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SIGNIFICANCE OF DEVELOPING ADVANCED FUEL CANDU REACTOR TECHNOLOGY IN CHINA AND THE GENERAL REQUIREMENTS FOR AFCR

Zhang Zhenhua, Qiao Gang, Zou Li, Meng Zhiliang, Liu Xuebin, Fanshen
Third Qinshan Nuclear Power Company, Zhejiang, China

Abstract

Upon the demands of energy source structural adjustment and environmental optimization, China's nuclear power industry is anticipated to be continuously developing quickly in future. The sufficient supply of nuclear fuel will be the mostly concerned part at the progress of China's nuclear power development. Advanced Fuel CANDU Reactor technology could play an active and important role in mitigating the condition of strained nuclear fuel supply, in promoting the reprocess industry of nuclear fuel, and in supplementing China's closed nuclear fuel cycle system. This paper presents the current status of Chinese nuclear closed fuel cycle and the incentive and significance for development Advanced Fuel PHWR Technology in China. This paper also describes the practice and roadmap of developing Advanced Fuel PHWR Technology. Finally this paper also raises the general requirements on the design of Advanced Fuel PHWR after Fukushima accident from point view of the owner.

1. Introduction

As China's economy is developing rapidly, the total demand for energy is therefore increasing significantly. According to the prediction of Chinese State Council Development Research Center, the total primary energy consumption will reach 5 billion tons of coal in China by 2020. Now the main energy supply in China is sourced from coal, but it is requested urgently to adjust the energy structure due to global climate change and growing air pollution problem. In order to reduce greenhouse gas emissions and reduce environmental pollution, more non-fossil energy sources should be developed and utilized. Chinese government promulgated the "Air Pollution Prevention Action Plan" in September of 2013, it stipulates that the coal consumption ratio in total energy consumption shall be less than 65% and the non-fossil energy consumption ratio shall be increased to 13% by 2017, further, the non-fossil energy consumption ratio shall be increased to 15% by 2020. Therefore, China's energy development is now facing with dual pressures of total amount assurance and structural control.

At present, China is also making great efforts to develop new energy source such as hydropower, wind power, solar power, shale gas etc, but these new energy sources at this stage can't effectively meet our energy demands due to some limitations. As for nuclear power energy, because of its advantages such as high energy density, no pollution, no regional limitation, relatively mature technology, sustainable resource and breeding potentiality, it is deemed as the rational and realistic option for energy development in China. According to "China Long-term Nuclear Power Development Plan (2011-2020)", the nuclear power capacity in operation will reach 58 million kilowatts and the nuclear power capacity in construction will reach 30 million kilowatts by 2020. From long-term point of view, as per energy development strategy research report by Chinese Academy of Engineering, the nuclear power capacity is proposed to reach 200 million kilowatts by 2030 and to reach 400 million kilowatts by 2050.

Supply of uranium resources will be a great challenge due to large-scale development of nuclear power in China. Uranium Red Book reports that the total economic nature uranium reserves (cost <$ 260 / kg) in the world is about 7.1 Mt. According to China's nuclear power development plan, the potential demands for uranium resources are estimated in Table 1 below:

Table 1 Potential scale of China's nuclear power and uranium demands

Year	Nuclear power capacity （G We）	Nuclear power ratio (%）	Annual demand for uranium (Tons / year)	Lifetime demand for uranium （Tons）	% of the global amount （<$ 260 / kg）
2011	12	1.1	2,160	129,600	2%
2020	58	4	10,400	624,000	12%
2030	200	10	36,000	2160,000	30%

As per the above table, we could find out that, to support China's future nuclear power development, a considerable part of the natural uranium may need to be imported. So, in view of long run, a single nuclear energy development mode solely relying on the development of PWR is not sustainable. In order to fully utilize the limited uranium resources, to break through the uranium resources limitations on nuclear power development, to minimize the nuclear waste, to ensure the sustainable development of nuclear power, Chinese government insists on the implementation of closed nuclear fuel cycle technology roadmap, combining with thermal reactor - fast reactor -fusion reactor "three-step" strategy, to ensure the long-term and sustainable development of China's nuclear energy.

The construction of closed nuclear fuel cycle system has been started in China, but the technology roadmap has not been planned perfectly. At current, the thermal test of post-processing pilot plant has been completed, MOX fuel production test line is under construction, fast-breed experimental reactor has been completed. In addition, the utilization of reprocessed uranium has not been practically planned which is actually one type of important energy source.

Third Qinshan nuclear power company, as the operating owner of two CANDU6 units in China, cooperating with Candu Energy Inc. and China domestic design institute and fuel element manufacturer, are researching and developing the reprocessed uranium technology, which chancely presents a trial scheme to complement with our PWRs: firstly to develop the full core applications of nature uranium equivalent in operating CANDU6 Units which is the mixture of PWR reprocessed uranium and depleted uranium with the similar fuel characteristics as natural uranium), and finally to realize the direct and efficient utilization of reprocessed uranium in new-built Advanced Fuel CANDU Reactor, also to realize the application of thorium fuel when required. Further, the application of reprocessed uranium from PWR into new-built CANDU reactors, will also positively supplement and promote the development of China's closed nuclear fuel cycle system.

2. Suggested strategic role of CANDU reactor in China's closed nuclear fuel cycle

2.1 Technical features and advantages of CANDU reactor

In 2002 and 2003, two CANDU6 units were built in Zhejiang of China. The construction of the first unit created the shortest heavy water reactor construction period (54 months) record. Under the constant efforts and continuous improvements of the two CANDU6 units' owner staff, WANO performance index of these two units has kept as the world advanced level for seven years (2006 ~ 2012). These two heavy water reactor units have obtained excellent economic benefits, environmental benefits and social benefits.

CANDU reactor is known as pressure-tube reactor with heavy water as moderator and coolant. The reactor could use natural uranium as fuel. Fuel channels are arranged horizontally. The capacity factors are high. Fuel Conversion ratio(0.8) is higher than that of light water reactor(0.5). Neutron economy is good and the uranium consumption is relatively low. The reactor could be refueled while running with high fuel flexibility, and fuels of NU, RU, LEU, Thorium can be used . Generally, compared with other reactors, CANDU reactor has many unique technical advantages, such as economic use of reprocessed uranium, nuclear power application of thorium resources, large-scale isotope production, etc.

The enrichment of RU from PWR is about 0.8 to 1.2%, which is higher than that of NU fuel in CADNU reactors. The RU need not to be enriched when used in CANDU reactor, and it could be used directly or used as NU equivalent. The radioactivity level of RU fuel used in PHWR is only 3 ~ 4 times than NU fuel, while the RU fuel used in PWR is about 20 times than NU because of the enrichment process. In addition, because of the better neutron economy and higher fuel conversion ratio, RU used in PHWR is more efficient then in PWR which resulting more electric power generation of ~ 32%. Therefore, the prospective economic benefit of RU application in CANDU reactor is nice, and the benefit would be more obvious when natural uranium prices rising in future.

It's relatively easy to realize the nuclear power utilization of thorium in CANDU reactor. As we know, thorium is the potential nuclear energy resources with abundant reserves. The global reserves is about 3 times than uranium, and thorium resources in China is also very considerable. Because the natural thorium is radioactive and mixed with other mineral resources, it is brought out when mining other mineral resources and causes serious environmental pollution. After 2000, the redevelopment of global nuclear power causes more attention on thorium/uranium fuel cycle. IAEA has held several conferences on nuclear utilization of thorium resources. According to the research results, the utilization of thorium resources in current CANDU reactor is technically feasible, and the safety could be further enhanced, and the benefit expectation is good. In addition, low-enriched uranium (~ 2 wt %) could be used as the driving fuel for thorium fuel in CANDU reactor.

2.2 Suggested Strategic Role of CANDU reactor in China's closed fuel cycle

As mentioned above, CANDU is currently the best way to use RU and Thorium resources. Chinese nuclear industry has decided to develop the closed fuel cycle, but there are still many challenges, and it seems that CANDU is one of the best way to resolve these problems. We could use CANDU as the economic and effective means to use the plentiful RU produced by the closed fuel cycle and as the platform to achieve the breakthrough of nuclear application of thorium resources, which could help to mitigate the difficulty of nuclear resource supply and provide effective supplementation to our closed fuel cycle system.

In the construction and optimization process of our closed fuel cycle system, PHWR can play its unique role, and the positioning suggestion is as follows:

First, technology accumulation stage: build the testing MOX fuel production line to produce fuel for experimental fast-reactor, realize the full-core application of RU from the pilot reprocess plant in PHWR, start to build the Demonstration Fast-reactor, develop commercial fast-reactors, start to build two AFCR for RU application and Thorim fuel irradiation.

At this stage, CANDU is positioned to achieve the direct use of reprocessed uranium, which could increase the efficiency of uranium utilization and the economy of spent fuel reprocess. The new built CANDU unit could be a test platform to conduct the research of nuclear utilization of thorium resources.

Second, commercial-scale closed nuclear fuel cycle system stage: construct 800 tons reprocessing plant and corresponding MOX fuel production line, construct and promote the demonstration fast-reactors to use the plutonium from reprocess plant, develop PWR MOX fuel technology, develop commercial fast-reactor technology independently, construct more AFCRs to use the RU from the reprocess plant, construct the demonstration PHWR for thorium utilization.

At this stage, CANDU is positioned to further utilize RU and to realize the nuclear power utilization of thorium, meanwhile to explore new resources of nuclear fuel and help to mitigate the demand of fast-reactor development.

Third, long-term Stage (2030 -): complete the technical development for closed fuel cycle of fast breeder reactor, switch the closed fuel cycle of thermal reactors to the closed fuel cycle of fast-reactors, develop the thorium-uranium cycle as the backup of uranium-plutonium cycle, develop the fusion reactor technology.

At this stage, CANDU is positioned to consume the accumulated RU for power generating, to provide the thorium-uranium cycle as a backup means of uranium-plutonium cycle, and to produce tritium as the fusion reactors’ fuel.

Generally, the development and construction of CANDU with NUE, and AFCR with DRU and Thorium fuel could increase the uranium utilization efficiency and realize the nuclear utilization of thorium resources, which would be helpful to provide the effective supplement to China’s closed fuel cycle, to promote the development of China’s reprocess industry, and to benefit the long-term sustainable development of China’s nuclear power industry.

3. Research and development practice of CANDU advanced fuel technology

Since 2008, TQNPC cooperated with domestic institutes and companies and Candu Energy Ltd. to conduct the research of utilizing reprocessed uranium from PWR spent fuel in CANDU reactor, the research of nuclear power utilization of thorium resource, the development of advanced fuel CANDU reactor in China, and we have reached a significant progress.

3.1 Practice and progress on research and development of RU nuclear utilization

In beginning of 2008, TQNPC initiated research and development of using reprocessed uranium from PWR spent fuel in CANDU reactor. According to our planning, the R&D is divided into two steps: first, the RU is used in form of natural uranium equivalent in Qinshan two operating CANDU reactors; and then RU will be used directly in new built CANDU reactor.

Recycled uranium equivalent requires the combination of 70-80% RU with about 20-30% depleted uranium, to keep the nuclear properties of the mixture being similar with that of natural uranium. And 37-element fuel bundle is used as carrier, fuel product line needs minor modification in principle. This scheme is simpler and technically feasible, and it will be easy to realize the large-scale engineering application with less risk on engineering investment. After the success of the project, two Qinshan CANDU reactors can consume about 140 tons of RU per year, saving about 200 tons of natural uranium resources per year.

In 2009, natural uranium equivalent fuel design was completed; in January of 2010, the fuel bundles for demonstration irradiation was completed and transported to Qinshan site; in-core irradiation was started in March of 2010 and completed in March of 2011, all spent natural uranium equivalent fuel bundles were discharged out of the core. Core monitor and in-bay inspection shows that RU fuel had very similar power-generating capacity and operation behavior comparing with those of natural uranium fuel. After that, a full core implementation project was defined and initiated. Up to now, safety evaluation was completed and the other works, such as post-irradiated examination, fuel production line modification, refueling simulation software updating, bulk purchase of RU had made significant progress. According to the project plan, it is expected to achieve full core implementation of RU by the end of 2014.

3.2 Practices and progress on nuclear power utilization of thorium resources

In December of 2008, China National Energy Board held a seminar on nuclear power utilization of thorium resources, the experts suggested using CANDU reactor to realize a technology breakthrough to lay the foundation for potential nuclear power utilization of thorium resources in the future. In July of 2009, TQNPC joint with three other parties to conduct a feasibility study on utilization of thorium as fuel of CANDU reactor. The feasibility study proposed to use Enhanced CANDU-6 Reactor to utilize thorium resources, use low-enriched uranium (~ 2wt%) as driving fuel. The study shows that this schemes is not only technically feasible, with enhanced safety , with well-expected economy, and can be practically constructed in the short term, this scheme will save about 20% of natural uranium resources compared with current CANDU unit.

Considering that there is no thorium-based nuclear reactor in service currently, and China is also lacking of nuclear power application experience on thorium resources, TQNPC developed a gradually progressing roadmap to realize thorium resources application in CANDU, firstly to conduct a serial key technology research and development, and then to conduct demonstration irradiation of thorium fuel in a suitable core platform, and finally to realize the full core application of thorium fuel.

3.3 Significance of developing CANDU advanced fuel technology and the roadmap

In order to gradually realize the strategy role of CANDU technology in China's closed nuclear fuel cycle system, to realize the complementary advantages in conjunction with China's large-scale developed PWR, to match with the construction of PWR and commercial reprocessing plant, basing on the current successful R&D of natural uranium equivalent, TNQPC and CE Company jointly proposed a development tentative plan for advanced fuel CANDU reactor (hereafter AFCR). Development of AFCR technology will be based on the proven CANDU technology, will be conducted with a progressive and conservative strategy, the first step is to realize the direct utilization of RU, and the following step will be the utilization of thorium.

Therefore, we established the following development roadmap, namely "completion of the demonstration irradiation and full core implementation of natural uranium equivalent in Qinshan CANDU operating units ", and continued to jointly develop "an AFCR reactor for direct utilization of RU with the capability of demonstration irradiation and utilization of thorium fuel ".

AFCR design will be based on the natural uranium fuelled EC6 of generation 3, will incorporate lessons from Fukushima. AFCR will have higher safety and meet the safety requirements of generation 3, it will have better economy with the construction cost being competitive with generation 2 PWR , with lower operating costs than CANDU-6. It will have more flexible fuel options, such as natural uranium fuel, slightly enriched uranium and RU and thorium fuel, etc.

As for the advanced fuel CANDU reactor technology, our suggested main design targets are:

- To take Canada EC6 as the base, adopt the latest generation 3 standards, draw lessons from Fukushima, to conduct technical improvement and safety enhancements, and to be practically constructable in near term.
- To realize direct utilization of RU based on the natural uranium equivalent technology, to improve utilization ratio of RU, to increase average burn-up and decrease spent fuel product volume significantly
- To conduct demonstration irradiation for thorium fuel in a few fuel channels.
- To have the capability of cobalt 60 production for improving the comprehensive advantages and economy of CANDU plant.

Based on the above considerations, in March of 2012, TQNPC and CE Company in conjunction with other two parties signed an agreement for Development and Testing of Advanced Fuel CANDU Reactor with the time-period of 2 years. The agreement is to conduct conceptual design and related R&D for AFCR based on high capacity factor CANDU reactors. By the end of 2013, the documentation responsible by TQNPC, such as the top-level technical requirements, project planning, equipment localization study were completed and the other work responsible by TQNPC, such as overall project management, licensing and risk assessment, operating experience feedback, design support were progressing smoothly. AFCR conceptual design (system, physics, fuel, etc.), safety analysis, licensing support, code verification by CE Company were almost completed. Nuclear Power Institute of China initiated the irradiation test preparation for thorium fuel smoothly. Chinese Nuclear North Fuel Company completed the study of nuclear grade thorium fuel purification process. Our current plan is to complete the AFCR overall conceptual design in middle of 2014, and at the same time to conduct site selection preparation, to try great efforts to build the first AFCR in about 2021 and then conduct demonstration irradiation of thorium in the new built AFCR. After the success of AFCR, two thorium-fueled AFCR is planned to be built for realizing the nuclear utilization of thorium resources in China.

We believe that the significance of developing AFCR technology in China will be:

- AFCR could set up a complementary operation mode with PWR to use RU in a more efficient and economic manner, to decrease consumption of natural uranium resources, without impact of Pu recycling in thermal or fast reactor. It would be an ideal option of closed fuel cycle in a relatively long time in China. Therefore, we would say that AFCR provides a feasible option for relieving the uranium supply pressure and decreasing the natural uranium demand for next 20 years' nuclear power development of China.

- The AFCR could be a R&D platform for nuclear power utilization of thorium. The nuclear power utilization of thorium will expand the nuclear fuel supply sources of China, will help to guarantee the nuclear fuel supply in different ways. Furthermore, the nuclear power utilization of thorium will help to solve the problem of secondary environmental pollution resulted from thorium ore.

- AFCR has the capability of cobalt-60 production in a large scale for meeting the domestic market demands, and the capability of tritium production for providing fuel for China's future fusion and fission-fusion hybrid reactor.

- The application of RU in AFCR will improve the economy of reprocessing industry and promote the development of China's reprocessing industry.

- Development of AFCR in China can take full advantages of China's existing resources of CANDU units. After a certain CANDU scale is formed, the operation costs can be reduced and the long-term safety and efficient operation of CANDU reactors can be ensured.

4. Owners requirements for AFCR

Considering the policy and the regulatory requirements for new-built nuclear power project in China, many years of operation practice from CANDU units, and the lessons learned from Fukushima Accident, TQNPC, being a potential owner, proposed the general requirements for Advanced Fuel CANDU Reactor. The requirements include aspects of safety, economy as well as the unique advantages of AFCR. And we hope these requirements could be used as the important references and bases at the design of Advanced Fuel CANDU Reactor.

4.1 China's policies and regulatory requirements for new-built nuclear power project

New-built AFCR should meet the requirements of latest Canadian nuclear safety regulations, as well as the current Chinese nuclear safety regulations, and the latest nuclear power international standards such as IAEA standard.

In addition, according to " China 12th five year" energy plan, the new-built nuclear power projects must comply with the safety standards of generation 3 NPP, must be provided with mature and latest requested passive and non-passive severe accident prevention and mitigation measures. For the future new-built nuclear power projects in China, the general requirements of "nuclear safety and radioactive pollution prevention 12th Five Year Plan and the 2020 future targets" shall be met. The NPPs constructed during the 12th Five Year period, shall meet the target of reactors melting frequencies below 10-5 / reactor-years, large-scale radioactive release frequency lower than 10-6 / reactor-years, the NPPs constructed during the 13th Five Year period, shall strive to eliminate the possibility of large release of radioactive material from design basis.

4.2 Safety requirements of AFCR

The design of ARCR shall meet the safety features of generation 3 NPP, shall incorporate sufficient design for severe accident prevention and mitigation measures according to the latest requirements, shall adopt mature, proven, simple, advanced technology, and the safety design shall be better than that of EC6. Meanwhile, the design shall follow and meet the international requirements and the latest Chinese nuclear safety requirements after Fukushima Accident, and fully consider the operating experience and design improvements from operating CANDU6 units and other NPPs. The general safety requirements for AFCR design is proposed in the following Table 2:

Table 2 Safety requirements of AFCR

Items	**Design requirements**
Design basis	➢ DBE level should not be less than 0.25g, both the structure and equipment for Main control room and Second control room should be DBE qualified. ➢ plant layout , safety equipment arrangement should be considered to prevent the flood in accordance with site situation ;
Reactor core –related design	➢ provide with flexible fuel option, to use mature and proven CANFLEX bundles as carrier, to use proven fuel design and physical code , and any design modifications should be fully assessed and validated
Mitigation capabilities under severe	➢ To reserve the inherent design features: the large capacity of moderator and light water could be taken as the passive decay heat sink after severe accident, and optimizing the design of reactor spray

accident conditions	system to provide passive cooling capacity to reactor core; ➢ it is suggested that, add the containment steel liner , consider the containment capacity during both MSLB and spray system dual failure in the containment design , perform the impact assessment of large aircraft collision in accordance with NEI0713 , consider radioactive gas filter ventilation system , consider passive and non-passive containment hydrogen detection and elimination capacity after severe accident ; ➢ be capable of establishing the core cooling through an external water source at severe accident condition , including appropriate water and electricity as well as piping and other seismic equipment , each unit configured with two nuclear class seismic qualified emergency diesel generator units and be equipped with seismic qualified battery packs with 24-hour loading capacity (including core cooling loop) .
NNSA Post-Fukushima Requirements on NPPs in Construction	The “Post-Fukushima General Requirements for Modification Actions to be taken by NPPs (Trial)” is published by China NNSA in June of 2012, and the major contents are: Modification Requirements for NPP anti-flooding capability ➢ Technical requirements for residual heat removing measures of emergency water make-up through secondary loop or primary loop, emergency water make-up for spent-fuel pool, and technical requirements for related equipment. ➢ Technical requirements for mobile emergency power supply and its configurations (such as the function, equipment and operation procedures) ； ➢ Technical requirements for monitoring of spent-fuel pool； ➢ Technical requirements for modification of hydrogen monitoring and control systems ； ➢ Technical requirements for inhabitability and function of emergency control center ； ➢ Technical modification requirements for monitoring and emergency preparedness at radioactive environment； ➢ Technical requirements for response to external natural disasters；

4.3 Performance and economic requirements of AFCR

Advanced Fuel CANDU Reactor shall be economically competitive in comparison with the concurrently constructed NPPs, and advanced plant management system shall be applied to reduce the cost for construction, operation and maintenance. The relevant requirements are given in the following Table 3:

Table 3 Performance and economic requirements of AFCR

Performance	**Design requirements**
Generating Power	740MWe
Design Life	60 years
Capacity Factor in Life Span	Higher than 90%
Fuel Consumption	Fuel Consumption of DRU fuel shall not be less than 10.5MWd/kgHE， Fuel Consumption of LEU/Th fuel shall not be less than 20 MWd/kgHE。
Construction Requirement	Modular and standardized construction: the time period from FCD to FLD of first unit will be 46 months, the time period from FCD to ISO will be 54 months.
Control System	Totally digital
Major Overhaul	Time interval between major overhauls will be 24-36 months; time period of each major overhaul shall be less than 30 days.

4.4 Consideration of experience and feedbacks from CANDU NPPs in operation

CANDU6 unit is of mature technology and have been operating in China for more than 10 years with excellent achievements. The operational feedbacks and modification experiences from these units shall be considered and satisfied in the e design of Advanced Fuel CANDU Reactor, such as to configure for spent-fuel dry storage capability, to enhance the operation reliability of circulated cooling water system, to optimize the maintainability and operability, to add stand-by auxiliary feed-water pump system, to realize the physical separation between channels of electrical rooms, to improve the localization of equipment.

5. Conclusion

With the rapid development of China's economy and the increasing importance attached to environmental protection, nuclear power in China will develop in large scale, and China is paying more attention to supplement and improve the closed nuclear fuel cycle system. CANDU reactor will be one of the ideal type of reactor to realize the utilization of reprocessed uranium, utilization of thorium for nuclear energy, and supplementation of China closed nuclear fuel cycle system. As per our judgment, the development and construction of Advanced Fuel CANDU Reactor in China is necessary.

As TQNPC and Candu Energy Inc. had successfully cooperated on the construction and operation of Qinshan CANDU units, and further, both parties together with other two affiliated parties had reached initial success on the research and development of "First using equivalent natural uranium in CANDU reactor, then directly using reprocessed uranium in Advanced Fuel CANDU reactor with capability of verification and using of thorium based fuel " , we deems that Advanced Fuel CANDU reactor is safe and economic, and the construction of AFCR in China will be technically and commercially feasible.

We sincerely hope that, with further friendly cooperation between our parties and Canadian nuclear power companies, the Advanced Fuel CANDU Reactors will be successfully developed and constructed in China in near future, by which, the technical advantages of CANDU reactor at "utilization of reprocessed uranium" and "utilization of thorium resources" will be fully exercised, the closed nuclear fuel cycle system in China will be effectively supplemented, the post-processing industry of China will be promoted for further development. And, these will help much to ensure the long-term sustainable development of China's nuclear power industry, and to promote the continuous development of CANDU technology.

References

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