

Article

Concept of an Accelerator-Driven Advanced Nuclear Energy System

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Academic Editor: Hiroshi Sekimoto

Received: 24 March 2017; Accepted: 10 May 2017; Published: 7 July 2017

Abstract: The utilization of clean energy is a matter of primary importance for sustainable development as well as a vital approach for solving worldwide energy-related issues. If the low utilization rate of nuclear fuel, nuclear proliferation, and insufficient nuclear safety can be solved, nuclear fission energy could be used as a sustainable and low-carbon clean energy form for thousands of years, providing steady and base-load electrical resources. To address these challenges, we propose an accelerator-driven advanced nuclear energy system (ADANES), consisting of a burner system and a fuel recycle system. In ADANES, the ideal utilization rate of nuclear fuel will be >95%, and the final disposal of nuclear waste will be minimized. The design of a high-temperature ceramic reactor makes the burner system safer. Part of fission products (FPs) are removed during the simple reprocessing in the fuel recycle system, significantly reducing the risks of nuclear proliferation of nuclear technology and materials. The ADANES concept integrates nuclear waste transmutation, nuclear fuel breeding, and safety power production, with an ideal closed loop operation of nuclear fission energy, constituting a major innovation of great potential interest for future energy applications.

Keywords: nuclear fission energy; nuclear fuel recycle; accelerator-driven advanced nuclear energy system (ADANES); ceramic reactor; simple high-temperature dry (HT-dry) reprocessing; future energy

1. Introduction

Energy-related issues have always played an important and inseparable role in the sustainable development of human survival and civilization. Currently, three main challenges exist for future energy development—energy safety, environmental pollution, and climate changes. Therefore, it is necessary to develop and improve the application of clean energy forms [1,2].

In general, the application of fossil energy sources has deeply impacted the environment and human life, and existing resources can hardly meet the expected rapid future increase of energy consumption. Theoretically, renewable energy technology, such as solar and wind, should be able to meet the world energy demand. Their role in the production of low-carbon electricity is unquestionable, but the intermittent characteristics of these technologies currently prevent them from providing steady and use base-load electrical supply. Some incomplete solutions to these problems are available today. For example, compressed-air energy storage [3], using molten salt to store the heat [4]. At any rate, many uncertain factors still exist for large-scale applications of these techniques.

Research results from the International Energy Agency have confirmed nuclear energy as a key technology for the reduction of carbon emissions [5]. At present, 1/3 of global low-carbon electricity is held by nuclear power [6]. Its application decreases the usage of fossil fuels, making it an

environmentally friendly, highly efficient energy form which yields low carbon emissions and whose production is scalable. If the three issues of nuclear fission energy, namely the low utilization rate of nuclear fuel, nuclear proliferation, and insufficient nuclear safety can be solved, nuclear fission energy could provide sustainable energy for thousands of years.

Current reserve estimates indicate that there is sufficient natural uranium available at competitive prices to last 50–100 years, and uranium resources could be increased by mining from the ocean [7]. However, the utilization rate of natural uranium in a light water reactor (LWR) is as low as 1%, and waste management is another problem [8]. At present, a long-term solution for the safe disposal of nuclear waste is still needed. The longstanding idea of permanently burying waste in a geological repository has been called into question and the U.S. administration is planning to stop this process in the Yucca Mountain repository [9]. Most of the nuclear energy is derived from the fission of uranium, and the radioactive waste constitutes a problem, as the reactor contains weapons-grade plutonium. At present, spent nuclear fuel (SNF) is stored on site at nuclear energy plants in liquid pools and dry cask storage systems. This solution has now been employed safely and satisfactorily for 50 years, and its application is expected to continue for 50 more years, however, this strategy is not sustainable, and governments need to establish how to dispose of long-lived waste components.

Several strategies to address this problem have emerged from research on fission. As an example, the partitioning and transmutation (P&T) strategy with a fast breeder reactor has been used in many respects [10–13]. Many countries have reduced the waste volume by a factor of two or three by reprocessing SNF, i.e., by extracting the still-fissionable isotopes of uranium and plutonium, and reconverting them into new fuel elements. However, reprocessing is an expensive and inefficient process which suffers from the risk of nuclear proliferation, i.e., the extracted plutonium is usable in nuclear weapons. In the full P&T strategy, highly radioactive residues should be separated and destroyed by fast neutron transmutation facilities, which poses a proliferation hazard since the techniques are still developing and immature. This problem can in principle be avoided using an independent source of neutrons, which is referred to as a hybrid system. The idea of the accelerator-driven system (ADS) was born from this concept [14,15] by adopting an accelerator-based neutron source to supplement the chain reaction for transmutation and nonproliferation. In general, for nuclear energy to be competitive with other energy forms, the key problem is how to obtain the ideal nuclear fission energy. Therefore, more intense research efforts towards the advance of nuclear technology are needed.

Finally, if the ideal fission energy were achieved, the uranium resource utilization rate could be increased up to 100% (in the long term, the thorium resource utilization rate can be expected to reach unity as well), with a consequent elimination of the discharge of radioactive waste. It is legitimate to hope for this system to provide a long-term, safe, and stable energy supply to meet the world's energy needs in a green and sustainable way. The nuclear waste output shall be minimized and easy to manage, which can significantly reduce the burden of long-term settlement and greatly improve the impact on public health and on the environment. Meanwhile, this system should provide protection from nuclear proliferation, leading to a less significant risk of nuclear fuel thefts and terrorist attacks.

2. Accelerator-Driven System and the Accelerator-Driven Advanced Nuclear Energy System Concept

In a critical nuclear reactor, fission is sustained by a chain reaction that occurs when the created neutrons are captured with other nuclides, releasing more neutrons because of splitting reaction. This reaction is easily sustained as long as the fuel is fresh and there are no other elements for the neutrons to hit, besides the fissile nuclides. However, when the fission process continues, the fuel accumulates excessive fission nuclides, most of which only absorb neutrons without feeding the chain reaction. Eventually, the chain reaction stops when too many neutrons have been absorbed, and the fuel becomes waste, even though in these conditions most of the original fissile material is still present.

At present, several schemes are being studied as solutions of the above problem [16]. The first is a fine partitioning scheme. In the nuclear cycle, U, Pu and the neutron poison products, the short-lived and long-lived fission products (FPs) after fine partitioning, Pu was mixed with U to produce fresh mixed oxide fuel (MOX) fuels as reactors' new fuels [10]. Neutron poison products, the short-lived and long-lived FPs must be stored or disposed. However, the fine partitioning indicates major economic costs and nuclear proliferation risks. Moreover, after the partitioning, although a part of the nuclides still has significant application values, the remaining part still needs to undergo transmutation processing and high-risk storage. The second scheme is a rough partitioning scheme. The neutron poisons, U and transuranium (TRU) elements are separated from the fuels which cannot be used for further burn-up. Most of the depleted uranium elements are stored, and some of them are mixed with freshly extracted U to prepare fresh fuels. Accordingly, the burn-up in the critical reactor system can be sustained by refueling. In the meantime, the burn-up process only involves TRU elements. However, the burner of TRU elements should be carefully devised by considering several factors, including the balance between the loading capacity and the stability as well as the choice of proper construction materials. However, the partitioning cost using this scheme is not significantly reduced compared with the first scheme, and further difficulties are raised by the loading of a large amount of TRU elements in the burner. The third scheme is a transformative scheme, which combines breeding and burn-up. The ideal scheme of this form uses an ideal Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production (CANDLE), the complete burn-up during the critical process can be achieved by using the mobile breeding burn-up wave [17]. However, the development of this process poses several challenges concerning heat transfer, materials, and structure. Some alternative methods have also been proposed, the main idea being to consider breeding while the burn-up is improved to the maximum, and then simply reprocessing the SNFs that are discharged from the system. Other challenges regard the reasonable balance between the coarseness of the nuclides after partitioning and the multigeneration circulation in the burner, such as simple disposal of the final nuclear waste, completeness of the fuel cycle in the multigeneration circulation and the higher power density of the burner.

The difficulties of the critical system lie in the following aspects: sustaining the chain reaction restricts the allowance of the critical system, and it is not easy to find a reprocessing method for the achievement of an ideal nuclear fuel system with a completely closed cycle without partitioning or through simple partitioning only. Moreover, it is a difficult task to design a critical burner in which the breeding and burn-up can be quickly started. In principle, this problem can be solved by ADS that adopts the accelerator-based neutron source as the above-described independent source of neutrons to supplement the chain reaction (besides, fusion reactions can also be used as the source of neutrons) [14,15,18]. If the amount of neutrons is sufficient by itself, in contrast, the extra freedom and fuel cycle flexibility provided by an independent source of neutrons may be beneficial, and perhaps necessary, to achieve the practical sustainability of nuclear energy.

2.1. Brief Progress of Accelerator-Driven System

At present, no ADS device has been built anywhere in the world. However, the European Union, US, Japan, and other countries have developed long-term development plans and roadmaps for ADS development and carried out appropriate nuclear waste research.

In 1999, the US Department of Energy developed a roadmap for an accelerator transmutation of waste (ATW) program [19,20]. From 2001 onwards, Advanced Accelerator Applications, which has been already started, aimed at developing a technology base for the transmutation of transuranics and long-lived FPs [21,22] to demonstrate that this as an approach for long-term nuclear materials management and to build an accelerator-driven test device (ADTF) in 2010. Now, the ADS study is an integral part of the US advanced nuclear fuel cycle system. At the same time, sodium-cooled, Pb–Bi cooled, and gas cooled systems ADS design concepts have been published [22,23].

The European Union regards ADS as one of the key technologies for nuclear waste management. Rubbia led a team to develop a research and development program framework [15]. The framework

presents the EUROpean Research Programme for the TRANsmutation of High Level Nuclear Waste in an Accelerator Driven System (EUROTRANS) program planned to form the design concept of eXperimental Transmutation in an Accelerator Driven System (XT-ADS) and lead-cooled European Facility for Industrial Transmutation (EFIT) in 2005–2010 [24]. Under the guidance of the Framework Program, European countries have adopted the corresponding national research programs. Particularly noteworthy is the Belgian proposed Multi-purpose hYbrid Research Reactor for High-tech Applications (MYRRHA) [25,26] planned for materials and fuel component research, isotope production, transmutation, and bioapplications research. The MYRRHA program is an accelerator-driven Pb–Bi cooled fast neutron subcritical reactor system scheduled to run in 2023. For an advanced nuclear fuel cycle, some studies reported that ADS has a higher neutron spectrum, neutron yield, and other characteristics than fast reactors. Thus, it may be possible that the ADS has a higher supporting ratio than the incineration of actinide elements in a fast reactor [16,27].

Japan launched an Option Making Extra Gain from Actinides (OMEGA) program for the final disposal of nuclear waste from October 1988 [28]. After studying the performances of ABR and ADS, it is considered that ADS is the best choice for the transmutation of minor actinides (MA). Japan has completed the ADS conceptual design of sodium cooled, Pb–Bi cooled, and molten salt cooled systems, and also carried out nuclear fuel separation, fuel reprocessing, and special nuclear database and calculation program research and development work. Recently, Japan has built a Japanese strong current proton accelerator device J-PARC to carry out ADS materials and neutron experiments. In 2008, Kyoto University Critical Assembly (KUCA) was equipped with a fixed field alternating gradient (FFAG) accelerator originally developed by High-Energy Accelerator Research Organization (KEK) in Japan [29].

Since the 1990s, China has developed the ADS concept research. Supported by two “973” Programs, the China Institute of Atomic Energy has built a fast-thermal coupling ADS subcritical platform “Venus No. 1”. After that, a series of research results were obtained, including the strong current ECR ion source, ADS neutron research software system, ADS microscopic data evaluation library, accelerator physics and technology, and subcritical reactor physics and technology. In 2011, Chinese Academy of Sciences (CAS) timely started “ADS strategic priority research program” [18]. This program aimed at verifying ADS principle and solving key technical issues in the accelerator, spallation target, and reactor system. At the same time, CAS used the supporting of “Twelve-Five” national major scientific and technological infrastructure—China Initiative Accelerator-Driven System (CIADS), to master the ADS system integration and study the effectiveness of scale [30].

Currently, diverse international ADS research groups are investigating the key technologies, components, and integration of nuclear energy systems. The next step is to build a system integration device to provide a solid technical foundation and accumulated operational experience for the construction of the final industrial demonstration plant. The European Union, US, Japan, China, and other countries have carried out industrial-scale practical ADS design research and planned to build a demonstration device.

2.2. Concept of Accelerator-Driven Advanced Nuclear Energy System

At present, the main goal in ADS is to transmute nuclear waste. If ADS is to become the pillar of energy supply in the future, nuclear waste transmutation, nuclear fuel breeding, and safety power production should be effectively integrated. At the same time, ADS should satisfy the following characteristics [31]: sustainable energy production and minimization of nuclear waste for thousands of years; full-cycle, cost-effective, and similar investment risk with other types of energy; extremely operational safety and reliability, basic elimination of core melting and off-site emergency response; prevention of the proliferation materials and technologies; combined with the existing industrial system, especially the effective use of SNFs from water reactors. To satisfy these characteristics, a complete fuel cycle system is required, including an advanced burner system and a simple fuel recycle system.

For the future development of nuclear energy requirements, we propose the concept of an accelerator-driven advanced nuclear energy system (ADANES) [32], as illustrated in Figure 1. The

ADANES consists of a burner system and a fuel recycle system. The burner system is constructed based on the existing principles of the ADS. The waste transmutation, breeding, and power production are implemented in the burner driven by the neutron source outside the accelerator. The external neutron source in the burner system may use new granular spallation target [33] to increase the potential target power and harden the neutron spectrum. Ceramic materials can be used in the reactors' core to enhance the system safety and economic performance for a long-period operation [34]. The nuclear raw materials in this system can use depleted uranium, natural uranium, or thorium [35].

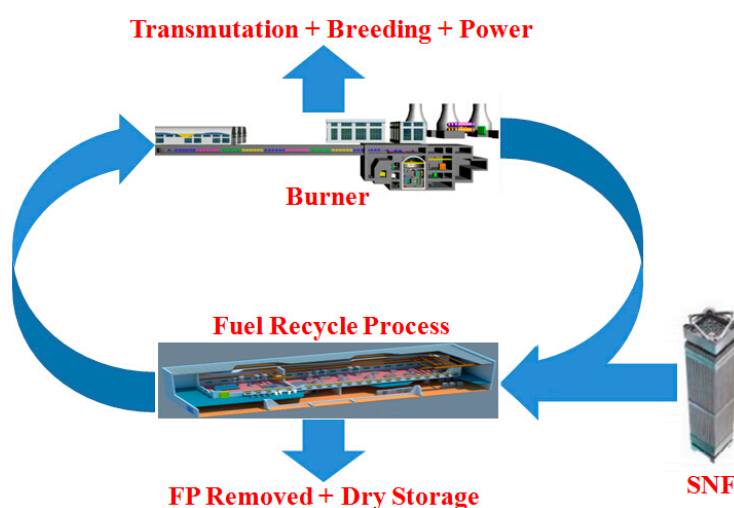


Figure 1. Schematic of the accelerator-driven advanced nuclear energy system (ADANES). FP: fission product; and SNF: spent nuclear fuel.

The burner system can provide breeding and burn-up for a long-period operation, and then the fuels and SNFs from the water reactor can be processed in the fuel recycle, a simple high-temperature dry (HT-dry) reprocessing [36]. In this reprocessing, part of the nuclides containing neutron poison in the SNFs can be separated and disposed while the remaining nuclides can be reused to produce the carbide fuels. Using this method, only a fraction of the FPs is eliminated, without fine partitioning. The discharged poisonous neutron nuclides, after stockpiling for hundreds of years, can also become part of the available rare-earth resources. This simple HT-dry reprocessing in ADANES is economical and significantly reduce the risks of nuclear proliferation, while reducing the final disposal of nuclear waste.

3. Study of Accelerator-Driven Advanced Nuclear Energy System

The detailed operating principle in ADANES can be described as follows: Using a small amount of ^{235}U as the starting fuel, the subcritical reactor core is driven by the high-energy neutrons generated by the high-power neutron source and the breeding is conducted on ^{238}U in the SNFs. While the fissile ^{235}U is being burned, the long-lived nuclides are transmuted. At the end of the whole burn-up cycle, in addition to the produced energy, the amount of fissile ^{239}Pu will exceed the amount of consumed ^{235}U . The fissile ^{239}Pu will be used in the next burn-up cycle. The system is driven by neutrons from the external source and has the inherent safety of ADS. The energy which is consumed by the high-power neutron source can be compensated by the higher energy production efficiency of the subcritical core at high temperatures. Only a small amount of ^{235}U in this system is adopted as the starting fuel, which makes the breeding rate of the reactor in 40-year of operation as large as possible. The second-generation reactor will directly use the fissile ^{239}Pu as the starting fuel. At the end of a burn-up cycle, part of the nuclides with neutron poison are removed through simple HT-dry reprocessing and the rest of nuclides recycling in the next generation reactor. Accordingly, a closed cycle is formed, which has a simpler reprocessing procedure than the current MOX fuel cycle. Moreover, this closed cycle can be used for several

times. The finally discharged nuclear waste can contribute the available rare-earth resources after dry stockpiling for hundreds of years.

3.1. Neutron Source and Operating Mode

The burner system is a nuclear reactor (power: 0.5–2 GW) formed by coupling a nuclear reactor core with a high-energy accelerator-driven neutron source as shown in Figure 2. The neutrons needed for sustaining the fission are produced by a particle accelerator, producing neutrons by spallation.

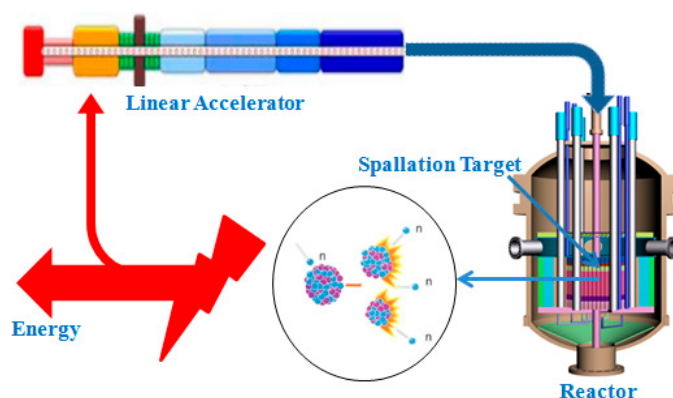


Figure 2. Schematic of the ADANES burner system.

The power of the neutron source should be of the order of 10 MW for the reactor to properly work. It is generally known that a higher-power neutron source is always the objective that many scholars urgently desire and pursue [37]. The development of 10 MW neutron sources has led to a great advance in the fields of condensed matter physics, materials science, and energy. Recent results available in the literature demonstrate that the most efficient 10 MW neutron sources are obtained with a superconducting linear accelerator and a spallation target [38]. At the beginning of spallation target development, some solid targets (U, Ta or W) were employed. The thermal conduction of the target material limits heat removal. In later years, heavy-liquid-metal (HLM) targets such as lead-bismuth eutectic (LBE) have been proposed and designed. However, several problems (including heat removal, shock waves, the chemistry, and radio toxicity) were found in the MEGAwatt Pilot Experiment (MEGAPIE) target [37].

Thus, a new high-power dense granular target (DGT) can be used here [33,39,40]. This target is driven by gravity and has a compact structure. To achieving high-power operation, the target material is a large collection of discrete solid particles, namely granular materials, which can exhibit both solid and fluid behaviors [41–48]. For the DGT (Figure 3), a hopper holds the granules flow into the beam interaction region because of gravity and the proton beam from a high-energy linear particle accelerator (HELPA) interacts with the flowing granules below the pipe. The granules rapidly pass through the beam interaction region and carry fission heat out of the orifice of the hopper. The DGT provides an opportunity to obtain good features which include high neutron yield, high thermal conductivity, high heat capacity, low corrosion and low chemical toxicity. The granular target, formed under the drive of gravity, may be a very promising target for powers ranging from 10 MW to 100 MW.

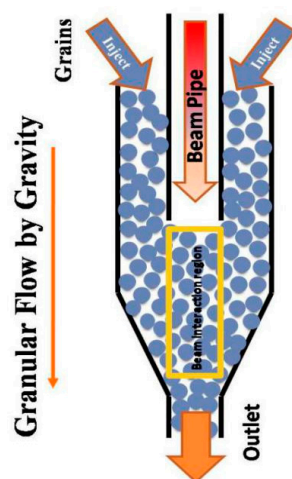


Figure 3. Schematic of a dense granular target (DGT).

Since the external neutron source consumes additional power, an ADANES power generation system can adopt the dual-accelerator redundancy mode as displayed in Figure 4. In this setup, each reactor is ignited causing the system to enter a critical operation state by the accelerator, and then another reactor is ignited in turn. The time of ignition, the reactor's critical operation time and the number of reactors should be optimized. In principle, a long critical operation time of the reactor leads to a high economic efficiency.

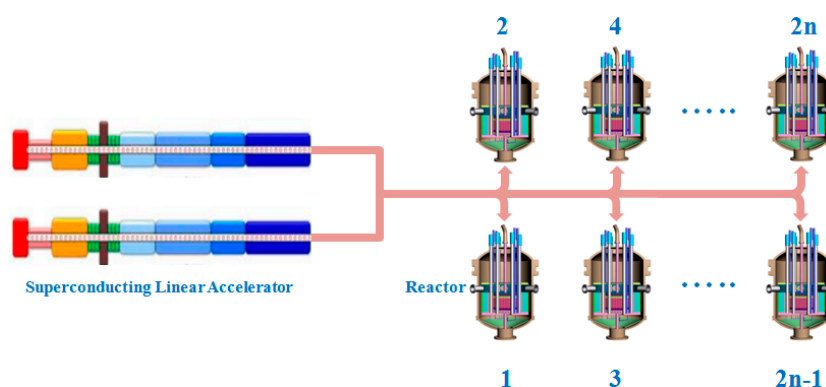


Figure 4. Dual-accelerator's redundancy mode in ADANES.

3.2. Ceramic Reactor

As concerns the reactor of the ADANES, with the aim of achieving the integration of breeding, power production and transmutation into one system, the reactor core should allow the system to operate under an appropriate fast-neutron spectrum, high temperature, and radiation resistance environment.

Any fast neutron reactor can be used in this system, and the desired results can be acquired by selecting the appropriate fuels, construction materials and coolant [34]. From the perspective of neutron physics, the breeding burn-up required by the ADANES can be achieved under the drive of the strong accelerator neutron source. At early operation stages, the system can operate under a subcritical condition driven by the high-through-put external neutron source. When the system has achieved a certain degree of breeding, it can begin to operate under a critical condition for a long time, without the need to be sustained by an external neutron source. Of course, this system can choose two operation modes (full subcritical mode, subcritical, and critical alternative mode). The selection of an appropriate coolant can prolong the breeding burn-up process, which is a crucial issue for the system.

In this study, ceramic materials with a high temperature resistance, good neutron performance, high corrosion resistance, antiradiation resistance, high thermal conductivity, high strength, good

inclusion, and stability were chosen. Figure 5 shows the time-dependent distribution of an effective neutron multiplication factor (K_{eff}) curve for the ceramic reactor, including the physical ideal curve and theoretical control curve. During a 40-years operation period, K_{eff} was initially set at 0.97, increased to a peak of ~ 1.025 after 18 years, and then gradually decreased to ~ 1.0 in the end. The theoretical control K_{eff} is controlled by the accelerator and control rods in the subcritical mode and control rods in the critical mode. In the actual operation of reactor, the K_{eff} is nearly ~ 1.0 in the critical mode.

At the beginning of 5 years, the system can operate under a subcritical condition driven by an external neutron source. The main reason is that the reactivity of the initial nuclear raw materials (e.g., spent fuel, depleted uranium, natural uranium, or thorium) in the reactor core is not very clear. Using the accelerator-driven mode, the reactivity of the reactor can be safely detected and controlled in a short time. Moreover, the reactor achieved more breeding. Therefore, the accelerator is necessary, especially in the beginning of the fuel cycle. About 5 years later, the system runs under the critical mode for decades without an accelerator.

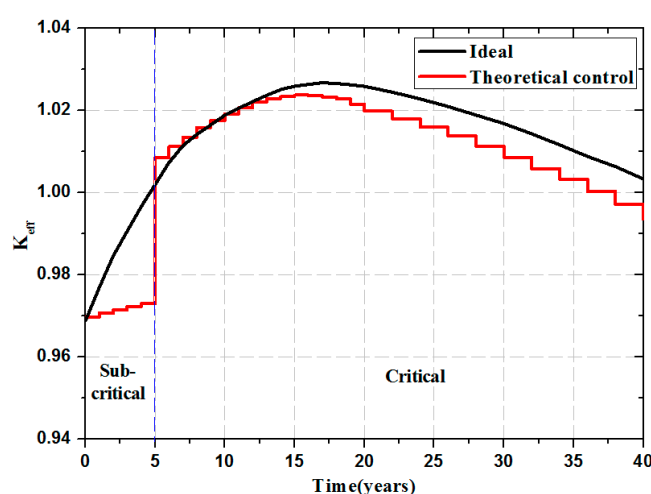


Figure 5. Time-dependent distribution of the ideal and theoretical control K_{eff} in subcritical and critical alternative mode.

In all, the entire process of nuclear fuel cycle consists of the combustion process of a reactor for decades and combined fuel reprocessing as mentioned below. In a fuel cycle, the amount of ^{239}Pu produced from ^{238}U will exceed the amount of consumed ^{235}U . The fissile ^{239}Pu will be used in the next burn-up cycle. In ADANES, multiple fuel recycling is carried out to achieve a high fuel utilization rate and low final nuclear waste.

3.3. Fuel Reprocessing

Figure 6 shows the proposed nuclear fuel recycle system. After a long-time burn-up, the fuels, as well as the SNF discharged from the water reactors, should undergo a simple HT-dry reprocessing [36]. The design goal of the fuel circulating system is to get rid of part of the FPs by means of high-temperature oxidation/reduction and centrifugal separation. By using Atomic International Reduction Oxidation (AIROX) process, the high-toxicity gaseous FPs and volatile FPs (Kr, Xe, I, ^{14}C and ^3H), 90% of the semi-volatile FPs (Cs and Ru), and 75% of FPs (Cd, Te and In) are removed, collected, and disposed of in a customary manner. Using the purification method for rare-earth elements, more than 50% of the rare-earth elements can be discharged. In the final waste storage, the radiotoxicity will be $<1\%$, to that in SNF before the reprocessing. Using voloxidation, most of the SNFs and discharged fuel from ADANES burner can be regenerated to produce carbide fuels after the milling and blending, and they can subsequently re-enter the ADANES burner for the next burn-up. The finally discharged nuclear waste is mainly constituted by neutral nuclides with neutron poison, without the problem of radio toxicity (i.e., rare-earth elements), which can subsequently contribute to the available rare-earth resources after dry stockpiling for hundreds of

years. In short, this reprocessing would exclude part of the toxic fission products and minimize actinide losses for improving the fuel utilization rate.

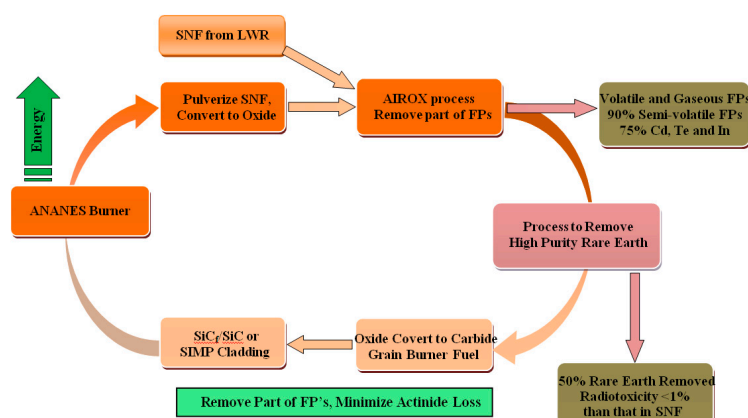


Figure 6. Nuclear fuel recycle system in ADANES. LWR: light water reactor; and HT-dry: high-temperature dry.

Figure 7 shows the relative values of radioactivity of the SNFs obtained from LWR and FPs separated after HT-dry reprocessing (100% separated and 50% separated). The radiotoxicity is dominated by the FPs. A few hundred-thousand years after the dry reprocessing, the radiotoxicity of the FPs (mainly including rare-earth elements) drops to the natural toxicity level. The separation of FPs would reduce the radiotoxicity of the remaining spent fuel and the radiotoxicity time has been shortened from 10^6 years to 10^3 years. Therefore, this reprocessing method can significantly reduce the radioactivity and decrease the risks of nuclear proliferation and terrorism.

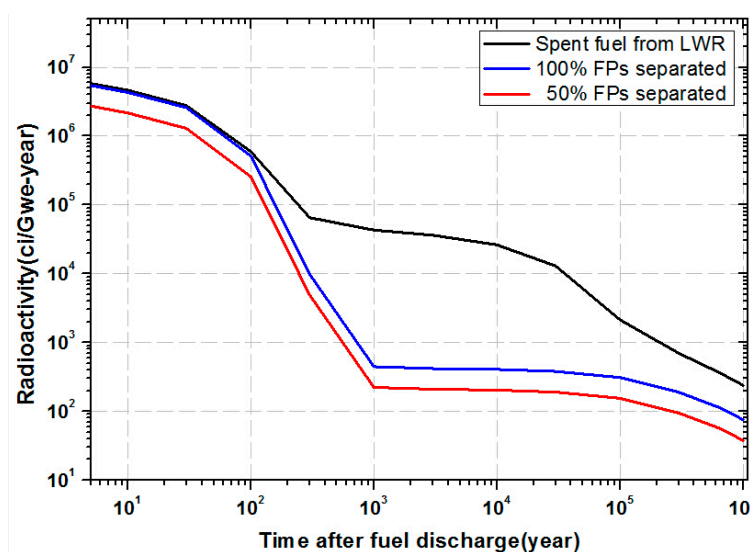


Figure 7. Relative values of radioactivity of the SNFs from LWR and fission products (FPs) separated after reprocessing.

4. Characteristics of Accelerator-Driven Advanced Nuclear Energy System

To satisfy the higher demand of the current nuclear fission energy market, ADANES should be improved with respect to sustainability, inherent safety, nonproliferation, and economy [31].

4.1. Sustainability

Consistent with the scenarios described by various international organizations and considering only the current uranium-consuming water reactor technologies with thermal neutrons, the uranium resource will be consumed in less than 100 years [6]. The use of once-through fuel cycle in

water reactors will produce a large amount of nuclear waste [49], and long-term risks from geologic repositories cannot be excluded. ADANES system is a closed nuclear power system, and the ideal utilization rate of nuclear fuel can reach more than 95%. This can extend the use time of nuclear fission energy from the current hundreds of years to thousands of years or even more. The final nuclear waste will be significantly reduced, the impact on the environment is minimal, and it will be one of the future sustainable energy systems.

4.2. Inherent Safety

ADANES burner system operates at the subcritical state, the reactor's reactivity controlled by the accelerator is more flexible. It can ensure that the reactor shuts down in the case of an accident. The ceramic reactor core can withstand temperatures up to 1600 °C, so the reactor makes the passive residual heat removal system more reliable and safer than the currently available reactors. The system can eliminate the risk of core melting and off-site emergency response in the event of extreme incidents. ADANES reprocessing system has advantages over the existing water reprocessing (e.g., plutonium uranium redox extraction (PUREX) based on liquid–liquid extraction ion-exchange) [50]; no highly radioactive liquid and waste is generated.

4.3. Nonproliferation

The ADANES reprocessing system is a simple dry reprocessing system without the separation of uranium and plutonium, only excluding part of FPs; thus, there is no risk of nuclear proliferation in nuclear technology and materials.

4.4. Economy

To become economically competitive, a series of measures were adopted in ADANES:

- (1) Based on good thermodynamics properties and neutron performance of ceramic, the ceramic fast reactor has a good economy [51]. A high safety can simplify the design of safety system. Long-term operation will reduce the operation and maintenance costs. The high outlet temperature of the coolant will increase the power generation efficiency;
- (2) A simple HT-dry reprocessing (only excluding part of FPs) without fine partition can significantly reduce the cost of reprocessing;
- (3) The ADANES burner can select the subcritical and critical alternative mode with good economy. At the same time, the dual-accelerator redundancy mode (e.g., two accelerators + 8–10 reactors) can share the pressure of economic costs.

Considering the above characteristics, also including general research foundation, robustness in technical scheme, smoothness in industrial applications and nuclear system compatibility, the future nuclear fission energy strategy can combine waters reactors, fast breeder reactors and ADANES system [52–54]. This can achieve the perfect docking of current nuclear industrial system. This strategy is one of the most balanced operational strategies in the future clean energy system which should solve the spent fuel reprocessing problem and improve the utilization rate of nuclear fuel resources.

5. Conclusions and Outlook

In this paper, we have proposed the concept of ADANES for the future global energy system. Considering the rapid accumulation of nuclear waste and energy demand, the development roadmap of ADANES in China has three phases. Phase I: Principle verification and implementation of key technologies (2010–202X). Achieve the principle of verification and solve the key technological problems of the burner and fuel recycle systems, achieve small-scale system integration, and develop a design of the system. CAS has launched the ADS strategic priority research program, supporting the foundation of ADS research. Phase II: System integration and study on scale effectiveness (2016–202X). By constructing CIADS, the scale system integration and

preliminary experiment are studied and optimized. Phase III: Industrial facility and full-size technological integration (202X–203X).

ADANES can integrate multiple functions, allowing various possible fertile materials including the SNFs after simple reprocessing to be converted into nuclear fuel. The inherent safety of operating in high-temperature ceramic reactor can ensure that it shuts down in the case of an accident and make the passive residual heat removal system safer. Using this system, the cost of fuels and reprocessing can also be reduced. During the separation of SNFs at high temperatures and the generation of new fuels, part of FPs are removed, preventing their accumulation. Radioactivity can also be significantly reduced, reducing the risks of nuclear proliferation and terrorism. Compared to the existing commercial nuclear power, ADANES will satisfy the sustainability, safety, nuclear nonproliferation, and economic requirements. This represents a near-term deployable and truly sustainable energy solution. Depending on the above characteristics, ADANES has the potential to become an easily-achieved, low-discharge, and high cost performance in an ideal clean nuclear fission energy system, which can be expected to operate safely for thousands of years.

In the future, the amount of oil and coal will continue to decrease, and the development of natural gas and hydropower will be relatively stable, whereas the growth of nuclear power and renewable energy is relatively fast. In the energy structure, ADANES, renewable energy and other low-carbon clean energy will be utilized in a large scale instead of coal and oil and add global energy production.

Acknowledgments: This work was supported by the “Strategic Priority Research Program” of the CAS under Grant No. XDA03030100 and the Natural Science Foundation of China under Grant No. 11605264. Thanks to the support of supercomputer Graphics Processing Unit (GPU) sub-center of CAS, supercomputer center of ADS System, and supercomputer center of Heavy Ions Research Facility in Lanzhou (HIRFL).

Author Contributions: Xuesong Yan did simulations and wrote the final manuscript. Lei Yang wrote the first manuscript, provided major revisions, and supervised the project. Xunchao Zhang provided revisions, analyzed the corresponding data and drew some pictures. Wenlong Zhan proposed the original idea.

Conflicts of Interest: The authors declare no conflict of interest.

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