

## Future Advanced Nuclear Fission Energy–ADS Transmutation System Postprint

**Authors:** Institute of Modern Physics, Chinese Academy of Sciences, Institute of High Energy Physics, Chinese Academy of Sciences, Hefei Institutes of Physical Science, Chinese Academy of Sciences

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### Abstract

Nuclear fission energy represents a safe, low-greenhouse-gas-emission, and economically favorable energy source. However, its sustainable development confronts numerous challenges, particularly following the Fukushima accident in Japan, which has engendered public apprehension toward nuclear energy development and consequently imposed more stringent safety requirements on future advanced nuclear energy systems. Under the precondition of ensuring safety (safety and security), the long-term sustainable development of nuclear fission energy must economically and feasibly resolve two critical issues: the stable supply of nuclear fuel and the safe disposal of nuclear waste. The latter constitutes a significant challenge that the nuclear energy community, both domestically and internationally, cannot circumvent, and remains an unresolved global challenge.

### Full Text

### Strategic Priority Research Programs (Category A) of the Chinese Academy of Sciences

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### 1 Project Background and Significance

Nuclear fission energy is a safe, low-greenhouse-gas-emission, and economical energy source. However, its sustainable development faces numerous challenges, particularly after the Fukushima accident in Japan, which has instilled public fear about nuclear power development and imposed more stringent safety requirements on future advanced nuclear energy systems. Under the premise of ensuring safety and security, the long-term sustainable development of nuclear

fission energy must economically address two major issues: the stable supply of nuclear fuel and the safe disposal of nuclear waste. The latter represents an unavoidable and significant problem for both China and the international nuclear energy community, constituting an unresolved global challenge.

The Accelerator Driven Sub-critical System (ADS) comprises three major sub-systems: the accelerator, spallation target, and reactor. Its working principle involves using a high-energy, high-intensity proton beam generated by the accelerator to bombard heavy nuclei, producing broad-spectrum, high-flux neutrons as an external source to drive continuous chain reactions in fission materials within a subcritical core. This process transmutes long-lived radionuclides into stable or short-lived nuclides while maintaining reactor operation (Figure 2 [Figure 2: see original paper]).

ADS technology offers powerful transmutation capabilities, excellent neutron economy, and superior system safety. It not only holds irreplaceable advantages in nuclear waste transmutation but also possesses the potential for nuclear fuel breeding and thorium utilization for power generation. Consequently, it is internationally recognized as the most promising technical approach for the safe disposal of long-lived nuclear waste through transmutation (Figure 1 [Figure 1: see original paper]).

Currently, no ADS facility has been constructed worldwide. However, nuclear technology leaders including European Union countries, the United States, Japan, and Russia have all formulated medium- and long-term ADS development roadmaps, gradually transitioning from key technology 攻关 to the construction of integrated ADS principle research facilities (Table 1 ). China initiated ADS concept research in the 1990s, conducting preliminary studies with support from the Ministry of Science and Technology, the National Natural Science Foundation, and the Chinese Academy of Sciences.

In January 2011, the Chinese Academy of Sciences strategically launched the Strategic Priority Research Program “Future Advanced Nuclear Fission Energy –ADS Transmutation System” (hereinafter referred to as the “ADS Program”). During its implementation, China gradually formulated a development roadmap for the Accelerator Driven Advanced Nuclear Energy System (ADANES) (Figure 3 [Figure 3: see original paper]), structured in four phases: (1) principle research and key technology 攻关; (2) system integration and scale verification through the “ADANES Major Project” ; (3) demonstration engineering construction; and (4) industrial application of ADANES systems, with commercial promotion led by enterprises.

## 2 Progress Achieved

As the first phase of the ADANES roadmap, this program aims to systematically address individual key technical issues in ADS accelerators, spallation targets, and reactor systems. Simultaneously, it conducts prospective research based on demonstration device requirements and develops the foundational platforms

necessary for ADS research, including applying for the “12th Five-Year Plan” national major scientific and technological infrastructure project, the China Initiative Accelerator Driven System (CIADS). Leveraging CIADS construction support, the program seeks to master ADS key technologies, system integration, and commissioning experience at the integrated system level, laying the foundation for subsequent ADANES demonstration facility construction.

Since the program’s launch, significant progress and breakthroughs have been achieved in superconducting proton linear accelerators, heavy metal spallation targets, subcritical reactors, and nuclear energy materials, with some key technologies reaching internationally leading or advanced levels. Overall, China’s ADS research has begun transitioning from basic research to engineering implementation.

## 2.1 Superconducting Proton Linear Accelerator

The program achieved breakthroughs in individual technologies required for superconducting linear accelerators, including ion sources, RFQ (Radio Frequency Quadrupole) accelerators, low- superconducting cavities, high-power couplers, power sources, superconducting magnets, and cryostats, and has conducted system integration.

In individual technology breakthroughs, the program successfully developed a high-stability, high-current proton source. The 162.5MHz@2.1MeV ADS RFQ accelerator passed expert technical testing organized by the Bureau of Major Scientific and Technological Tasks of the Chinese Academy of Sciences, becoming the second continuous-wave proton beam RFQ accelerator worldwide to achieve or exceed 10mA after the LEDA RFQ at Los Alamos National Laboratory (LANL), and currently the highest beam intensity among stably operating continuous-wave ion beam RFQ accelerators internationally. The 325MHz@3.2MeV ADS RFQ accelerator ranks highest globally in average beam power. The Spoke012 superconducting cavity possesses the lowest  $Q$  value internationally, having achieved dual-cavity system integration and beam operation at 2K cryogenic temperature. The vertical test performance indicators of Spoke012, Spoke021, and HWR010 superconducting cavities have reached internationally advanced levels.

In system integration, Injector I achieved a 10 MeV, 2.1 mA continuous-wave (CW) proton beam. Injector II successively obtained a 10.06 MeV, 11.8 mA pulsed beam and a ~10 MeV, 1.1-2.7 mA CW beam. The performance metrics of both injectors meet the ADS program requirements and exceed those of Israel’s SARAF facility, the only CW high-intensity superconducting linear accelerator currently under commissioning, placing China at the international leading level. Subsequently, the ADS accelerator team will continue advancing toward the next-stage energy target of 20-25 MeV.

## 2.2 Heavy Metal Spallation Target

Comprehensive technology verification and bench experiments based on the granular flow target have been fully initiated. All prototype subsystems and loops are ready, with joint commissioning experiments imminent.

## 2.3 Subcritical Reactor

The program completed the detailed design of an innovative 10MW ADS lead-bismuth cooled research experimental reactor capable of dual-mode operation (critical and accelerator-driven subcritical), which passed a series of international peer technical reviews and design assessments. The multifunctional lead-bismuth reactor technology integrated test loop KYLIN-II was constructed, integrating material service, thermal-hydraulics, and safety experiments to provide a platform for basic research and engineering verification of lead-bismuth reactor material performance, thermal-hydraulics, passive residual heat removal technology, and reactor accident safety characteristics. Prototype development of key components for the CIADS lead-bismuth cooled reactor, including refueling mechanisms and control rod drive mechanisms, was completed under lead-bismuth environments. The engineering design of the lead-based reactor engineering technology integrated test facility CLEAR-S was finished, along with installation, commissioning, and critical preparation of the zero-power facility.

## 2.4 Platforms and Supporting Facilities

The program established a superconducting cavity welding and processing laboratory, superconducting cavity treatment and test platform, cryogenic station, radiochemical experiment and material calculation platform, comprehensive test platform for synergistic effects of nuclear material irradiation/radiation/high temperature, spallation target design/simulation software/hardware platform, nuclear data measurement platform, and liquid lead-bismuth spallation target key technology research platform, ensuring the smooth progress of all program research activities.

## 2.5 Overall Design and Site Selection

The CIADS overall design scheme was finalized and the project proposal was approved by the National Development and Reform Commission at the end of 2015. The site was selected, and preliminary feasibility analysis reports and environmental impact assessments for the new park site selection phase were completed.

## 2.6 Prospective Exploration Research

In materials research, 5-ton scale SIMP steel preparation has been completed. Additionally, SiC composite fiber material development was conducted, and a

third-generation SiC composite fiber pilot production line was established. In nuclear fuel preparation, uranium nanomaterial preparation and synthesis of series actinide organic compound crystals were completed, producing uranium and cerium spheres of different sizes. Research on 50% fission product removal methods and new fuel element preparation containing minor actinides was conducted, with basically feasible principles. In advanced reactor secondary loop design, optimized design schemes for the main heat exchanger and regenerator were obtained and experimental prototypes were fabricated, and an LBE-He heat exchange comprehensive test platform was constructed.

During the mid-term review of the CAS Strategic Priority Research Program, the ADS system and key technology research received high recognition from experts. In international evaluations, it was rated as “International leadership” and included in relevant IAEA working group cooperation plans. In the “12th Five-Year” review of CAS institutes, the breakthrough in ADS key technology by the Institute of Modern Physics was rated as “Excellent” among the top 100 CAS achievements. The ADS research team of the Institute of Modern Physics was honored with the “2015 CAS Advanced Collective” award, and the ADS Program ranked first in the 2015 Class-A Strategic Priority Research Program performance evaluation.

### 3 Originality

China’s ADS R&D has undergone a difficult journey from scratch, from following international research to achieving original innovation. With the implementation of the ADS Program, numerous original theories, methods, and technologies have been continuously proposed and optimized through iterative testing and understanding, including:

- (1) The ADANES new concept and scheme, which has basically completed principle simulation test verification. This advanced closed nuclear fuel cycle technology integrates nuclear waste transmutation, nuclear fuel breeding, and power generation. ADANES has been submitted to national authorities by the Chinese Academy of Sciences and approved, receiving positive domestic and international responses. The joint evaluation by the Ministry of Science and Technology, National Development and Reform Commission, and State Administration of Science, Technology and Industry for National Defense recommended “supporting ADANES development with phased implementation,” and strategic cooperation agreements have been signed with CGN, Guangdong Provincial Government, and Fujian Provincial Government.
- (2) The creatively proposed new fluidized solid granular target concept with completed preliminary design. Small-scale bench principle experiments coupled with electron beams have been successful. This scheme has received positive evaluation and attention from peer experts. CERN has jointly conducted beam experiments with multiple European laboratories,

and Belgium' s MYRRHA team has allocated personnel and funding for related research.

- (3) In materials research, independently formulated and developed SIMP steel demonstrates performance indicators superior or comparable to current international mainstream irradiation-resistant structural materials for nuclear facilities, showing promise as a new candidate structural material for nuclear installations.

#### 4 Significance for Industry

The ADS Program conducts ADS principle and key technology research with the entry point of achieving safe nuclear waste treatment in China. Leveraging support from CIADS and ADRUF construction projects, it lays the technical foundation for ultimately building China' s ADANES industrial demonstration facility and commercial promotion, which will significantly impact the assurance of long-term sustainable development of nuclear fission energy in China. Simultaneously, the program emphasizes close integration of key technologies with industrial applications. For instance, the independently designed and developed SIMP steel will undoubtedly be widely applied in China' s nuclear industry.

#### 5 Recommendations for Future Deployment

- (1) ADANES R&D involves numerous disciplines and requires joint efforts from relevant research institutes, universities, government, and enterprises. The R&D is a long-term process that must undergo principle research and key technology 攻关, system integration and scale verification, and engineering demonstration before achieving commercial promotion. Therefore, ADANES R&D must be incorporated into national medium- and long-term planning, with clear positioning and role in national nuclear energy sustainable development strategy.
- (2) With support from the ADS Program, "973" Program, and other projects, China has established a stable ADANES R&D force that is transitioning from principle research and key technology 攻关 to system integration and scale verification. This development should be continued through multiple channels such as national major projects.
- (3) Dedicated programs with matching special funds should be established, along with scientific personnel mechanisms and diverse hiring systems to actively attract excellent researchers and engineers domestically and internationally to participate in ADANES research. Through engineering projects supporting young domestic scientists and engineers to undertake important tasks, participate in international exchanges, and conduct interdisciplinary research, a cohort of young scientific and engineering talent can be trained and developed.

The ADS Program has been driven by national strategic needs for nuclear energy

sustainable development to achieve safe nuclear waste treatment and disposal. As a pre-research project for China's Accelerator Driven Advanced Nuclear Energy System (ADANES), the program has achieved a series of major breakthroughs in key core technologies for the ADANES burner, with some reaching internationally advanced or leading levels, attracting widespread attention from peers both domestically and internationally. During implementation, a technically skilled R&D team with reasonable age structure and complete expertise has been formed. As the subsequent integration verification facility for the ADS Program, the "12th Five-Year Plan" national major scientific and technological infrastructure—China Initiative Accelerator Driven System (CIADS)—has received NDRC approval and is about to commence implementation. The ADANES spent fuel recycling and reprocessing system experimental facility has signed cooperation agreements with Fujian Province and CGN. Overall, China's ADS research has transitioned from basic research to engineering implementation, maintaining pace with international ADS mainstream R&D countries. The future development of ADANES will undoubtedly significantly impact the assurance of China's long-term sustainable nuclear fission energy development.

**Wei Baowen**, nuclear physicist, CAS academician, researcher, and doctoral supervisor, graduated from the Department of Physics at Peking University in 1957. He has served as Director of the Institute of Modern Physics of CAS, President of Lanzhou Branch, and Director of the Lanzhou Heavy Ion Accelerator National Laboratory. His primary research focuses on nuclear physics and accelerator physics, and he has received the National Science and Technology Progress Award (First Class) and CAS Science and Technology Progress Awards (First and Second Class).

ADS possesses powerful transmutation capability, excellent neutron economy, and superior system safety. It not only holds irreplaceable advantages in nuclear waste transmutation but also has potential for nuclear fuel breeding and thorium utilization for power generation, being internationally recognized as the most promising technical approach for safe disposal of long-lived nuclear waste through transmutation. Since the launch of the ADS Program, important progress and breakthroughs have been achieved in superconducting proton linear accelerators, heavy metal spallation targets, subcritical reactors, and nuclear energy materials, with some key technologies reaching internationally leading or advanced levels. The innovatively proposed ADANES scheme is expected to become an advanced nuclear energy system concept surpassing international Generation IV reactor technologies.

**Waclaw Gudowski**, academician of the Royal Swedish Academy of Engineering Sciences and the Mediterranean Academy of Arts and Sciences, professor at the Royal Institute of Technology, Sweden. His research focuses on neutronics and reactor physics, nuclear waste transmutation, accelerator driven transmutation systems, advanced reactors, Generation IV reactors, and nuclear waste disposal.

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv – Machine translation. Verify with original.*