achievement of large scale controlled thermonuclear fusion will solve the energy problems of human society fundamentally.

9.3 Introduction of ITER

The International Thermonuclear Experimental Reactor (ITER) project is one of the world's largest and most far-reaching international research cooperation projects. It takes about 10 years and 15 000 million euros to build. The ITER device is a superconducting tokamak which can produce large scale nuclear fusion, commonly known as the "artificial sun". The seven members undertaking the ITER project together are China, the European Union (including Switzerland by a treaty of cooperation), India, Japan, Russia, South Korea and the USA. The seven parties include the world's leading nuclear powers and major Asian countries, covering nearly half of the world's population. For the construction of ITER, after specialized negotiations, the parties formed an independent international organization.

The heads of governments have taken different ways to make official statements to participate in the ITER project during the past few years. These are unprecedented in the history of international science and technology cooperation, which show that the governments and technology communities attach great importance to the plan.

The results of implementing the ITER project will determine whether we could use fusion energy quickly and massively, which may affect the course of solving the energy problem fundamentally. Nowadays energy, environment and resource prospects are of high concern in the world. The participating countries insisted on consultations and cooperation spirit and set aside many contradictions and conflicts of interests. Finally an agreement that was acceptable to all the parties was reached. The seven members began to work together to build the world's first large fusion experimental reactor.

The ITER project was initiated in 1985. The research and design work of the experimental reactor started in 1988. After 13 years of effort, the design of the ITER project was completed in 2001 on the basis of integrating the main technical achievements worldwide. After five years of negotiations, the seven parties in the ITER project signed the joint implementation agreement in 2006 and launched the ITER project. It will last for 35 years: 10 years for construction, 20 years for operation and exploitation, five years for deactivation. The world's largest experimental tokamak nuclear fusion reactor is currently being built in Cadarache, in southern France.

9.4 Fusion Related Activities in China Before Joining ITER

Magnetic confined fusion research in China started in the 1950s [2]. The Institute of Physics, Chinese Academy of Sciences (CAS) in Beijing, the China Institute of Atomic Energy in Beijing, the Beijing University and some other institutes developed basic research in this field. Several important facilities had been constructed by then.

From 1964 to 1983, the magnetic confined fusion research in China experienced significant adjustments. Engineering achievements prevailed in this phase. In 1965, the Southwestern Institute of Physics in Chengdu, Sichuan Province, was founded, and soon became one of the largest institutes focusing on investigation of plasma physics and magnetically confined nuclear fusion in China. Various experimental facilities for magnetically controlled fusion research had been developed in CAS including a Pulse Compress Mirror, a Stellarator (1971), the MM-2 (super-conducting magnetic mirror, 1972) and the HL-1 Tokamak (1984).

In 1978, the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) in Hefei, Anhui Province, was founded for the purpose of the peaceful utilization of the fusion energy, primarily based on the tokamak approach. Meanwhile, the Department of Modern Physics of the University of Science and Technology of China in Hefei established the discipline of plasma physics, and successfully built a tokamak with smaller size – the KT-5B – as well as conducting related experiments. The facility had been redeveloped into KT-5C afterwards.

Since 1984, the key to magnetic confined fusion research has become the tokamak experiment. In 1984 and 1994, the HL-1 Tokamak and the HL-1M Tokamak were developed respectively. Much progress and important contributions to nuclear fusion and plasma physics have been made on these devices.

9.5 ITER in China

9.5.1 The China Domestic Agency (CNDA)

In order to implement the ITER project after China entered the ITER program, to strengthen the international cooperation in the field of nuclear fusion research, to deliver the in-kind procurement packages assigned to China, and to promote the development of nuclear fusion research in China, the China Domestic Agency (CNDA) was established in October 2008 by the Ministry of Science and Technology (MOST) in accordance with the related provisions of the ITER Agreement signed on November 21, 2006, by the minister of MOST on behalf of the Chinese government, which was approved by the State Commission Office for Public Sector Reform [3]. China will provide its contributions to the ITER international Fusion Energy Organization (ITER Organization) through CNDA.

9.5.2 Organizational Structure

CNDA consists of five divisions. The Division of Administration is responsible for handing administrative affairs and management [4]. The Project Engineering Division and Project Management Division are responsible for negotiating, reviewing and signing agreements, organizing and coordinating the implementation of the in-kind procurement packages, and supervising domestic manufacturing tasks. The International Cooperation Division is responsible for international cooperation affairs. The Division of Domestic Research and Development is responsible for studying and analyzing the nuclear fusion energy research development status and trends, participating in the organization and management of research and development programs supporting the ITER project.

9.5.3 The ITER China Team

China has built two science and engineering research institutions on nuclear fusion: The Southwestern Institute of Physics and the ASIPP [5].

In order to train professionals, the University of Science and Technology of China, the Huazhong University of Science and Technology in Hubei Province, the Dalian University of Technology, the Tsinghua University in Beijing and others provide major courses of nuclear fusion and plasma physics. Some universities even have built special institutes. The researchers in many universities including Beijing University, Shanghai Jiaotong University, Zhejiang University, Sichuan University, Donghua University in Shanghai, University of Science and Technology Beijing and others have launched nuclear fusion research. This way, many young professionals have been trained and many influential research achievements have been acquired.

There are many institutes studying nuclear fusion, such as the China Academy of Engineering Physics in Mianyang, Sichuan Province, the China Institute of Atomic Energy, the China Nuclear Power Engineering Corporation, the Nuclear Power Institute of China, the Hefei Institute of Physical Science, Chinese Academy of Sciences, the Shenyang Research Institute of Metal, Chinese Academy of Sciences, the Beijing Research Institute of Automation, Chinese Academy of Sciences, the Institute of Coal Chemistry, Chinese Academy of Sciences in Beijing, the Institute of Electrical Engineering, Chinese Academy of Sciences in Beijing, the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences in Beijing, the Northwest Institute for Non-ferrous Metal Research in Xi'an, Shaanxi Province and many others.

9.5.4 Mission and Objectives

CNDA actively organizes and participates in the ITER project related activities and management [6]. CNDA is responsible for safeguarding China's interests as an equal partner of the ITER organization and performing China's commitment to the program. CNDA will fully participate in the management and decision making of the ITER project, master the knowledge transfer and intellectual properties produced during the ITER project implementation, unite and foster science research and engineering technology talents, promote domestic nuclear fusion energy research and development, develop the independent innovative capacity in nuclear fusion energy, and lay a solid foundation on the independent design and development of a nuclear fusion demonstration reactor in the future. The mission contains:

1. To participate in the decisions and management of the ITER project comprehensively.
2. To promote the bilateral cooperation and multilateral cooperation of nuclear fusion research.
3. To build and perfect the implementation management mechanism of the in-kind procurement packages assigned to China and management systems of the outlay, schedule, quality and standard to formulate the implementation plan.
4. To cultivate a group of high-level scientific research personnel and engineering technology teams with steadfast determination.
5. To promote the transformation of Chinese large and medium size nuclear fusion equipment, to arrange China's contribution to the ITER project.
6. To digest, assimilate and master the research results of the ITER project.

9.5.5 China's Contribution to the ITER Project

9.5.5.1 Procurement

In the construction phase, China undertakes 9% of the in-kind procurement package manufacturing tasks [7]. At the same time it also participates in the management, overall coordination and implementation of the ITER International Organization. China also provides financial contributions, recommends and dispatches personnel to work in the organization's headquarters. The in-kind contribution accounts for about 80% of China's expenditures. The financial contribution accounts for about 20%. The financial contribution to the ITER project is the annual operation and plant construction costs submitted to the ITER International Organization according to the "Organization Agreement".

The main form of contributions in the construction phase is in-kind contribution. The ITER member countries undertook the component development, installation, test and adjustment of the ITER device together. According to the adjustment of the procurement arrangement agreed by the ITER International Organization and the parties by early 2010, China is now undertaking 12 procurement tasks. These are Magnet Supports, Correction Coils, Feeders, Feeder and Correction Coil Conductors, Toroidal Field Coil Conductors, First Wall, Shield Module, Gas Injection System and Glow Discharge Cleaning System (GIS&GDC), Pulsed Power Electrical Network (PPEN), Alternating Current/Direct Current (AC/DC) Converters and a Diagnostic System.

Some of the 12 procurement packages are processing tasks according to the design drawings provided by ITER. According to the schedule agreed by the parties, China is responsible for finishing the manufacturing tasks within the prescribed time and transporting them to the designated place. For other parts of the procurement tasks such as GIS&GDC, the Diagnostic System, the AC/DC Converters and PPEN, China needs to provide the detailed design and finish the manufacturing tasks according to the functional parameters provided by ITER. Some of the manufacturing tasks are undertaken by ASIPP [8]. ASIPP has experience in developing superconducting tokamaks. So it is in a leading position in producing tokamak components such as superconducting conductors and the shielding cladding. As of May 2010, China had signed five procurement arrangements with ITER Organization.

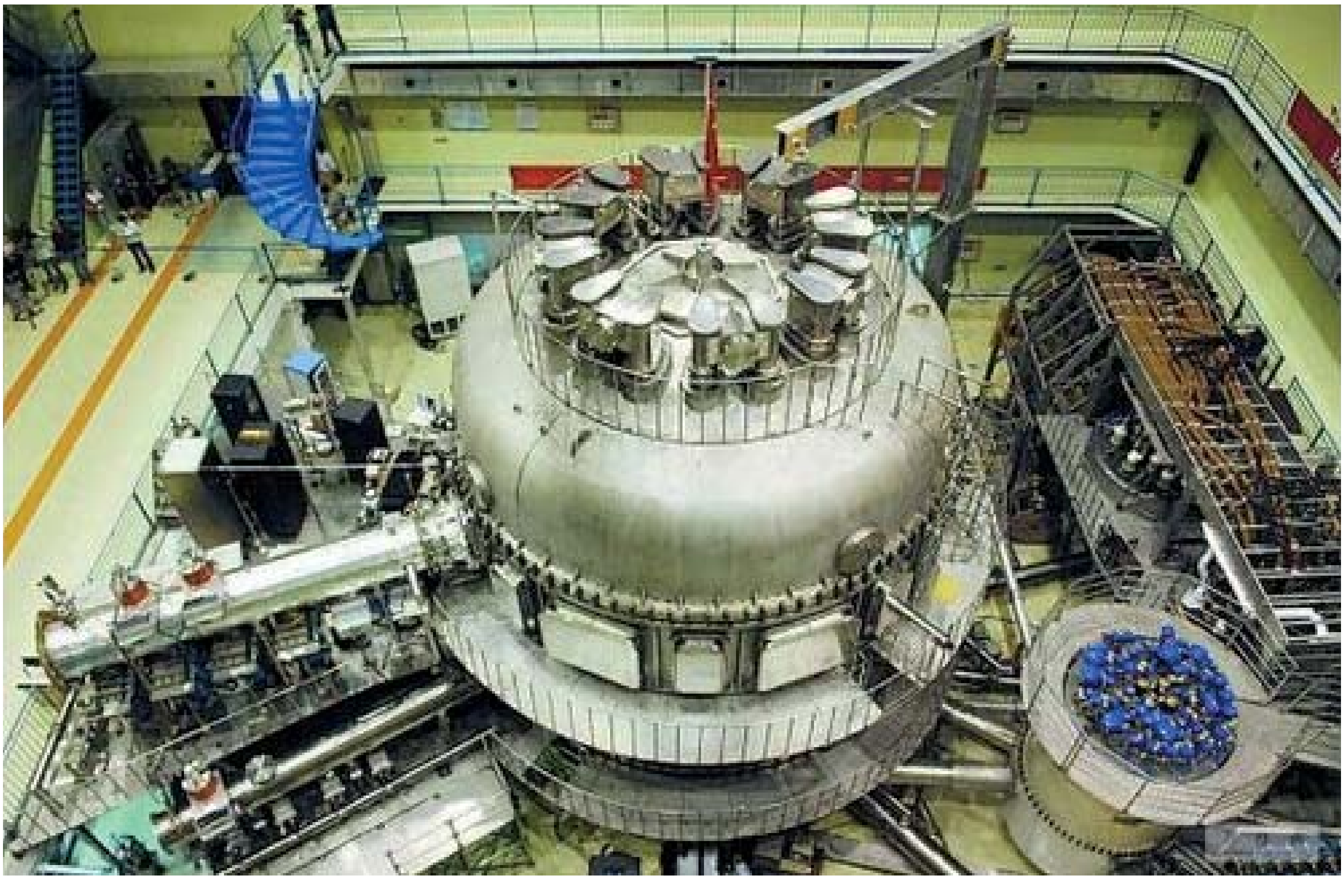


Fig. 20 – The Experimental Advanced Superconducting Tokamak (EAST) in Hefei Province [8]

9.5.5.2 The Experimental Advanced Superconducting Tokamak (EAST)

In the 1990s, there was no precedent in the world for a device that could form magnetic fields with superconducting systems only. Chinese scientists submitted an application and got the national project of building the Experimental Advanced Superconducting Tokamak (EAST) in 1998. Now it is located in ASIPP in Hefei Province. EAST is one of the world's most advanced devices in exploring controlled nuclear fusion. Because of its success, China is standing in the forefront of nuclear fusion research.

The rapid changes of the magnetic field will make superconductors lose superconductivity easily. All kinds of complex instruments need to be gathered in a small space and to work reliably under extreme and complex conditions. Each subsystem needs more complex systems for support and also a variety of new designs. All of this makes it very difficult to realize the fully superconducting tokamak.

Chinese scientists have overcome many difficulties and made several achievements. In 2006, EAST achieved the first ignition: producing plasma and inducing fusion. In next to no time, it achieved continuous running for 1000 seconds, which was an unprecedented achievement at that time. Chinese scientists used the high temperature superconductor current leads in EAST for the first time worldwide. If this technology can be successfully applied in ITER, it can save CHF 1.54 million per year of electricity consumption as well as reduce CHF 23.1 million in the construction cost of the cryogenic system [9]. At present, EAST and other experimental devices continue to make breakthroughs in the plasma parameters such as temperature, density and discharge duration and it becomes a priority reference model for similar devices worldwide.

The major task of the ASIPP is to do observations and research on plasma in the cavity of EAST. Scientists have to ignite, wait, measure and calculate. Besides, they also have to explore the unknown factors in the theory. On February 10, 2015, a major upgrade of EAST was completed. It now has become one of the most advanced fusion devices achieving 400-second long pulse high performance discharges.

9.5.5.3 The HL-2A

In December 2002, the HL-2A (the first divertor tokamak in China) was put into operation, and some ITER-relevant research was undertaken. So far, important progress has been achieved on the HL-2A, and the operation parameter regime has been greatly extended. The plasma current in HL-2A tokamak has reached 450 kA, and the plasma duration is up to 4200 ms. A number of achievements have been made on the physics of plasma transport, plasma turbulence and energetic particles. The heating and current drive systems in the HL-2A include a 3 MW Electron Cyclotron Wave (ECW), a 1.5 MW Neutral Beam (NB), and a 1 MW Lower Hybrid Wave (LHW). High-power heating and current drive experiments equipped with all these systems improved the plasma confinement.

In spring of 2009, ELMy H-mode (a disruptive instability occurring in the edge region of a tokamak plasma under the highly constrained mode) discharges were obtained in the HL-2A divertor configuration. It was a milestone in the history of magnetic confinement fusion experiment research in China.

Besides, China is investing heavily in building its own reactor, the China Fusion Engineering Test Reactor (CFETR). The superconducting tokamak technology used in ITER will be applied on CFETR. The construction is planned to be started in 2020 and electricity will be produced in 2026. If it comes true, China will change the course of human history in using fusion energy.

9.6 The Significance of China's Participation in the ITER Project

China is a large developing country under sustained and rapid development. Energy issues have become increasingly prominent. Because fusion is able to solve the energy problem thoroughly, a lot of research arrangements are made for it. Discussions on the ITER project are given high attention.

The ITER project is the largest-scale multilateral international cooperation project in which China participated since the reform and opening-up (1978). Participating in the ITER project is helpful for China to enhance the level of participating in international cooperation in science and technology. It will also help to promote China's development of fusion energy. Besides, it is conducive for China to learning and mastering the construction, management, operation and maintenance of large-scale international science projects. Research and development capabilities in many areas such as the superconducting technology, rare metal material technology, high voltage technology etc. will be improved. Last but not least, it accelerates the training of high-level researchers, engineering technicians and managers, which lays a solid talent resource foundation for the development of fusion.

9.7 Conclusion

China's government fully supports the ITER project [10]. In the construction phase, China not only actively organizes domestic relevant institutes to carry out manufacturing tasks of procurement packages, but also carries out international cooperation under the framework of the "Joint Implementation Agreement of the ITER" and promotes the implementation and management of various tasks together with other parties during the construction phase. In recent years, China's investment on fusion energy research and development showed almost exponential growth. Active policies establish an unprecedented period of development of fusion energy.

In the future, China will continue to target fusion science and national needs for energy following the National Fusion Energy Research and Development Strategic Plan. While actively developing the next generation of the superconducting fusion reactor, China is trying to achieve an indispensable role in the international field of nuclear fusion and to become the world's advanced magnetic confinement fusion research base carrying out pilot and prospective studies.

References

[1] Baidu baike: The ITER Project: *http://baike.baidu.com/*

[2] Iterchina: Fusion related activities in China: *http://168.160.11.36:800/Activities/*

[3] Iterchina: Iter International: *http://168.160.11.36:800/About/International.html*

[4] Iterchina: Organizational Structure: *http://168.160.11.36:800/About/Organizational.html*

[5] Iterchina: Iterchina Team: *http://168.160.11.36:800/About/Team.html*

[6] Iterchina: Mission & Objectives: *http://168.160.11.36:800/About/Mission.html*

[7] SINA: China's Contribution to the ITER Project: *http://news.sina.com.cn/o/2010-06-17/120120490656.shtml*

[8] Tencent: China is in the World Leading Position in Controlled Nuclear Fusion: *http://news.qq.com/a/20120612/000301.htm*

[9] Chinanews: China is Actively Carrying out the Design and Research of the Next Generation Superconducting Fusion Reactor: *http://www.chinanews.com/gn/2013/11-07/5474716.shtml*

[10] Embassy of the People's republic of China in Japan: The Second ITER Technical Cooperation Meeting of China, Japan and South Korea was Held in Japan: *http://www.china-embassy.or.jp/chn/gdxw/t1287569.htm*

10

Introduction of the Low Energy Nuclear Reaction (LENR) and the Research Status in China

10.1 Basic Information and Historical Background of Low Energy Nuclear Reactions (LENR)

LENR are fusion reactions occurring at a low temperature. They are affiliated to the category of condensed matter nuclear science [1]. Usually we say that LENR can happen at room temperatures or several hundred degrees centigrade only. The raw materials used in LENR are hydrogen and elements such as carbon, nickel, platinum, or palladium.

In 1989, Martin Fleischmann and Stanley Pons of the University of Utah designed a fusion experiment based on the characteristic that palladium can absorb a lot of deuterium. They claimed to have discovered that a large amount of energy was produced in the experiment and then held a press conference to publicize the success of LENR. This discovery pointed out a method to obtain large amounts of clean energy.

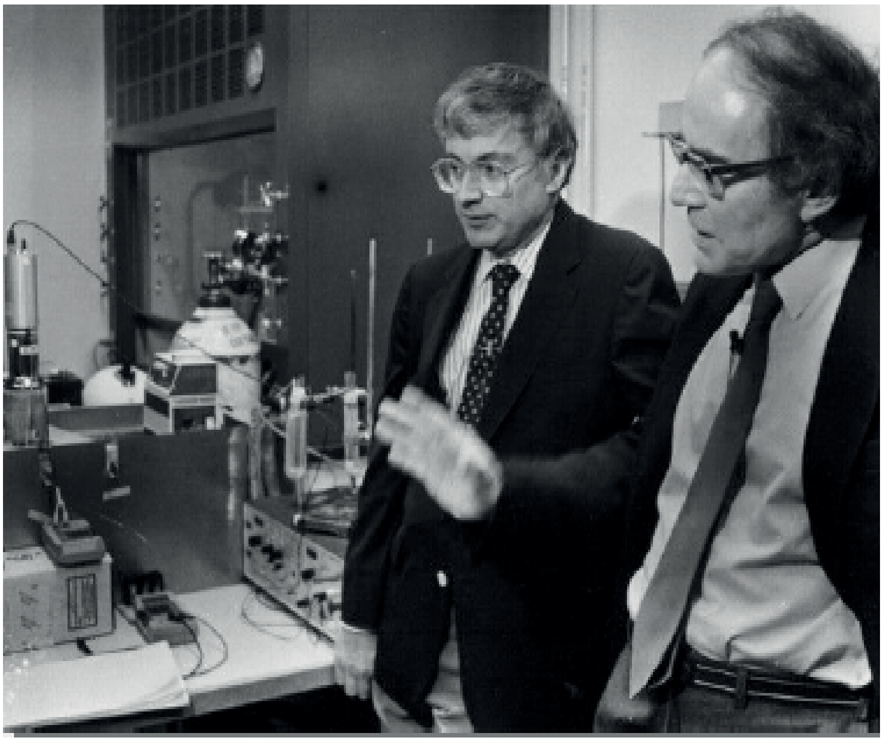


Fig. 21 – Martin Fleischmann and Stanley Pons, University of Utah [2]

However, because nobody (including themselves) could reproduce the result of their experiment, their findings were not accepted by the public. Although most people rejected their scientific theory, there were still some people feeling that this phenomenon just needed more development. Therefore, LENR went on being developed by scientists quietly.

If the results of Fleischmann and Pons' experiment could be confirmed, then we could eventually generate heat or even electricity in a non-centralized way. Each family could generate heating and electricity by itself. And water could be assumed as fuel. But the study of LENR requires a lot of time to do the experiments to prove and understand the phenomenon. It will take decades or even longer to develop such a technology and a lot of investment and new plants are needed, just like space engine experiments.

10.2 Prospect and Significance of LENR

10.2.1 Social Aspects

The phenomenon revealed by LENR provides a new way to explore the microscopic world. That is to say, some nuclear reactions which before could only be done by a large accelerator can now be achieved on a desktop. If the technology of LENR would get mature someday, automotive power, mobile power of electronic equipment etc. might be replaced by energy generated from LENR. Then we would no longer rely on coal, oil and other fossil fuels. There will be no pollutants or greenhouse gas emissions as well. The emission of small particulate matter on micrometer scale (PM2.5 and PM10) will be massively reduced.

LENR promise to provide us with inexhaustible cheap energy solving a lot of environmental problems. Large industrial manufacture will eventually be replaced by 3D printing and LENR. Mankind would go through a new industrial revolution. This revolution could lead to the development of intelligent power terminals and the Internet of Things.

But by now, all this is speculative.

10.2.2 Economic Aspects

The potential economic benefits of LENR would be amazing. First, LENR would help mankind to get rid of the high pollution and the dependence of the relatively inefficient fossil energy. In addition, it would reduce energy costs, saving the living expenses of the public and the production costs of enterprises. It would impact the energy consumption market with its revolutionary quality of safety and performance.

Second, LENR is a truly revolutionary energy. It would shock the financial and stock markets and become the focus of banks and investors. Finally, LENR being the most advanced technology would change the allocation of labor force in the energy industry. In the long run, it would help to accelerate the realization of the labor and industry upgrading. LENR would not only provide energy for production and life, but also promote prosperity and the development of the world economy.

10.3 Development Status of LENR Worldwide

Since 1989, there has not been any major development in the LENR development until 2011. In January 2011, a LENR device called the “Energy Catalyzer” (E-CAT) was published by two Italian scientists, Andrea Rossi and Sergio Focardi. According to Rossi’s introduction, the initial input power of his E-CAT was 400 W. After the start of fusion reactions, the input power was no longer needed for the self-sustaining reaction. The output power under the steady state was 10 kW. If Rossi’s claims can be verified independently, his E-CAT would be a milestone in the development of LENR.

Meanwhile, the National Aeronautics and Space Administration (NASA) in the USA also announced that they had developed a low energy fusion device. In the last several years there were other companies announcing a success. There were, for instance, Defkalion in Canada and Brillouin in the USA. In the International Conference on Cold Fusion (ICCF) held at the University of Missouri in 2013, Defkalion demonstrated their low energy fusion technology. The equipment ran dozens of hours continuously. The output energy reported was much larger than the input energy.

In April 2015, the LENR Industry Association was established, which officially started the commercialization process of LENR technologies. In the future, several companies in the world announced to launch mature commercial products. If true, these products will gradually enter the industrial and the civil fields.

Fig. 22 – Conceptual graph of the E-CAT [3]

10.4 General Situation of LENR Development in China

The research on the LENR in China began after Fleischmann and Pons’ experiment in 1989 [4]. At that time, a lot of research institutes were engaged in the study of LENR. Basically, all of them were trying to repeat Fleischmann and Pons’ experiment. A lot of results were published in professional journals. Some experiments also generated excess heat and radioactive materials. Later, the voices against LENR in the world became stronger and stronger. LENR was suspected by some scientists as pseudoscience.

China gave up further support for LENR and the researchers also lost their enthusiasm. This made the study of LENR stagnant in China. In China’s research environment, scientists are required to make achievements as soon as possible. Under this pressure, experimental studies seemed no longer possible. Some scientists published some theoretical articles about LENR occasionally, but these articles did not arouse large attention.

Prof. Li Zhongxing in the Department of Engineering Physics at Tsinghua University and Prof. Gou Qingquan in Sichuan University persisted in this area silently and published a series of articles. Tian Zhongqun, an academician of the Chinese Academy of Science, studied LENR at the University of Utah in the 1990s. He was also an active promoter of LENR. He proposed to carry out LENR studies under “the condition of non-consensus” in the fifth meeting of the expert committee in the National Science Foundation of Chemistry in

2011. Since then, China has restarted to support LENR research at the national level officially.

China's LENR activities have already been launched. The research and development of LENR is depending on industry support. Rossi's American partner – Industrial Heat – has already started to advertise the concept of LENR in China. According to the news published on the official government website of Baoding, Hebei Province, the leaders of Industrial Heat in the USA have exchanged views on the domestic production of the Nickel Metal Hydride Reactor (NiMHR) with related Chinese departments. This makes it possible to launch mass production of the E-CAT in China. The strategy of developing LENR in China will be supplying the domestic market with technology, just like the way it did in other industries.

10.5 The Research Process of LENR in China

10.5.1

The Experimental Measurements of the Excess Heat and Fusion Products Generated from the Electrolysis of Heavy Water by the Titanium Cathode

Fleischmann and Pons' announcement on their LENR achievements on March 23, 1989, caused strong shock and controversies in the scientific community [5]. At that time, Prof. Gou Qingquan pointed out that LENR were possible in crystals and clarified that such fusion reactions were mainly exothermic. He-4 was also emitted at the same time.

Measuring the excess heat in the experiment is very important. It could be used to ascertain the existence of LENR. Chinese scientists had kept using titanium rods as cathodes to electrolyze heavy water and to study the reason of this excess heat phenomenon for more than a decade. They improved their test methods continuously and measured this excess heat accurately. After a few years they put two titanium rods in parallel as the cathode and a platinum solenoid as the anode to do the heavy water electrolysis experiment. The excess heat phenomenon was obvious. The excess heat power could reach the magnitude of 100 W. The repeatability of this experiment was also very good. The calorimetry system used in this experiment was a high-power open system developed by them, using computers to have real time experimental data acquisition and processing. This system could be used to measure the excess heat power from 2 W ± 0.5 W to 150 W ± 0.5 W. The measurement result was reported to be accurate and reliable.

Here are some research results of this experiment:

1. Experiments show that TiD_2 can be formed after a long time of heavy water electrolysis and after deuterium is filled into the titanium cathode surface layer. The excess heat phenomenon happens after the formation of TiD_2.
2. The degree of the excess heat phenomenon is related to the surface area of the titanium cathode.
3. The comparative experiments of light water and heavy water electrolysis show that electrolyzing light water does not have excess heat but electrolyzing heavy water can have excess heat.
4. The X-ray diffraction analysis of the titanium rod with excess heat after the electrolysis shows that the structure of the surface layer has been changed from the hexagonal structure to the cubic structure of TiD_2. This experiment was repeated for several times and the same result was obtained. The TiD_2 crystal is an ionic crystal. D^- is an anion and has two electrons orbiting around the nucleus, which enhances the shielding effect of the Coulomb force between deuterons. This is beneficial to generate fusion reactions between two deuterons.
5. According to the measurements from the China Institute of Atomic Energy (CIAE), the nuclear product after LENR is mainly He-4. This indicates that the theoretical predictions proposed by Prof. Gou Qingquan are correct.

10.5.2

Research on the Excess Heat Production in Hydrogen-loaded Metals at High Temperatures

In May 2015, Prof. Jiang Songsheng of the CIAE published a research report on repeating the E-CAT experiment [6]. His report showed that excess heat was generated during the experiment. Fig. 23 shows the schematic diagram of his experiment set-up:

The amount of powder fuel (Ni + 10% (in weight) $LiAlH_4$) is 20 g filled in a nickel cell, located in the stainless-steel reaction chamber. The existing heater is made of nichrome wire, which is wound on a ceramic tube. A stabilized DC power supply is used. The heater is surrounded by MgO thermal insulation material, which is filled in an hollow cylindrical aluminum jacket with inner diameter of 55 mm, outer diameter of 25 cm and 40 cm long.

The temperature is measured by stainless-steel shielded K-type thermocouples. The thermocouple T1 is located on the outer surface of the stainless-steel reaction chamber. T2 is placed in contact with the outer surface of the nickel cell and T3 is inserted inside the container in contact with the fuel powders.

The experiment was carried out from May 4 to May 8, 2015, and lasted for 96 hours. In the first day, the reaction chamber was vacuumed to 10^{-4} mbar, and then was heated up. The $LiAlH_4$ was degassed, and the upper pressure in the chamber reached 400 kPa at temperatures of around 150-300 degrees centigrade. Then the pressure went down to 90 kPa in the subsequent 18 hours. In the next day, when the temperature of the thermocouple T3 was increased to

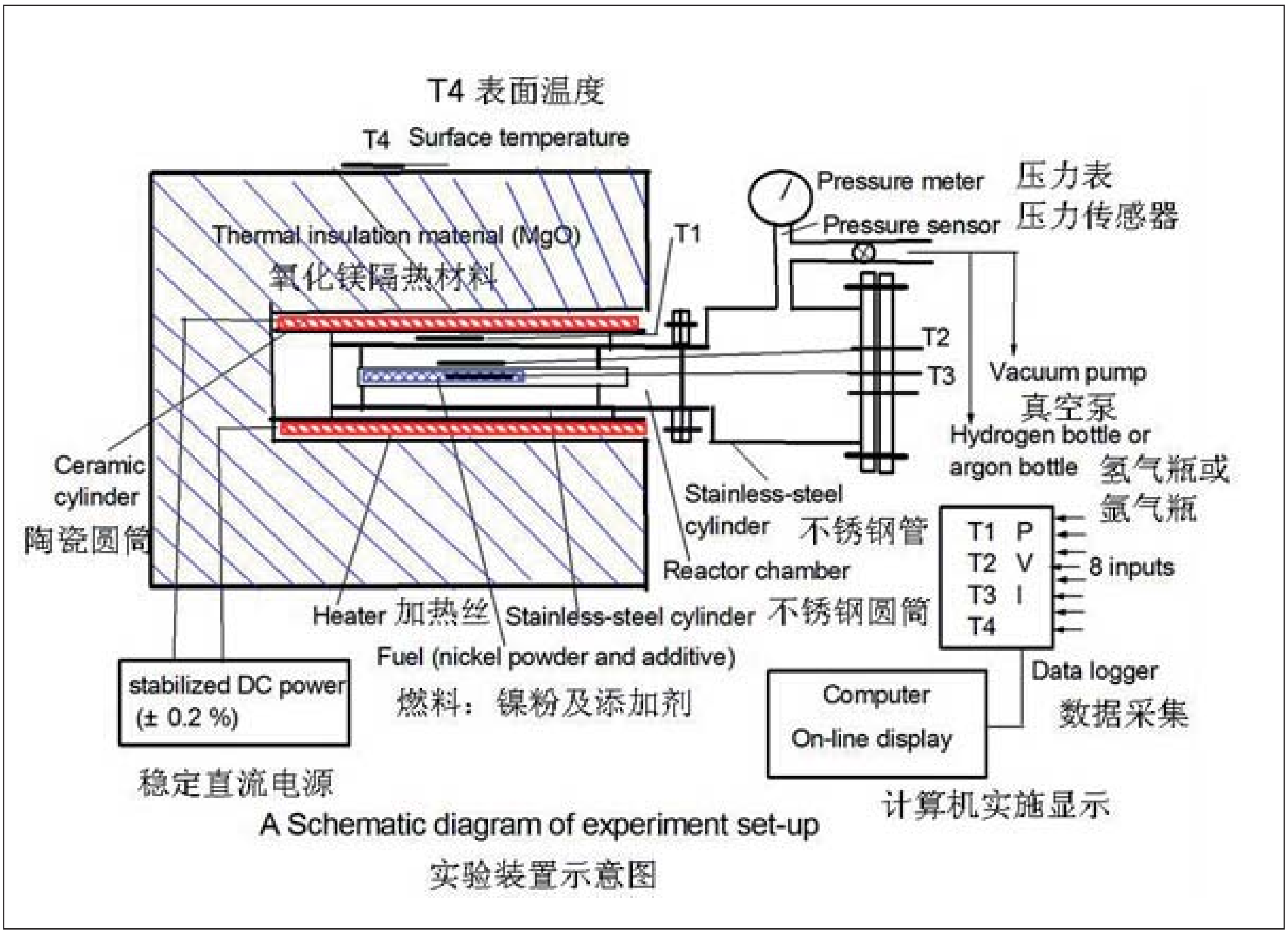


Fig. 23 – Schematic diagram of the experiment set-up by Prof. Jiang Songsheng [6]

about 950 degrees centigrade by increasing the electric power to 900 W, the temperature of thermocouple in the fuel cell increased rapidly.

Unfortunately, T3 was damaged at this time. However, T2 was still working well. And T2 (the temperature near fuel cell) was also increased rapidly to be higher than T1 (the temperature near the heater). When T2 temperature reached a temperature over 1300 degrees centigrade for 10 minutes, the power was turned off to protect T2 from damage.

The self-sustaining heat effect appeared and lasted about 20 minutes, then the T2 temperature went down rapidly. When the temperature decreased to less than 1000 degrees centigrade, the power was turned to 900 W again, and an exciting state of excess heat production appeared again because T2 was back to be higher than T1 again. During most of the running time, T2 temperature was kept less than 1200 degrees centigrade by controlling the electrical power.

The excess heat production in the Ni + $LiAlH_4$ fuels has been observed repeatedly. The heat production can be controlled by the input power and can last for a longer time. The T2 temperature placed on the outer surface of the fuel cell is about 405 degrees centigrade higher than the T1 temperature. T1 is placed on the outer surface of the reaction chamber and near the heater. The estimate power of excess heat is about 600 W. The ratio of the excess heat of 600 W to input power of 780 W is 0.77. Considering the self-sustaining effect, the input power might be significantly decreased if a chopper supply can be used to keep excess heat production.

How to calculate the ratio of total produced heat energy to electrical input energy with this kind of supply remains a question in present work. The consumption of the nickel container and the Ni + $LiAlH_4$ powder was checked to be less than 1 g after the experiment. The calculated energy density is four orders of magnitude greater than the value of gasoline. Therefore, the origin of excess heat cannot be explained by any chemical reaction. The isotope abundances of nickel and lithium in the fuels after the experiment will be analyzed by mass spectrometry technique. A further experiment will be carried out.

10.5.3 Selective Resonant Tunneling

The research work on LENR in Tsinghua University in Beijing is based on the theory of the selective resonant tunneling model developed by the university's own team [7]. According to the general formula of quantum mechanics, when resonance happens, the cross section of inelastic and elastic scattering should be increased at the same time. This will lead to the correlation between the excess heat (inelastic scattering) and diffusion (elastic scattering).

Based on this thinking, a post-doctor from the Tsinghua University Department of Physics did an experiment using a high-precision micro calorimeter and confirmed that there was a relationship between the deuterium flux and the excess heat in the palladium pipe filled with gaseous deuterium. On this basis, another doctoral student found evidence of nuclear transmutations by repeating 80 times the charge and discharge of a palladium sheet. This report was well received in the 17th ICCF in 2012.

In return, the confirmation of the relationship between the deuterium flux and the excess heat is another support for the selective resonant tunneling model. Today, the selective resonant tunneling model not only gets support from the three-deuterium reaction experiments done in the United States Naval Research Laboratory, but also from the cross section data of the thermonuclear fusion. It can well describe the cross section data of light nuclear fusions. It was also cited by the International Atomic Energy Agency (IAEA) in its monograph named Frontiers of Plasma Physics and Technology.

10.6 Conclusion

The potential significance of LENR can be simply summarized as a cheap, clean, compact and portable energy source with high capacity [8]. Our world would welcome this revolutionary energy. Its invention and popularization could bring countless benefits to commercial, industrial and other economic fields. It would affect every aspect of our society.

But there is still a certain period before the scientific research on LENR is expected to achieve easy repeatability and stability. Viewed from LENR science, the traditional thermonuclear fusion reaction theory and the whole nuclear reaction theory limited the thinking of LENR researchers and regulated the majority view of the scientific community. From the perspective of the technology and its applications, the huge potential commercial future of LENR made the researchers and supporters become utilitarian. Their competition not only limited the freedom of the scientific exchange, but also reduced the transparency and credibility of the research results.

In China, the research on LENR is still at the beginning stage. China is still holding back to see whether the international LENR field will have a breakthrough [9]. China's attitude towards LENR is to wait until there is a reliable message indicating that there has been a real breakthrough in this field. LENR supporters regret that this also means that China is probably to miss the best chance to develop LENR technology in case this phenomenon can be used commercially.

References

[1] Baidu baike: The Cold Fusion: *http://baike.baidu.com/*

[2] Utah News, Sports, Weather and Classifieds: Renowned 'Cold Fusion' Scientist Martin Fleischmann Dead at 85: *http://www.ksl.com/?sid=21590341*

[3] Extremetech: Cold Fusion Reactor Verified by Third-party Researchers, Seems to Have 1 Million Times the Energy Density of Gasoline: *http://www.extremetech.com/extreme/191754-cold-fusion-reactor-verified-by-third-party-researchers-seems-to-have-1-million-times-the-energy-density-of-gasoline*

[4] The World of LENR: The Development Situation of LENR in the World by 2014: *http://www.lenr.com.cn*

[5] Gou Qingquan, Zhang Qingfu, Sun Yue: Review on the Research Progress of Cold Fusion, Journal of Atomic and Molecular Physics, Vol. 25 No. 3, June 2008

[6] The World of LENR: The China Institute of Atomic Energy (CIAE) Successfully Repeated the Nickel-hydrogen Low Energy Nuclear Fusion (LENR) Device-E-CAT: *http://www.lenr.com.cn/*

[7] Dong Zhanmin, Gong Cunkui, Li Xingzhong. The 18th International Conference on Cold Fusion (ICCF) Documentary, August 7, 2013.

[8] The World of LENR: 25 Benefits of LENR: *http://www.lenr.com.cn/*

[9] The World of LENR: Prof. Li Xingzhong Talks about the Domestic Status of LENR: *http://www.lenr.com.cn/*