Future Advanced Nuclear Fission Energy—Thorium-based Molten Salt Reactor Nuclear Energy System (TMSR) Postprint

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Abstract

The development philosophy of "innovation, coordination, green development, openness, and sharing" points the way for China' s sustainable energy and environmental development. Research predicts that while vigorously developing renewable energy, total global nuclear energy will increase 2-4 fold; due to its lower baseline, China' s growth will be far greater than this projection. Generation IV advanced nuclear energy systems with superior economics, safety, sustainability, and nuclear non-proliferation characteristics will provide technical support for future nuclear energy development.

Full Text

Preamble

The development concept of "innovation, coordination, green development, openness, and sharing" points the way toward sustainable energy and environmental development in China. Research predicts that while vigorously developing renewable energy, global nuclear power capacity will increase two- to four-fold. Given China' s lower baseline, its growth will far exceed this projection. Fourth-generation advanced nuclear energy systems, offering superior economics, safety, sustainability, and proliferation resistance, will provide the technological foundation for future nuclear development. The Thorium Molten Salt Reactor Nuclear Energy System (TMSR) is one of six candidates for fourth-generation advanced nuclear energy systems, comprising three subsystems: thorium-based nuclear fuel, molten salt reactors, and comprehensive nuclear energy utilization. Thorium-based nuclear fuel is abundant, offers excellent proliferation resistance, and generates less nuclear waste, representing a viable solution for long-term energy supply. Molten salt reactors use high-temperature molten salt as a coolant, featuring high temperature, low pressure, high chemical stability, and high heat capacity—eliminating the need for heavy and expensive pressure vessels and enabling compact, lightweight, and low-cost small modular reactors. The waterless cooling technology requires only minimal water to operate, allowing efficient power generation in arid regions. The high-temperature nuclear heat output above 700°C from molten salt reactors can be used for power generation, industrial heat applications, high-temperature hydrogen production, and hydrogen-based carbon dioxide conversion to methanol, effectively mitigating carbon emissions and environmental pollution (Figure 1 [Figure 1: see original paper]).

Molten salt reactor development began in the United States in the late 1940s. In 1965, Oak Ridge National Laboratory built the Molten Salt Reactor Experiment (MSRE), the only liquid-fuel molten salt reactor ever constructed and operated worldwide, and the only reactor to successfully utilize thorium-based nuclear fuel (uranium-233). However, due to Cold War considerations that prioritized military applications, the civilian-oriented molten salt reactor program was terminated, and U.S. molten salt reactor development ceased. In the early 1970s, China also selected thorium-based molten salt reactors as the starting point for civilian nuclear energy development. Shanghai's "728 Project"built a zero-power, cold-state molten salt reactor in 1971 and achieved criticality. Yet constrained by the scientific, industrial, and economic conditions of the time, the "728 Project" was redirected toward constructing light water reactors. Since then, national-level molten salt reactor development efforts worldwide have largely ceased.

1. Background and Significance

At the turn of the 21st century, energy crises, environmental challenges, and nuclear weapons technology proliferation concerns have renewed global interest in thorium-based nuclear energy and molten salt reactor development. The Generation IV International Forum selected molten salt reactors as one of six candidate reactor types, with related research showing a sharp upward trend internationally. In response to long-term energy supply and greenhouse gas reduction needs, the Chinese Academy of Sciences launched the first batch of Strategic Priority Research Programs (Category A) in January 2011— "Future Advanced Nuclear Fission Energy—Thorium Molten Salt Reactor Nuclear Energy System (TMSR)" —with a 20-year plan to become the first in the world to achieve thorium-based molten salt reactor applications while establishing a complete industrial chain and scientific workforce for TMSR. The program is led by the Shanghai Institute of Applied Physics (SINAP) of the Chinese Academy of Sciences, with participation from ten domestic and international research institutions including the Shanghai Institute of Organic Chemistry, Shanghai Advanced Research Institute, Changchun Institute of Applied Chemistry, and Institute of Metal Research.

2. Overall Progress of the Special Project

Since its launch, the TMSR special project has assembled and developed a professional, energetic domestic thorium-based molten salt reactor research team of approximately 750 personnel across multiple institutions. The project has constructed a TMSR low-level non-nuclear (cold) test base comprising basic research laboratories and R&D platforms covering all TMSR fields and directions, forming a complete disciplinary layout. Breakthrough progress in scientific research has been achieved, with overall capabilities reaching internationally advanced levels and laying a solid scientific and technological foundation for TMSR development. The World Nuclear Association (http://www.world-nuclear.org) has assessed that "China is leading international molten salt reactor research."

The project has conducted targeted international cooperation focused primarily on the United States to achieve program objectives. In 2011, the Chinese Academy of Sciences and the U.S. Department of Energy signed a Memorandum of Understanding on Nuclear Energy Science and Technology Cooperation (CAS-DOE NE MoU). Under this framework, the TMSR Center signed cooperative research agreements with Oak Ridge National Laboratory and the Massachusetts Institute of Technology to jointly develop molten salt reactor technologies. Relevant Chinese institutions collaborated with U.S. partners to establish molten salt reactor material processing standards and technical access standards—these collaborations were included in the specific outcome lists of the sixth through eighth rounds of the U.S.-China Strategic and Economic Dialogue. The TMSR Center has become an observer on the International Generation IV Forum Molten Salt Reactor Technical Committee.

Recently, the U.S. Department of Energy formulated a new nuclear energy development strategy, redefining Generation IV reactors as "non-water reactors" (reactors not cooled by water), with plans to have at least one Generation IV reactor reach technological maturity and begin deployment by 2030. Simultaneously, it has reformed traditional reactor development approaches by encouraging private sector participation in advanced reactor development, with nearly ten U.S. companies selecting small modular molten salt reactors for R&D. The TMSR special project focuses on achieving complete autonomy in key materials and equipment manufacturing, design, and engineering construction, realizing systematic breakthroughs in prototype systems and key technologies, and laying a solid scientific and technological foundation for experimental reactor construction. Joint experimental reactor engineering design has been conducted with the China Nuclear Power Research Institute and Shanghai Nuclear Engineering Research and Design Institute. Under the guidance of the National Nuclear Safety Administration, preliminary technical work for experimental reactor site selection has been carried out in cooperation with the Shanghai Nuclear Engineering Research and Design Institute, and a cooperation agreement has been signed with the State Nuclear Power Technology Corporation to jointly advance TMSR experimental reactor site selection.

Meanwhile, with support from the special project and Shanghai Municipality, the first thorium-based molten salt simulation reactor (without fuel) is being constructed in Shanghai' s Jiading District.

3. Main Technical Innovations

3.1. Innovative Development Strategy and Optimized Technical Route

Addressing national needs for long-term energy supply and greenhouse gas emission reduction, and considering international frontiers in molten salt reactor R&D, the project has identified a TMSR development strategy that simultaneously pursues both liquid-fuel molten salt reactors (suitable for efficient thorium-based nuclear fuel utilization) and solid-fuel molten salt reactors (known as Fluoride Salt-Cooled High-Temperature Reactors in the United States, tailored for nuclear hydrogen production and carbon dioxide reduction and capable of partial thorium fuel utilization). This strategy accommodates major applications including thorium-based nuclear energy, waterless cooling, and high-temperature hydrogen production, with respective development roadmaps formulated and dynamically adjusted. Recently, the project has further clarified its plan to use small modular thorium-based molten salt reactors as the demonstration reactor type, continuing the dual liquid-solid approach with an anticipated 10-year R&D cycle for the demonstration reactor. The formulation and implementation of this TMSR development strategy represents an international innovation. The TMSR R&D plan and content developed under this strategy demonstrate outstanding systematicity, completeness, and coherence, placing the TMSR special project in a leading position in international molten salt reactor R&D after just five years of implementation.

3.2. Establishment of Four Prototype Systems

(1) Thorium-Uranium Fuel Cycle System. An innovative thorium-uranium cycle scheme has been proposed, where nuclear fuel utilization efficiency continuously increases with each cycle, ultimately achieving a fully closed thorium-uranium fuel cycle. Using advanced dry processing technology, a completely new reprocessing flowsheet has been screened and established, achieving cold commissioning of the online processing process segment including fluorination volatility and vacuum distillation technologies.

(2) Molten Salt Experimental Reactor Design System. A software system has been developed and established to meet the needs of neutronics, thermal-hydraulics, and structural mechanics design and analysis for molten salt experimental reactors. The detailed conceptual design of a 2 MW liquid-fuel molten salt experimental reactor and the preliminary engineering design of a 10 MW solid-fuel molten salt experimental reactor have been completed, solving multiple key technologies including design of the main vessel, internals, and their sealing, support, and insulation in high-temperature molten salt environments.

Prototype development and related testing and experimental verification of key equipment and instrumentation for experimental reactors have been completed.

(3) Series High-Temperature Molten Salt Loop Systems. Key technologies have been mastered including thermal-hydraulic and structural mechanics design methods for molten salt loops, as well as high-temperature sealing, measurement, and control. The first domestic set of fluoride salt system pumps, valves, instrumentation, and heat exchangers has been successfully developed. A nitrate thermal test loop and an engineering-scale fluoride salt (FLiNaK) high-temperature test loop have been successively constructed, with prototype testing and operational trials of key equipment conducted, obtaining molten salt loop operational experience and important thermal-hydraulic data.

(4) Thorium-Based Molten Salt Reactor Safety and Licensing System. The seismic design standards for molten salt reactor structures on bedrock and the safety classification demonstration for Category II molten salt experimental reactors have been completed and recognized by the National Nuclear Safety Administration. As a joint chair member unit, the project has participated in the formulation of international solid-fuel molten salt reactor safety standards (ANSI/ANS-20.1) and compiled safety design criteria for solid-fuel molten salt experimental reactors. An engineering-scale passive molten salt natural circulation experimental facility has been constructed (Figure 2 [Figure 2: see original paper]), demonstrating for the first time the inherent safety of the passive molten salt natural circulation residual heat removal system.

3.3. Achieving a Batch of Core Technology Breakthroughs

(1) High-Purity Fluoride Salt Preparation and Detection Technology. The project has mastered fluoride molten salt coolant and fuel salt preparation and purification technologies, independently developing high-purity fluoride molten salt preparation and purification equipment. Nuclear-grade FLiBe molten salt and high-purity FLiNaK molten salt have been successfully prepared, establishing a production capacity of tons of fluoride salts annually. The difficult problem of testing key parameters of high-temperature molten salts has been solved, and a systematic and comprehensive molten salt physical property and structure research platform has been established.

(2) Fluoride Salt Corrosion Control Technology. A fluoride molten salt corrosion evaluation platform has been constructed, with systematic research conducted on fluoride molten salt corrosion mechanisms, corrosion evaluation and protection technologies for reactor-grade alloy materials. The corrosion control challenge of fluoride salt coolants has been solved through molten salt purification, alloy composition optimization, and surface treatment technologies (Figure 3 [Figure 3: see original paper]).

(3) Domestic High-Temperature Nickel-Based Alloy Preparation and Processing Technology. The project has mastered batch production, manufacturing, processing, and welding technologies for high-temperature nickel-based alloys, achieving domestic production of corrosion-resistant nickel-based alloys (domestic designation GH3535). Routine performance evaluations show equivalence with imported alloys. Technical bottlenecks in processing and heat treatment of high-hardness alloys have been overcome, enabling industrial trial production of wide and thick plates, large-diameter pipes, and large ring-rolled components.

(4) Domestic High-Density Fine-Grained Nuclear Graphite Preparation Technology. The first fine-grained nuclear graphite NG-CT-50 specifically for molten salt reactors has been successfully developed, with industrial production technology mastered. Routine performance evaluations show it meets molten salt reactor requirements, with molten salt infiltration resistance superior to imported nuclear graphite. A domestic nuclear graphite routine performance database has been established, directly promoting the establishment of international specifications for molten salt reactor-specific nuclear graphite.

(5) Isotope Extraction Centrifugal Separation Technology. An environmentally friendly solvent extraction centrifugal separation technology for lithium isotopes has been developed to replace the traditional amalgam method, eliminating mercury pollution. Laboratory-scale cascade experiments have been completed, obtaining lithium-7 with purity above 99.99% to meet molten salt reactor requirements. A solvent extraction process for nuclear-grade thorium has been developed, breaking through the limits of solvent extraction separation of trace impurities and achieving 99.999% purity with continuous batch preparation.

(6) Dry Separation Technology Based on Fluoride Salt Systems. Dry separation technologies including fluorination volatility, vacuum distillation, and fluoride salt electrochemistry have been developed. A temperature gradient-driven distillation technology has been established, improving molten salt recovery rate and quality while reducing dust emissions. A stepwise pulsed current electrolysis technology has been established, achieving over 90% separation rate of metallic uranium through electrolysis in FLiBe-UF4 molten salt systems.

(7) Molten Salt Reactor Radioactive Gas Monitoring Technology. The project has mastered high-efficiency bubble degassing technology for tritium removal from molten salt, low-temperature separation technology for tritium separation in multi-gas environments, collection technology for efficiently capturing multiple forms of tritium in the atmosphere, and simultaneous online monitoring technology for HTO, HT, Kr, and Xe in multi-gas coexistence atmospheres.

4. Significance for Industry

Beyond nuclear energy applications, molten salts can be used in solar thermal collection, large-scale thermal energy storage, and high-power batteries due to their high boiling points and other physicochemical characteristics. Widespread use of molten salts will bring revolutionary changes to energy systems. Key technologies for molten salt utilization include molten salt preparation and purification, structural material preparation and processing, corrosion control, and design and manufacturing of key molten salt loop instrumentation. Related technologies also include environmentally friendly light isotope separation, material surface modification based on composite fluoride salt thermal diffusion, advanced measurement and control of high-temperature molten salt loops, molten salt reactor core equipment design and manufacturing, advanced thermal energy conversion and utilization, high-temperature electrolysis hydrogen production, dry separation and processing of molten salt reactor spent fuel, nuclear-grade thorium preparation, molten salt reactor fuel preparation, and trace radioactive gas detection and control in the environment. Currently, these industries are virtually blank in China, and the TMSR special project will lay the scientific and technological foundation for the entire thorium-based molten salt reactor industrial chain. The TMSR team has begun collaborating with government, capital, and market stakeholders to industrialize the laboratory technologies mastered during the special project implementation, promoting development of the complete TMSR industrial chain.

5. Conclusion

Over 40 years ago, China conducted thorium-based molten salt reactor R&D, but the work could not be sustained due to technological limitations at the time. With improvements in economic, scientific, and industrial capabilities, China restarted thorium-based molten salt reactor research in 2011. Although the special project has achieved major progress and made a good start for China' s thorium-based molten salt reactor development, overall this remains an extremely challenging long-term task. Completing this mission requires long-term national support, cross-industry and cross-departmental technical collaboration within China, and leveraging international advanced experience. The project research team will continue as always, focusing on both immediate and long-term goals, pioneering innovation, and conducting joint research to strive for the rapid transition of thorium-based molten salt reactors and related technologies from laboratory to industrial application.

(Undertaken by: Shanghai Institute of Applied Physics, Chinese Academy of Sciences)

Expert Evaluation

In January 2011, the Chinese Academy of Sciences launched the Thorium Molten Salt Reactor (TMSR) special project at the Shanghai Institute of Applied Physics (SINAP). Since then, TMSR has made rapid progress, establishing the scientific and technological foundation for developing and deploying modern molten salt reactors (MSR). In November 2014, I participated as a member of the international expert group in the evaluation of TMSR. Our conclusion was that the TMSR project is world-leading.

Fifty years ago, research began on using molten salts in nuclear reactors, but significant technical challenges were encountered. Based on technological conditions at the time, water-cooled reactors proved easier to demonstrate and scale up. In the early 1970s, both China and the United States halted MSR research.

Once key technical problems are solved, molten salts have very desirable reactor heat transfer characteristics. Compared with water and helium, molten salts offer high-temperature, low-pressure operation, avoiding the need for heavy and expensive pressure vessels. Compared with liquid sodium, molten salts have high chemical stability and heat capacity, enabling compact, lightweight, and low-cost reactors. Molten salts can achieve very high average outlet temperatures, allowing efficient power generation even in arid regions.

The chemical form of cesium in molten salts prevents it from becoming gaseous during accidents. In water-cooled reactor accidents, cesium forms a reactive chemical species that readily disperses. Cesium-137 release was the primary cause of long-term regional contamination at Fukushima and Chernobyl. MSR cannot have accidents that cause long-term regional contamination.

When using liquid molten salt fuel, MSR can utilize most of the energy from thorium-uranium (water-cooled reactors utilize only 1% of the energy) and produces minimal waste. This is the primary reason why Bill Gates' TerraPower is now researching new MSR designs.

Technological advances over the past 50 years have prompted researchers to reexamine MSR technology. Today' s reactors employ passive safety (a technology that can remove heat and prevent fuel melting after reactor shutdown without relying on electrical power), such as the AP1000. Similarly, advances have been made in materials, reactor physics, and advanced computational simulation.

SINAP successfully built the world-class Shanghai Synchrotron Radiation Facility. Our expert group' s conclusion is that SINAP has also effectively solved the key technical problems of MSR and can achieve the world' s first scientific demonstration and pre-commercial demonstration of MSR. An important example is the successful demonstration of environmentally friendly lithium-7 enrichment technology.

The benefits of successful MSR technology development and commercialization are transferable. SINAP has greatly promoted MSR technology development through successful international cooperation, such as with Oak Ridge National Laboratory in the United States. The Chinese Academy of Sciences' TMSR project has adopted the correct approach to solving key scientific and technical problems and will continue to successfully lead world MSR development.

Per Peterson is a renowned American nuclear energy scientist, Professor at the University of California, Berkeley, former Chair of the Nuclear Engineering

Department, and current Executive Associate Dean of the College of Engineering. He is a Fellow of the American Nuclear Society, member of the National Research Council, and the only nuclear scientist on President Obama' s Blue Ribbon Commission on America' s Nuclear Future. He has served in multiple international academic institutions and is dedicated to advanced fission nuclear energy research, co-proposing the new concept of Fluoride Salt-Cooled High-Temperature Reactors in 2002.

Refers to the International Expert Diagnostic and Evaluation Group organized by the Bureau of Development and Planning of the Chinese Academy of Sciences for SINAP' s "One-Three-Five" planning and implementation. The group was chaired by Professor Ralph Eichler, President of ETH Zurich and former Director of the PSI Institute, and included ten experts from the United States, Germany, Japan, and China, including academician Li Guanxing, Chairman of the Chinese Nuclear Society, Professor Per Peterson, Professor Lin-wen Hu of MIT, Professor David Holcomb of Oak Ridge National Laboratory, and other nuclear energy experts.

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