Annals of Nuclear Energy 83 (2015) 246–257

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Sustainability of the Chinese nuclear expansion: Natural uranium resources availability, Pu cycle, fuel utilization efficiency and spent fuel management

F. Fiori *, Z. Zhou

INET, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 24 December 2014
Received in revised form 19 March 2015
Accepted 21 March 2015

Keywords:
China nuclear fuel cycle
ADS
Nuclear energy policy
Nuclear energy sustainability
Proliferation

ABSTRACT

The civil nuclear energy deployment in China is important for future "Nuclear Renaissance" of China and worldwide. Compared to the other nations that developed their nuclear power energy system in last century, China can take advantage of the research and mistakes made by those states in relation to the back-end of the nuclear fuel cycle (NFC). The spent fuel accumulated by decades of operations of civil nuclear power is today a big burden for the industry. China must carefully plan the NFC for a sustainable development of the nuclear energy with special consideration to close the fuel cycle. The present paper addresses the NFC options and implications of a LWR scenario development and of a fast reactor park developed after 2035 and 2050, and covers the historical development of nuclear energy in China (i.e. from the first criticality of the first reactor) to the year 2100. The paper studies the partition and transmutation strategy with the use of accelerator driven system (ADS) to burn the minor actinides (MA) to understand the ADS impact on the NFC and to estimate the number and the necessary deploying schedule of the ADS reactors to limit the minor actinides stock build up. The other aspects taken into consideration for the comparison of the different scenarios are the natural uranium resourced used, the efficiency of fuel utilization, the proliferation and diversion risks associated to each scenario and the overall spent fuel production and flow. The code INFCIS developed by the International Atomic Energy Agency (IAEA) is used in the present study.

1. Introduction

The rapid development of China and the consequent shortage of energy need to be addressed in a sustainable way in order to reduce the environmental impact of the human activities. In this respect, traditional energy sources such as coal and oil pose a heavy burden on the quality of life of the population due to the detrimental environmental effect that the wastes have, which arises from the burning of fossil fuel i.e. global warning, air pollution, burden of transportation, etc. (Zhou, 2010). To make nuclear energy environmental friendly and sustainable it is necessary to close the fuel cycle. A more rational solution than the once-through fuel cycle should be found. In this respect, China is committed to the partition and transmutation of the spent fuel and to the development of a nuclear park with regional centers for transmutation of HLW (XNA, 2010). The present study focuses the attention on the nuclear power development scenario until the year 2100, taking into account the nuclear power plant operation since the beginning of the Chinese civilian use of nuclear energy. This study first highlights the necessity for China to find a solution to close the nuclear fuel cycle, showing that a once-through option will pose a huge burden on the final geological repository. The LWR scenario development option with the recycling of Pu in the form of MOX

Abbreviations: ADS-MA, double strata fuel cycle; BR, breeding ratio; CAS, Chinese Academy of Science; CCFR, Chinese Commercial Fast Reactor; CDFBR, Chinese Demonstration Fast Breeder Reactor; CEFR, Chinese Experimental Fast Reactor; CLEAR, Chinese LEAd Reactor; CIAE, Chinese Institute of Atomic Energy; CNNC, China Nuclear National Corporation; FP, fission product; HTGR, high temperature gas cooled reactor; ILW, intermediate level waste; INET, Institute of Nuclear and New Energy Technology; INFCIS, Integral Nuclear Fuel Cycle Information System; INPRO, Innovative Nuclear Reactors and Fuel Cycles; LBE, lead bismuth eutectic; MA, minor actinide; MOX-TRU, MOX recycling-TRU burning fuel cycle; NDRC, National Development and Reform Commission; NFC, nuclear fuel cycle; NFCIS, NFC information system; NFCSS, NFC simulation system; OT-NFC, once through nuclear fuel cycle; P&T, partition and transmutation; SF, spent fuel; SNTPC, State Nuclear Power Corporation; SWU, separative working unit; TRU, TRansUranic elements.

* Corresponding author at: Energy Science Building B207, Tsinghua University, Beijing 100084, China. Tel.: +86 1369 1145 937.

E-mail address: filippofiori85@gmail.com (F. Fiori).

http://dx.doi.org/10.1016/j.anucene.2015.03.051
0306-4549/

and the transmutation of MA in a dedicated ADS system in case of low, medium and high speed development of nuclear energy in China has been studied and it is considered as the reference scenario. The gradual switch to fast reactor technology in 2035 and 2050 has been studied with the fixed target of 400 GWe installed by 2050 and the results have been compared with the LWR reference scenario. In all the three cases, the reprocessing capacity up to 2035 is fixed to the most updated available literature prediction (Chen et al., 2012) and thereafter it is increased to answer the increase of material that need to be reprocessed, thus assuming that China has enough manufacturing capabilities in the field to cope with the needs. The main focuses of the study are the uranium ore availability and natural uranium requirement and supply, the fuel efficient utilization, and the diversion and proliferation risks. The main achievement is the estimation of the number of ADS and the time of commercial operation of each new ADS necessary to control the MA stock buildup.

2. IAEA nuclear fuel cycle simulation system, INFCIS code

Nuclear fuel cycle starts with the mining of unused nuclear materials from nature and ends with the safe disposal of used nuclear materials into nature. The complete set of processes to make nuclear fuel from uranium ore is known as the front end of the nuclear fuel cycle. The processes in the front end of the nuclear cycle are mining and milling, conversion, enrichment and fuel fabrication.

After producing energy in the reactor, the nuclear fuel becomes spent fuel. Spent fuel has to be processed in a storage facility or in a reprocessing facility if it is being recycled. Temporary storage, reprocessing, long-term storage, or final storage of spent fuel makes up the back end of the nuclear fuel cycle.

The INFCIS (IAEA/INFCIS, 2011) is a code capable of calculating the NFC requirements for all types of reactors by year over a long period. The range of calculation is valid from a single reactor to the reactor parks in the entire world. The code can cover the entire fuel cycle, from the front end: natural uranium requirement, conversion and enrichment, to the back end: reprocessing of the primary and second coolant if any (i.e. MOX fuel), spent fuel disposal, ILW and HLW production. Furthermore, quantities and qualities of the unloaded fuels can be evaluated, allowing the user to apply the desired recycling strategy. The code is simplified (i.e. less input data requirement) and the calculation speed is quick enough to enable making the comparison of various fuel cycle strategies. Historical data used comes mainly from the Agency database PRISM. Fresh fuel requirements and spent fuel isotopic composition can be input by the user or automatically calculated from a set of internal parameters that have been selected by experts and introduced in the program. The user may then choose to use spent fuel stockpiles to develop a recycling strategy. The estimation of accumulation of actinides including MAs is one of the capabilities of the code. Those accumulation estimations might be used to compare any future fuel cycle options for transmutation of minor actinides. The code homepage (IAEA, 2009) states: ‘‘*With its capacity to estimate future fuel cycle material and service requirements NFCSS can be utilized as a tool for Innovative Nuclear Reactors and Fuel Cycles (INPRO)*’’.

3. Nuclear power strategy and long term perspective

3.1. State of the nuclear power

The civil nuclear power development in China started only in 1970s, and the first nuclear power reactor came online only in 1994 (*Qinshan phase 1 NPP*), a historical phase defined as ‘‘*The Slow Transition*’’ by Zhou et al. (2011). In 2004, China had a total nuclear installed capacity of 9.1 GWe (WNA, 2014a) producing 2.3% of the nation’s electricity generation (NBSC, 2009). It was only at the beginning of this century that China strongly committed to the development of civil nuclear power. In 2006, China’s State Council approved the National Development and Reform Commission (NDRC)’s ‘‘*Medium and Long-term nuclear Power Development Plan* (*2005–2020*)’’ that plans for an installed capacity of 40 GWe in 2020. A 2007 State Council Information Office White Paper, ‘‘*China’s Energy Conditions and Policies*’’, increased the target for the installed capacity to 60 GWe (Zhou, 2011). As of June 2014 mainland China has 20 nuclear power reactors in operation, 28 under construction, and more about to start construction (WNA, 2014a,b). As a consequence of the Fukushima accident, the construction of inland NPP has been halted by the government with a decision pending. In case the inland construction of nuclear power plants is allowed, there will be a boost in the installed capacity that could reach 70–80 GWe by 2020. Predictions for the medium-long term future called for an installed capacity of 250 GWe in 2035 and 400 GWe in 2050. Before 2050, the Chinese reactor fleet will constitute mostly of LWRs between the sizes of 1.0–1.6 GWe. In addition to the domestic CPR-1000 and CNP-1000 developed by CGNPC (China General Nuclear Power Co.) and CNNC (China National Nuclear National Corporation) respectively, based on the AREVA M310 reactor, there will be the construction of AP1000 from Westinghouse and EPR from AREVA and VVER reactor of Russian design. Among the indigenous designs, the CAP1400 developed by SNTPC in cooperation with Westinghouse based on the AP1000 reactor stands to be a potential favorite. The indigenous Hualong I jointly developed by CNNC and CGNPC has been recognized as the Chinese generation III nuclear power reactor aiming at export to other countries worldwide. The Chinese nuclear fleet includes also a prototype High Temperature Gas-cooled Reactor built in 2003, designed in-house by INET of Tsinghua University. In 2012, the construction of a demonstration HTR reactor HTR-PM with 210 MWe started and it will reach criticality in 2017. In the fast reactor sector, China is committed to developing its own design: the CDFR, which is slated to become critical in 2025 with an installed power of 1000 MWe. A demonstration unit, called CDFBR, with 1200 MWe and a breeding ratio of 1.2 is projected for 2028, and subsequently the Commercial Fast Reactor version called CCFR, with an installed power of 1000 MWe and metal fuel, to become critical in 2030. The first milestone in the fast reactor field has been reached with the criticality of the Chinese Experimental Fast Reactor (CEFR) of 25 MWe in operation at the Chinese Institute of Atomic Energy (CIEA) (Xu, 2008). In addition to the above, two BN-800 Russian reactors are planned for construction at the Sanmin site of Fujian Province. These reactors are referred to by CIAE as Chinese Demonstration Fast Reactors (CDFRs), with construction originally planned to start in 2013 and the commissioning in 2018–2019. However, as the agreement on the final price has not been reached so far, the construction is delayed (Guang and Wenjie, 2010).

3.2. Future development of nuclear power and nuclear fuel cycle

The back end of the nuclear fuel cycle is still an open topic in many countries in the world. The astonishing growth of nuclear power capacity in China calls for rational thinking in order to find a solution on how to close the nuclear fuel cycle as early as possible in order to avoid the accumulation of large amounts of spent fuel for reprocessing. Different studies have recently been published on the topic (Chen et al., 2012; WNA, 2014a,b; Zhou, 2011). Although every study called for reprocessing the SF, a common direction on which way to pursue the management of the minor actinide (MA) and fission product (FP) has not been identified.