REINVENTING NUCLEAR ENERGY THROUGH START: A PIONEERING THORIUM-BASED FUEL CYCLE FOR MORE SUSTAINABILITY AND PROLIFERATION SAFETY

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Abstract

The global push for carbon neutrality by 2050 demands sustainable nuclear energy solutions. The START (Subcritical Transmuting Accelerated Regenerative Technology) project promotes a proliferation-resistant thorium-based fuel cycle, reducing nuclear waste while generating energy and Thorium/Uranium-233 fuel for reactors. Currently in conceptual design with completion by 2025, START aims for deployment in the mid-2030s. This system, coupling a 20-MW multi-staged cyclotron with a 600-MWth subcritical core cooled by molten lead, will produce 220 MWe. Its subcritical nature enhances safety by mitigating risks of reactivity fluctuations. Transmutex, along with research and industry partners, collaborates on cyclotron design, fuel reprocessing, and lead-cooled nuclear systems, with anticipated synergies between the START design development and installations at the Mioveni site. This paper discusses the current design progress and START's contributions to the future of nuclear energy, emphasizing its potential to reduce greenhouse gas emissions, enhance energy security, and ensure proliferation resistance.

Keywords: *START, Thorium, Transmutation, Lead*

Introduction

The imperative to decarbonise our global system is urgent and extensive, extending beyond traditional energy production to include heavy industries, transportation, and district heating - key sources of greenhouse gas emissions. Nuclear energy stands out as a potent solution capable of addressing these challenges comprehensively. However, its deployment on a massive scale is encumbered by several critical issues.

Firstly, the risk of nuclear proliferation remains a significant barrier, especially for countries new to nuclear technology. These nations often become reliant on other countries for their nuclear fuel supply, complicating their energy independence. Furthermore, the establishment of nuclear energy systems in these newcomer countries necessitates the creation of independent safety authorities and entails years of intensive training for personnel. An international collaborative education program is essential for the successful global implementation of nuclear technology.

Public perception of nuclear safety – or the lack thereof – also hinders nuclear energy's deployment. There is a crucial need for extensive public education and transparency efforts to enhance understanding of the rigorous safety protocols that underpin modern nuclear energy systems.

Complicating matters further, the recent announcement at COP28 to triple nuclear power capacity from current levels, comes at a time when Kazatomprom, the world's leading uranium producer, has warned that it may be unable to meet uranium demand post-2030 [1]. This forecast suggests that uranium extraction will become increasingly costly and complex as new mining sites are developed and sourcing diversifies.

Moreover, the issue of nuclear waste management remains largely unresolved. With the projected increase in nuclear energy production, the accumulation of spent nuclear fuel (SNF) will exacerbate current challenges and escalate costs. For instance, the Yucca Mountain project in the US, which was estimated to cost 96 billion USD in 2008 and to have a capacity for 60,000 tons of SNF, underscores the financial and logistical burdens of nuclear waste storage. Tripling nuclear output will necessitate a similar facility every decade in the US only, significantly impacting the overall cost of nuclear energy's lifecycle.

This article will explore the START system proposed by Transmutex, detailing its design and the potential it holds for optimizing the nuclear fuel cycle. Additionally, it will discuss the ongoing challenges of such innovative systems and the potential synergies with existing research facilities, providing a comprehensive view of the future of nuclear energy deployment.

The START System

On the basis of the above findings, the main objectives of Transmutex are to make the nuclear energy system cheaper, more sustainable, and to reduce the proliferation risks, with an intrinsically safe system. Fulfilling these objectives should contribute to a global deployment of nuclear energy to reduce our greenhouse gas emissions. In this section, we describe the safety approach adopted by Transmutex and the system under development.

Safety philosophy

The core safety philosophy of the Transmutex system adheres to the primary safety objective established by the International Atomic Energy Agency (IAEA) [2], which aims to "protect people and the environment from the harmful effects of ionizing radiation". In pursuit of the highest feasible safety standards, the system incorporates the following strategic measures:

"(a) To control the radiation exposure of people and the release of radioactive material to the environment;
(b) To restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation;
(c) To mitigate the consequences of such events if they were to occur."

To fulfil these safety objectives, Transmutex has integrated several principles into its design to align with the specified safety goals. The design also includes intrinsic safeguards to minimize proliferation risks, enhancing global acceptance of the technology.

Encapsulation of radioactive materials

The system employs the multi-barrier concept to significantly lower the risk of radioactive material escaping into the environment. The primary loop operates at near-atmospheric pressure within a pool-type primary vessel, which encapsulates all elements of the primary loop. Under normal and accidental conditions, the release of radioactivity in the environment is not anticipated with the current design.

Radiation protection

All operations near the vessel are conducted remotely to minimize radiation exposure to personnel. The design prioritizes simplicity in maintenance tasks to enable remote handling. In addition, materials are selected based on their ability to minimize long-term activation and to facilitate decommissioning.

Reactivity and Criticality Control

Opting for a subcritical system configuration, Transmutex significantly curtails the risk of a criticality accident. The design features a negative void coefficient and robust resistance to any positive reactivity insertions, with sufficient margin maintained against all design-based accidents. Reactivity levels are continuously monitored through inverse point kinetic, modified source multiplication, and power monitoring methods.

Cooling of Fuel Assemblies

The subcritical assembly is cooled using molten lead and ensures continuous cooling even during a station blackout through natural circulation and passive heat removal systems. The design includes two distinct passive heat removal systems, each with four redundancies. The outlet lead temperature of the fuel assembly is monitored to detect any potential flow blockage.

Non-proliferation

Transmutex has chosen a denatured Thorium cycle to virtually eliminate the proliferation risk associated with its system. This cycle utilizes a mixture of fertile, fissile, and radioactive elements in isotopic dilution, rendering the material impractical for military use.

System description

Transmutex utilizes a subcritical nuclear core driven by an external neutron source, an idea first conceptualized at Los Alamos National Laboratory [3] and further advanced in the 1990s by Nobel Laureate Professor Carlo Rubbia at CERN [4]. The Transmutex's system (see Fig. 1), known as START (Subcritical Transmuting Accelerated Regenerative Technology), heralds a new era in nuclear technology. It operates on a closed fuel cycle, efficiently consuming transuranic elements while generating 600 MW of thermal power and 220 MWe of net electrical power in a base-load configuration. The neutron source, integral to this system, involves a 20-MW cyclotron that accelerates a 5-mA proton beam to 800 MeV. This beam strikes a target, inducing spallation reactions that produce neutrons. Positioned at the centre of the subcritical core, the spallation source drives the nuclear chain reaction, with the output power being directly proportional to the beam current.

To complete the fuel cycle, Transmutex plans to integrate a fuel reprocessing and fabrication facility on the same site. This facility will reprocess spent fuel, vitrify fission fragments, and produce new thorium-transuranic (Th-TRU) fuel for the START system, as well as thorium-uranium (Th-U) fuel for thermal reactors. The proposed nuclear centre will host between five and ten accelerator-reactor islands along with one reprocessing/fabrication facility.

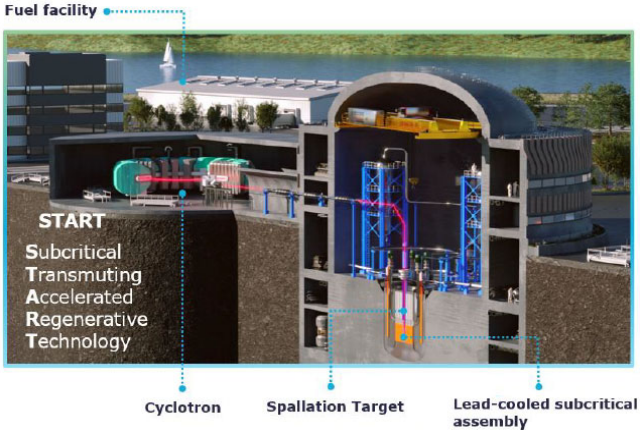


Fig. 1. Illustration of the START system.

The accelerator design

The cyclotron technology is selected because it is more compact and energy efficient than a linear accelerator. The main drawback of a cyclotron is its reliability because several elements are reused for the proton beam acceleration.

The machine is a three-stage normal conducting cyclotron that accelerates a 5-mA proton beam to 800 MeV, based on Paul Scherrer Institute (PSI) technology. Leveraging PSI expertise and background, Transmutex found ways to improve the accelerator reliability by two orders of magnitude. This system incorporates redundancies to meet the high reliability requirement.

The spallation neutron source design

The spallation target is cooled by liquid metal because it is the only way to have a compact source that can fit at the centre of the core, with the target unit occupying a radial footprint equivalent to 7 fuel assemblies and is able to remove the heat dissipated by the proton beam while efficiently producing neutrons. The target can absorb 4-MW proton beam power where almost 3-MW is dissipated as heat. A liquid target technology is chosen to be able to extract the heat in a confined space. The spallation media is the primary coolant, i.e. liquid lead, which feature excellent properties for neutron production through spallation. A conical window separates the beam pipe vacuum from the lead to ensure the radioactive material confinement and to respect the multi-barrier concept.

The energy production unit design

The subcritical assembly surrounding the spallation neutron source is cooled by lead because of its transparency to neutrons, its low polonium production rate in comparison to LBE, its high thermal inertia, and its high boiling point. The main drawbacks of lead are its corrosion of most of steels and its high melting temperature (327.4 °C), which means that the system must always remain hot. The lead freezing will not cause any safety issues because lead does not expand when solidifying, but the machine would become inoperative. Another reason to choose lead is that the nuclear core and primary system is inspired from the ALFRED project [5], one the best safety-oriented design among all fast reactors.

Transmutex envisages a thorium fuel cycle as the ideal fuel cycle for the future, as it is less proliferant, produces less transuranics and improves energy production efficiency in thermal reactors through breeding. Combined with fast neutrons such as in START systems, this fuel cycle can be closed, consuming the transuranics and breeding fissile elements for fresh fuel production. START fuel is metallic Th mixed with transuranics to enhance their efficient transmutation. This cycle shows high efficiency for transuranic burning with a transmutation rate of 72 kg/TWh of electric energy.

Finally, as transuranics are fissioned, this system produces energy that is extracted to produce electricity. The balance of plant relies on a Rankine cycle and the high lead temperature contributes to a high thermal to electric conversion efficiency of 42%, which leads to a net electrical production of 220 MW.

The fuel facility design

The fuel facility consists of several units for spent fuel storage and reprocessing, fission fragments vitrification, and fresh fuel fabrication. This facility is co-located with accelerator-reactor complex to limit the transportation risks, improving safety, proliferation resistance and security.

The reprocessing plant is inspired by Argonne National Laboratory (ANL) reprocessing technology, a.k.a. pyro-processing. This dry reprocessing is considered as less proliferant than the aqueous process, such as PUREX. It consists in dissolving the fuel meat in a salt bath, and separating nuclide through electro-chemical reactions. The reprocessing can achieve high TRU extraction efficiency, i.e. more than 99.9%. The salt can be recycled which minimizes the waste production coming from the reprocessing. Since the reprocessing facility contains highly active materials, fully remote operation and maintenance is foreseen.

In addition, this reprocessing enables the extraction of a thorium fuel mixed with uranium, notably U-233. This fuel could be used in thermal reactor and its production is less proliferant than other technologies. Indeed, no plutonium is produced from thorium as the fuel always consists of a mix of fertile and fissile elements. In addition, in the Transmutex fuel cycle, the uranium, mixed with thorium, is in isotopic dilution with U-238 and with traces of radioactive nuclides coming from the decay of U-232. Therefore, this fuel cannot be used for military applications and is well safeguard trackable.

Benefit to global energy system

START system aims at being integrated to the current nuclear eco-system while bringing additional value to the fuel cycle. The intrinsic proliferation resistance of its fuel cycle will help in the global deployment of the technology. Being subcritical and implementing passive safety systems will guarantee the highest nuclear safety level for such a deployment. Additionally, reducing long-lived nuclear waste will likely increase public acceptance for nuclear energy, further aiding the decarbonisation of our energy systems.

Moreover, the START system introduces a new resource by utilizing thorium-uranium fuel, which diminishes the need for mining and enhances the sustainability of our fuel resources. It complements the current uranium-based nuclear systems, with potential mutual benefits between the two cycles.

One of the primary benefits of adopting this system is the significant reduction in the long-term burden of nuclear waste. By fissioning transuranic elements, the radiotoxicity of highly active waste can be reduced to the level of uranium ore within a few centuries, as opposed to several hundred thousand years when transuranics are present. This reduction in waste lifespan improves the safety analysis of deep geological repositories, transitioning from probabilistic to deterministic approaches.

The START system can also produce valuable nuclides for industrial and medical applications, either during the accelerator or reprocessing stages. However, the economic feasibility of such production hinges on market prices and needs further demonstration.

In addition to these capabilities, the START system generates carbon-free energy, contributing to global carbon neutrality efforts. Economically, the electricity generated can offset the initial investment and operating costs, making the system financially viable. Finally, this system not only addresses the issue of nuclear waste but also produces fuel and energy without carbon emissions, thereby reducing the overall costs, both economic and environmental, associated with the nuclear fuel cycle.

Challenges

The challenges facing the implementation of the START system are multifaceted, spanning material qualification, code qualification, technology reliability, training needs, supply chain issues, and regulatory adaptation.

One of the primary material qualification challenges involves the compatibility and corrosion resistance of materials used in the system. Since the START system employs lead cooling, which is incompatible with the cladding materials developed for sodium-cooled reactors, there is a need to develop new materials that can resist lead-induced corrosion.

Additionally, there is a notable lack of irradiation facilities capable of testing materials with fast neutrons, which are crucial for qualifying new materials under realistic conditions. To address this, Transmutex designs a system that can be operated with a first core of High-Assay Low-Enriched Uranium (HALEU) fuel before transitioning to a thorium-based equilibrium core. Indeed, more data is available for uranium oxide fuel in fast reactors and should be available earlier than a new thorium metallic fuel.

Moreover, thermodynamic and fluid dynamic studies are required to effectively simulate and manage lead cooling, especially during transient and accidental scenarios. This necessitates the establishment of experimental facilities to conduct the necessary tests.

Furthermore, several chemistry studies of lead also need to be thoroughly performed, for instance, the interaction of lead with the release of fission fragments.

On the code qualification front, there is a significant gap in simulation and modelling capabilities because existing codes are not fully qualified for this innovative technology. This highlights the critical shortage of experimental data and benchmarks essential for validating simulation codes. Additionally, enhanced precision in fast neutron cross-sections and access to fast research reactors are needed for accurate system analysis and design. However, research reactors are progressively being decommissioned worldwide.

Then, the reliability of cyclotrons, although significantly improved, still presents a challenge in achieving the reliability improvements by two orders of magnitude, especially since these systems are primarily research-based rather than industrial-grade.

The high-tech nature of the START system also necessitates a well-educated and skilled staff, requiring specialized training programs and knowledge transfer initiatives. Countries investing in this technology will need to adapt their educational systems accordingly.

Finally, most of the current regulatory frameworks and standards are not fully prepared to accommodate such innovative nuclear systems. For example, standard construction codes like ASME or RCC-MR do not fully encompass the unique requirements of the START system, necessitating the development or revision of construction standards. In addition, collaboration is hindered by the compartmentalized nature of national programs and varying international regulations.

Addressing these challenges requires a coordinated approach involving extensive R&D, regulatory adaptation, international cooperation, and substantial investments in training and facility development. A staged implementation strategy, starting with extensive experimental validation and a First-Of-A-Kind (FOAK) with several power stages, could facilitate gradual integration and scaling of the START system into the nuclear power infrastructure.

Conclusion

The START system developed by Transmutex represents a significant advancement in nuclear technology with the potential to address several of the critical issues facing the nuclear energy sector today. Its innovative design, which leverages a subcritical configuration and thorium-based fuel cycle, promises enhanced safety, reduced proliferation risk, and more efficient management of nuclear waste.

However, the system also faces considerable challenges related to material compatibility, system reliability, and regulatory acceptance that must be addressed through rigorous research and development, collaborative international efforts, and comprehensive educational initiatives.

Despite these challenges, the START system's potential to contribute significantly to global decarbonisation efforts makes it a crucial component of the future energy landscape. Successfully integrating this technology into existing nuclear power infrastructures could lead to a more sustainable, safe, and proliferation-resistant nuclear energy system, ultimately facilitating a transition towards a low-carbon global economy.

Finally, the subcritical reactor design being inspired by ALFRED configuration, we anticipate very important synergies between the START and ALFRED design development with a strong interest of Transmutex for present and future experimental installations availability at Mioveni site.

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