Fuel Cycle Analysis of an Innovative Lead-Cooled Subcritical System

Xuewei Fu, Minghuang Wang,* Yunqing Bai

*Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China
minghuang.wang@fds.org.cn

INTRODUCTION

The world needs a great deal of carbon-free energy for sustainable development. Nuclear power is one of the lowest carbon emitters available today to help meet the climate-energy challenge. However, the low utilization of uranium and the long-term radiotoxicity of nuclear wastes have been the key issues for nuclear development. Subcritical system, including Fusion Driven subcritical System (FDS) and Accelerator Driven subcritical System (ADS), might be the potential way to resolve these problems, because FDS and ADS could be used for waste transmutation, nuclear fuel breeding and energy production.

ADS studies have been performed for more than 20 years in China [1-3]. In 1996-1999, preliminary conceptual and physical feasibility studies were performed with the support from the China National Nuclear Corporation (CNNC) and the national natural science fund. In 1999-2004, the project "The physical and technical foundation research on accelerator driven clean nuclear power system" was launched with support by the national basic research program of China (973 Program), and based on the above research, another project named "Key technology study on accelerator driven subcritical system for nuclear waste transmutation" was launched in 2007 with support of 973 Program. After 2011, Chinese Academy of Sciences (CAS) launched the strategic priority research program of "The Future Advanced Nuclear Fission Energy - ADS transmutation system", and plans to achieve ADS commercial demonstration by three stages. A lot of research has been carried out including high power proton accelerator, spallation target and subcritical reactor. At the end of 2015, the Priority National Projects for Sciences and Technology approved the China Initiative Accelerator Driven System (CIADS) Project as a strategic plan to solve the nuclear resource and waste problems.

Fusion-fission hybrid studies have more than 30 years history in China. In the early stages, these studies were supported by the National High-tech R&D Program (863 Program). The related research units include the Chinese Academy of Sciences (CAS), the China Academy of Engineering Physics (CAEP), the Southwestern Institute of Physics (SWIP), and several universities and colleges [4]. China joined the ITER project in 2006, and since then, national support for fusion-related research has been greatly strengthened and has played an important role in promoting research into hybrid reactors. The FDS team has proposed many hybrid reactor concepts with different functions based on different types of fusion drivers [5-7], SWIP presented a design of hybrid reactor for fissile fuel breeding and nuclear waste transmutation based on conventional tokamak, CAEP proposed a hybrid concept driven by Z-pinch, etc.

In this contribution, an Advanced External Neutron Source Driven System has been proposed. The subcritical system is an innovation energy system with a subcritical nuclear power system driven by an external high intensity D-T fusion neutron source [8], and has the characteristics of FDS and ADS. The subcritical system chose lead as the coolant for its good performance on neutronics, thermal-hydraulics and inherent safety. Depleted uranium and spent fuel also could be burnt in this system. In particular, the identified uranium and thorium resources could meet the demand for thousands of years. Besides high uranium utilization, the subcritical system has many other advantages such as deep burn up and long service life.

SCENARIOS AND METHODS

Nuclear fuel cycle scenarios

China implemented the PWR once through fuel cycle in the past decades, because the reprocessing technology is still under developing in China. However, China insists the policy of closed fuel cycle since 1983, and advanced nuclear fuel cycle is inevitable with the rapid growth nuclear power demand and limited uranium resource. There are two nuclear fuel cycle scenarios analyzed in this summary, named once through fuel cycle and closed fuel cycle, respectively (see Fig.1). The subcritical system played an important role in closed fuel cycle for nuclear waste transmutation, fissile fuel breeding and energy production.

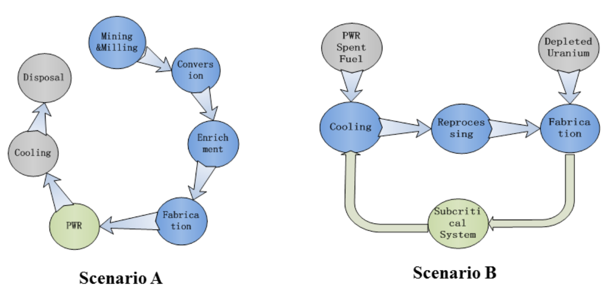

Fig. 1. Two fuel cycle scenarios.

Scenario A (once through fuel cycle): Only PWR is under operation. Nuclear fuel is used once and then sent to geological disposal without further reprocessing.

Scenario B (closed fuel cycle): Subcritical system would be introduced in 2040 without new PWRs built afterwards. The spent fuel from PWR and subcritical system itself would be reused after simple reprocessing.

According to the nuclear power projection to 2100, the potential contribution of the subcritical system in the 21st century of China is evaluated regarding following indicators: sustainability of resources, environmental impacts of nuclear wastes and economic. Several suggestions have been put forward in the end.

Methods

A dynamic model was built to assess the mass flow and levelized cost of electricity (LCOE) of the two nuclear fuel cycle strategies in China from year 2010 to 2100. The nuclear power projection, the time of subcritical system introduced to the energy mix and reprocessing capacity are three key factors.

According to the "long-term nuclear power development plan (2011-2020)" by the State Council and "China energy long term (2030, 2050) research on the development strategy" by Chinese Academy of Engineering, additional nuclear power plants (NPPs) are planned to give more than a three-fold increase to 58 Gwe by 2020, then 200 Gwe by 2030, and about 400Gwe by 2050, making nuclear power a mainstream in electricity system of China.

It is assumed that China's nuclear power per capita in 2100 would reach the world average level (refer to the Chinese population proportion of the world is 20% in 2013), and the world's nuclear power is projected in three levels reaching 5600Gw, 4300Gw, 3000Gw in 2100 respectively. The medium level is the typical forecast and nuclear power of China would reach 860Gw in this case. The nuclear power projection of China from 2010 to 2100 is illustrated in Figure.2.

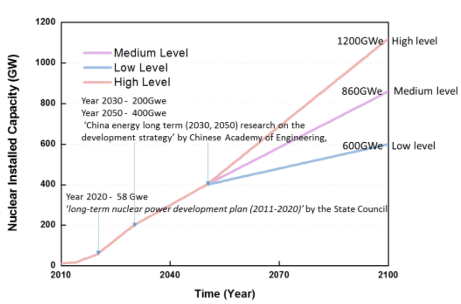

Fig. 2. Projection of nuclear power in China

The reprocessing technology of China is developing rapidly. A reprocessing plant (800 t/yr) is planned to be built around 2030 with the cooperation of France. So there should not be technology barrier after 2030 and reprocessing capacity is assumed to meet the needs in this work.

RESULTS

Fig 3 shows the demand of natural uranium (NU) every year in scenario A and B. The increasing demand of NU is totally conformed to the PWR projections in each scenario. According to the medium projection, China's accumulated consumption of NU would reach 6.38 million tonnes in scenario A till 2100. In scenario B, the total demand of NU was 2.88 million tonnes. And with decommission of PWRs, subcritical system would be the main stream in next century, so few NU would be in need since then.

According to the uranium "red book" published by IAEA, there is about 16.18 million tonnes identified conventional uranium resources worldwide, which means 39% of world's NU would be consumed by China until 2100 in scenario A. The identified uranium resource in China is only about 2 million tonnes. It means that the uranium resource of China would be depleted after 50 years in scenario A. Therefore, once through fuel cycle is incapable to satisfy the nuclear sustainability and energy security of China.

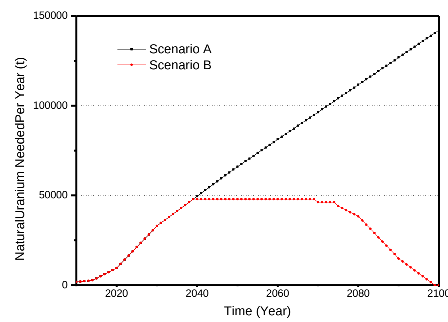

Fig. 3. Demand of NU per year

Fig 4 shows the total spent fuel inventory of scenario A and B. In scenario A, spent fuel would be buried deep in geological disposal repository after ten years storage in spent fuel pool. Spent fuel inventory would reach 650 000 tonnes in 2100. The inventory scale was equivalent of nine yucca mountains reserve. In scenario B, the spent fuel inventory was only 14 000 tonnes. There would be little reprocessing waste need to disposal in scenario B, reducing the environmental impact of long-term radiotoxicity effectively.

There have been about 0.4 million tonnes of spent fuel (as heavy metal) produced worldwide. About 90% are in storage ponds, and the balance are in dry-cask storage. If China insists on scenario A, the spent fuel inventory till 2100 would be twice as much as spent fuel produced worldwide today. The worldwide annual spent fuel generation is approximately 10 500 tonnes of heavy metal per year, with roughly 20% of heavy metal allocated for reprocessing and others going into long term storage, but most of them are in interim storage at reactor site. In scenario A, the annual production of spent fuel in 2060 would reach the world generation level today. In scenario B, the reprocessing capacity was assumed to meet all the reprocessing demand. The construction of reprocessing facilities calls for firm national plan and large investment. The government should issue the reprocessing and disposal capacity based on reasonable projection before it's too late.

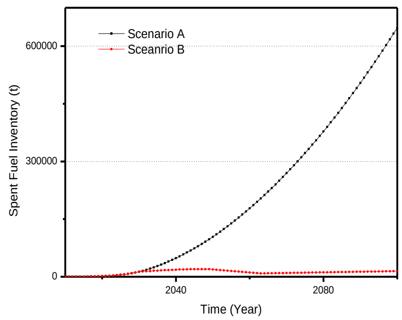

Fig. 4. Total spent fuel inventory

The LCOE results of the two scenarios are showed in Table I. The LCOE of once through fuel cycle was 35.57 mills/KWh. The LCOE of closed fuel cycle was 10% higher than that of once through fuel cycle.

Table I. LCOE of Scenario A&B

Cost(mills/kwh)	Scenario A	Scenario B
Levelized Cost of Construction	24.35	26.86
Levelized Cost of Operation and Maintaince	7.79	8.53
Levelized Cost of Fuel Cycle	3.43	3.81
LCOE	35.57	39.2

CONCLUSIONS

Nuclear Resource: Once through fuel cycle would consume 6.38 million tons natural uranium, and the closed fuel cycle based on subcritical system could reduce natural uranium consumption about 55% (2.88 million tons). In addition, closed fuel cycle will not rely on natural uranium supply after 2100; meanwhile, the uranium utilization could reach 75%, which is about 75 times compared with PWR. And the utilization of LLMA would be up to 90% which means the nuclear waste problem can be solved effectively.

Spent Fuel Inventory: Once through fuel cycle would produce 650 thousand tons spent fuel inventory until 2100, and the closed fuel cycle based on subcritical system could reduce about 98% of spent fuel. If the reprocessing capacity was limited, the ability of spent fuel reprocessing would be reduced appropriately.

Economy: Preliminary analysis of the levelized cost of electricity showed that closed fuel cycle with the subcritical system cost more to generate one kilowatt-hour electricity than the once through fuel cycle with PWR, but not exceed 10%. That suggested the economy of closed nuclear fuel cycle should be improved for more competitiveness in future.

ACKNOWLEDGMENTS

This work has been supported by the National Magnetic Confinement Fusion Energy Development Program under “Key Technologies of Nuclear Safety and Radiation protection of Fusion Energy” (2014GB112000) and “National Magnetic Confinement Fusion Science Program of China” (2015GB116000). Besides, the authors would like to express their gratitude to other members of FDS team.

REFERENCES

1. Y. Wu, FDS Team. “Design and R&D Progress of China lead-based Reactor for ADS Research Facility,” *Engineering*, 2, 124-131 (2016).
2. Z. Zhao, H. Xia, “Accelerator Driven Subcritical System (ADS) and Nuclear Sustainable Development,” *China Engineering Sciences*, 10(3): 66-72(2008).
3. W. Long, H. Xu, “The Future Advanced Nuclear Fission Energy-ADS transmutation system,” *Bulletin of the Chinese Academy of Sciences*. 27(3):375-381(2012).
4. J. Huang, K. Feng, B. Deng, Overview of fusion-fission hybrid reactor design study in China, *Fusion Science and Technology*, 42 (1): 138-145 (2002).
5. Y. Wu, Z. Chen, L. Hu, M. Jin, Y. Li, J. Jiang, J. Yu, C. Alejaldre, E. Stevens, K. Kim, D. Maisonnier, A. Kalashnikov, K. Tobita, D. Jackson, D. Perrault, Identification of Safety Gaps for Fusion Demonstration Reactors, *Nature Energy*, 1:16154 (2016).
6. Y. Wu, Conceptual design activities of FDS series fusion power plants in China, *Fusion Engineering and Design*, 81(23-24): 2713-2718 (2006).
7. Y.Wu, J. Jiang, M.Wang, M.Jin, A fusion-driven subcritical system concept based on viable technologies. *Nuclear Fusion*, 51(10):103036 (2011).
8. Y. Wu, Development of High Intensity D-T Fusion Neutron Generator HINEG, *International Journal of Energy Research*, 42(2): 68-72 (2018).