



Thorium MSR Energy

Is the Revolution Coming?

October 2023

Overview

- Initially introduced this concept to the Arctic Circle Assembly in 2019
- Update presented during 2021
- Developments in this document have all happened since October 2022
- Broadened the number of constituencies involved

A zero emissions game-changer for marine and onshore clean energy

History

- NS Savannah was the first nuclear-powered merchant ship and one of only four nuclear power cargo ships ever built
- Was funded 100% by US Government agencies
- Was in service from 1962 to 1972
- Part of President Eisenhower's "Atoms for Peace Initiative"



History (Cont'd)

- Oak Ridge National Laboratory (ORNL) in Tennessee became the first self-sustaining nuclear reactor in 1965
- In 1968, it became the 1st ever to run on Uranium – 233 (Thorium)
- ORNL operated a 7.34 MW (th) MSR Experiment from 1965 to 1969
- During this time, ORNL operated at full power for more than 13,000 hours
- However, it was also shut down 225 times; of these only 58 were planned



Maritime

- The maritime sector presently accounts for about 2.8% of all global greenhouse gases (GHG) emissions, mainly due to its rapid growth, its dependence on carbon-intensive bunkers, and the sheer size of its business (more than 80% of world trade by volume is via sea)
- International shipping in open seas is one the major sources of all emissions in Europe
- The International Maritime Organisation (IMO), the United Nations' agency responsible for regulating shipping, wants to reduce ocean-vessel emissions by 50% before 2050
- Numerous alternative fuels are being developed/used including LNG, (green) ammonia, methane and hydrogen

Molten Salt Reactors

Maritime's Nuclear Option

Decarbonization's" holy grail — believed to be a "small" thorium-fuelled, molten-salt reactor's (MSR) unlimited power to propel sea trade. So, over the past few years..

- An increasing number of people have become comfortable that the MSR is among a range dubbed Generation IV reactors praised for their "walk-away safety, proliferation resistance and very long refuelling cycles
- Thorium resources are found widely in over 35 countries all over the world; the largest include India, Brazil, Australia, Turkey, Egypt, Venezuela, Norway to name a few
- Over the past few years, thorium research reactors small modular reactors seem to be growing in number (in all, some 70 compact designs worldwide, according to the IAEA)
- Over the past few years, there has been increasing interest in determining how to embed this into the vessels
- Bill Gates's TerraPower (2015) launched funding for its sodium molten salt program

Maritime

Marine Molten Salt Reactor (MSR) Technology

- MSRs have an energy density 2 million times more than diesel; could generate 15-50 MW up to 6-30 years without refuelling
- MSR are 98% fuel efficient (little waste). The core could be removed, refuelled and used on other ships
- Operationally: fewer moving parts including no torque curve, smaller (no) engine room reducing running costs below diesel and LNG
- Could also add 10+ knots to speed
- One goal is a fuel production storage and offloading (FPSO) ship. Its MSR would produce enough power to combine hydrogen from seawater with nitrogen to form green ammonia, or CO₂ from the atmosphere to generate methanol (C2X – Egypt)
- In December 2022, HMG (UK) issued a notice which provides guidance on the application of the Merchant Shipping (Nuclear Ships) relating to commercial nuclear-powered ships

Maritime

Core Power (UK)

- UK company launched in 2018 with the goal of developing shipyard manufactured floating nuclear power plants (FNPP) that would produce green power from hydrogen and seawater anchored offshore at key bunkering ports
- Historical Funding:
 - Seed: Jan 2019; Raised \$3.5 million; pre-money \$7 million
 - Series A: Dec 2020; Raised \$15.4 million; pre-money \$76.4 million
 - Series B: Oct 2022; Raised \$85 million; pre-money \$265 million
- In April 2023, CEO announced that Core Power UK had reached the \$100m funding milestone. The funding had come from “the maritime industries by the industry for the industry”
- The world's first molten chloride fast reactor to be built by the end of 2025/early 2026 and commercialise between 2030-2032
- On 6th October, Core Power stated that the world’s first molten chloride fast reactor (MCFR) has successfully started pumped-salt operations in an integrated effects test (IET), which they described as a “major achievement in the development of fourth-generation MSR technology”

Maritime

Core Power (UK) – 2023 Partnership with Japan

- In May 2023, Core Power (UK) announced that it has attracted 13 Japanese companies, including Onomichi Dockyard and Imabari Shipbuilding, to invest circa \$80 million in the FNPP project. Japanese investment now represents more than 25% of total investment
- Core Power is interested in Japanese shipbuilding technology and hopes to work with Japanese companies to develop floating equipment for the project
- Core Power aims to build a track record overseas, then expand in Japan
- It is estimated that the demonstration vessel will require approximately JPY50bn (\$361m), and Core Power and the its three partner companies will share the cost
- The Japanese investment followed Core Power's 2021 partnership with Terra Power/Southern Company (both USA) and its 2022 award of research funding by USA's DOE Nuclear Energy University Program

Maritime

Seaborg Technologies (Seaborg) – Partnership with Korea

- Seaborg Technologies (Denmark) founded in 2014, is developing small mass-produced FNPP (power barges) using advanced TMSR for use in developing countries such as in South East Asia
- As at June 2022, Seaborg had raised \$28.5 million funding over 4 rounds. The Danish state was an investor in the January 2018 pre-seed round. Danish billionaire Anders Holch Povlsen was a key private investor in the 2020 round
- In April 2023, after having received design certification from ABS, Korea Hydro & Nuclear Power (KHNP), Samsung Heavy Industries (SHI) and Seaborg established a consortium to develop FNPP featuring Seaborg's CMSR technology
- Seaborg's design is for modular CMSR FNPP barges equipped with 200-800 MWe CMSRs, with an operational life of 24 years. (First project is expected to be a 200 MWe)
- The JVs time-line, led by Seaborg is for commercial prototypes to be built in 2026 with commercial production of Power Barges beginning from 2028
- In July 2023, Kepco Nuclear Fuel (KNF – Korea) and Seaborg signed a MoU to investigate developing a LEU fuel salt production facility in South Korea to supply for the global 4th generation nuclear energy market

Maritime

Arctic Needs – Cruise Ships at Svalbard Port



Maritime

Ulstein – Thor/Sif – Arctic Needs

- In May 2022, Ulstein (Norway) introduced Thor, its concept design for a 149-metre (489-ft) replenishment, research and rescue (3R) ship powered by a TMSR that can be used to recharge battery-driven cruise ships at sea
- With increased tourism in the Arctic, in particular cruise ships in polar regions, care needs to be taken to protect the coastal regions while icy seas complicate refuelling away from port
- To address these issues, Ulstein built Thor, both able operate in polar seas for research and rescue missions without refuelling, but could also recharge the next generation of cruise ships that run off large battery banks



Maritime

Ulstein – Thor/Sif – Arctic Needs

- Since Thor is designed to recharge these future cruise ships, Ulstein is also working on the Sif concept, which is a 100-m (330 ft), 80-passenger, 80-crew battery-powered Ice Class 1C vessel that could be recharged at sea by the nuclear-powered Thor that would not need refuelling for the life of the vessel
- Both Thor and Sif are based on Ulstein's X-BOW ship design and their electric propulsion allows for silent cruising. Along with the reactor, Thor's design has helipads, firefighting gear, rescue booms, workboats, laboratories, and a lecture lounge
- In China, we note that Ulstein Electrical Technology has completed numerous projects and, amongst many, succeeded with Ulstein Power & Control to provide one-stop Ulstein spare parts and aftermarket services to Sinocean
- Since this 100+ year old family company has only slightly over NOK 1.2 billion total capital, they will likely need a partner to complete the Thor design

Maritime

ABS HEC Study – July 2023

- ABS, a leading global provider of technical advisory services to the marine industry, commissioned Herbert Engineering Corp (HEC – consultants to the marine industry to carry out a study to explore the potential of MSR technology for commercial marine propulsion
- The study modelled the transformational impact of nuclear propulsion of a 14k TEU container vessel and a 157k DWT Suezmax tanker
- The container vessel had two lead-cooled, 30MW fast reactors. Results found it would likely increase cargo capacity and operational speed, while eliminating the need for refuelling during its entire 25-year lifespan
- On the Suezmax vessel, the study found the addition of four, 5MW, heat-pipe micro reactors, while decreasing cargo capacity, would raise operational speeds and only require refuelling once during its 25-year life
- The U.S. Department of Energy (DOE) has awarded ABS a contract to research barriers to the adoption of advanced nuclear propulsion on commercial vessels. The DOE has also contracted ABS to support research into thermal-electric integration of a nuclear propulsion system on a commercial vessel being carried out by the University of Texas

On-Shore Thorium SMRs

Canada

- CANDU (Canada Deuterium Uranium), is a Canadian pressurized heavy-water reactor (PHWR) design used to generate electric power, was developed in the 1950s
- PHWRs/CANDUs are well established small and medium reactors
- All of Canada's 20 nuclear reactors are of the CANDU design: these supply circa 15% of Canada's national electricity
- CANDU 600 MW units were built in Quebec and New Brunswick, as well as in Pakistan, Argentina, South Korea, Romania, and China
- In 1998, the IAEA began studying thorium fuel utilization allowing full exploitation of the energy potential of thorium fuel cycles in existing CANDU reactors – although research was published as early as 1975

On-Shore Thorium SMRs

Canada (Cont'd)

- In 2002, The Qinshan Nuclear Power Plant (near Shanghai), a multi-unit nuclear power plant using two CANDU reactors supplied by AECL, was online. These are the first heavy water reactors in China and was China's largest nuclear fuel plant. From 1st concrete to power was only 77 months, a record at the time
- In July 2009, AECL signed an agreement with the Third Qinshan Nuclear Power Co (TQNPC), the Nuclear Power Institute of China and China North Nuclear Fuel Corp to jointly develop and demonstrate the use of thorium fuel. In 2012, China started using thorium fuel rod partially in Qinshan
- In 2022, Ontario Power Generation (OPG) selected GE Hitachi's BWRX-300 SMR as Canada's first commercial, grid-scale, SMR
- Also in 2022, the U.S. DOE gave a \$3 million grant to Terrestrial Energy (Canada) to support licensing and commercialisation of its Integral Molten Salt Reactor (IMSR), a Generation IV nuclear power plant

On-Shore Thorium SMRs

Indonesia Thorium MSR

- In August 2020, it was announced that ThorCon (USA) would develop a 50MW Thorium MSR (TMSR) for Indonesia for either power generation or marine vehicle propulsion
- In 2019 the Ministry of Energy successfully completed a study of the safety, economics, and grid impact of the 500MW prototype
 - Phase 1: build and test it with step-by-step commissioning, ending in a licence for future power plants
 - Phase 2: shipyard production – at a world class shipyard -of multiple 500MW ThorCon plants to provide an additional 3000MW of zero emissions electric power
- At that time, the thinking was that the timetable for commercial development would be 10 years, in line with facility construction times
- In March 2023, ThorCon submitted a consultation paper to build a 500 MW TMSR in Indonesia. If successful, it would be Indonesia's first nuclear power plant. The consultation paper marks the start of the licensing process to build the power plant which is expected to cost \$1.1 billion
- In March 2023, US Trade and Development Agency (USTDA) awarded a grant to Indonesia Power for technical assistance to help develop Indonesia's first SMR also on Borneo. Indonesia Power chose partners NuScale Power (US) / Fluor Corporation (US) and JGC Corporation (Japan)

On-Shore Thorium SMRs

Indonesia/Danish Companies Sign Agreement for \$4 Billion Thorium SMR in Borneo

- In May 2023, four Danish companies signed a MoU with local ammonia producer Pupuk Kaltim and Pertamina New & Renewable Energy to potentially build a \$4 billion TSMR nuclear facility in eastern Borneo
- Danish companies components: Copenhagen Atomics (thorium SMR), Topsoe (electrolysis cell technology), Alfa Laval (heat exchangers) and Aalborg CSP (thermal energy storage systems) – combined with the local partners: Pupuk Kaltim and Pertamina Energy
- The proposed SMR will be 1,000 MW, consisting of 25 SMR units. The facility is expected to begin operation in 2028 and would run for 50 years
- The expected 1 m/t/yr of ammonia produced by the plant would be enough to produce fertiliser for the production of food for 45 million people, or about one sixth of the Indonesian population
- It was expected that over the next six months, final examinations must be completed with the facility operating in 2028

On-Shore Thorium MSRs

China Approves Commissioning of Thorium-Powered Reactor

- As stated previously ORNL operated a 7.34 MW (th) MSR from 1965 to 1969. It has been reported that SINAP had ambitions to build a TMSR since 1970
- In January 2011, the Chinese Academy of Sciences (CASS) launched a CNY3 billion (\$444 million) R&D programme on liquid fluoride thorium reactors (LFTRs), known as the thorium-breeding molten-salt reactor (Th-MSR or TMSR), to obtain full intellectual property rights on the technology
- Construction of the 2 MWt TMSR-LF1 reactor began in September 2018 and was reportedly completed in August 2021. The prototype had been scheduled to be completed in 2024, but work was accelerated
- In terms of A-shares, a number of listed Chinese companies have participated in experimental TMSR project, as well as full involvement in its construction – including a number of construction and engineering, iron and steel and manufacturing organisations
- In November 2022, it was reported that China's Ministry of Ecology and Environment gave Shanghai Institute of Applied Physics (SINAP) the green light to commission the experimental 2-MW TMSR in Wu Wei City, Gansu Province (Gobi desert)

On-Shore Thorium MSRs

China Thorium Molten Salt Experimental Reactor is Licensed for Operation

- In June 2023, it was announced that China's National Nuclear Safety Administration gave authorisation to SINAP to operate a 2MWt liquid fuel TMSR operation application for 10 years; and it will start by testing operations
- This marks the first 4th generation MSR since the US shutdown its ORNL test reactor in 1969
- If the TMSR-LF1 proves successful, China plans to build a reactor with a capacity of 373 MWt by 2030
- In 2019, the former Chairman of China National Nuclear Corp. (CNNC), said BRI nuclear projects could earn Chinese firms as much as 1 trillion yuan (\$145.5 billion) by 2030 as 41 BRI nations already had nuclear or were planning to develop nuclear power programs
- According to the press, thorium could power China for 20,000 years

On-Shore Thorium MSRs

To be Thorough...

India – Macro Only – not 2023 specific

- Three-Stage Nuclear Power Program which aims to utilize thorium as a fuel source in advanced reactors: (i) PHWRs that use natural uranium, (ii) the utilization of plutonium in fast breeder reactors (FBRs), and eventually the utilization of thorium in advanced reactors
 - Prototype Fast Breeder Reactor (PFBR): located in Kalpakkam, Tamil Nadu, is a fast breeder reactor using a combination of plutonium and uranium
 - Advanced Heavy Water Reactor (AHWR): aims to demonstrate the feasibility of thorium utilization in a commercial reactor setting
- R&D: India's Department of Atomic Energy (DAE) and its associated research institutions, such as the Bhabha Atomic Research Centre (BARC), are actively involved in thorium-related R&D
- Internationally: India and the USA signed a MoU in 2019 to collaborate on the development of advanced nuclear energy technologies, including thorium-based fuels and reactors



We believe that the TMSR story, once fully disseminated, will become as powerful as the 2023 film Oppenheimer, as this clean nuclear energy source, using thorium available with thousands of years supply, was requested by President Eisenhower as an example of nuclear power to be used in peace.

ONE PEOPLE... ONE PLANET

- HEALTH
- GREEN