CHALLENGES AND DEVELOPMENT IN MOLTEN SALT REACTORS AND THEIR FUTURE APPLICATIONS AND OUTLOOK

Lappeenranta–Lahti University of Technology LUT

Energy Technology, Bachelor's thesis

2022

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Examiner(s): Heikki Suikkanen, D.Sc. (Tech.)

ABSTRACT

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Challenges and development in molten salt reactors and their future applications and outlook

Bachelor’s thesis
2022
33 pages, 9 figures, 2 tables
Examiner: Heikki Suikkanen, D.Sc. (Tech.)

Keywords: Molten salt reactor, generation IV, thorium molten salt reactor, small modular reactor, development, material challenges, corrosion, safety

In the past decade molten salt reactor (MSR) research has gained renewed interest worldwide. Currently, many independent and national research projects are developing their own MSR design concepts. This research reviews the recent developments in the field of MSR development providing an updated view on MSR technology. The advancements in Generation IV reactor designs are reviewed, including thorium fueled MSRs and small modular MSRs. The viability and future prospects of MSR technology are examined. Furthermore, the existing problems in developing MSRs for commercial use are discussed, as well as the next steps in overcoming these challenges. Based on available data and conclusions drawn from existing literature, the literature review presents a broad picture of the current stage of MSR technological development and analyzes its prospects in the future energy generation.

TIIVISTELMÄ

Lappeenrannan–Lahden Teknillinen Yliopisto LUT

LUT Energiajärjestelmät

Energiatekniikka

Roosa Talala

Sulasuolareaktorien kehitysnäkymät, haasteet ja tulevaisuuden sovelluskohteet

Kandidaatintyö

2022

33 sivua, 9 kuvaa, 2 taulukkoa

Tarkastaja: Heikki Suikkanen, D.Sc. (Tech.)

Avainsanat: Sulasuolareaktori, sukupolvi IV, toriumsulan suolareaktori, pieni modulaarinen reaktori, kehitys, materiaalihaasteet, korroosio, turvallisuus

Viimeisen vuosikymmenen aikana sulasuolareaktorien tutkimus on herättänyt uutta kiinnostusta maailmanlaajuisesti. Tällä hetkellä monet itsenäiset ja kansalliset tutkimushankkeet kehittävät omia sulasuolareaktori konseptejaan. Tässä tutkimuksessa tarkastellaan viimeaikaista kehitystä sulasuolareaktorien tutkimuksessa tarjoamalla päivitetyn kuvan sulasuolareaktori teknologiasta. Neljännen sukupolven reaktorisuunnitelmien edistysaskeleita tarkastellaan, mukaan lukien toriumpolttoaineella toimivia sulasuolareaktoreita ja pieniä modulaarisia sulasuolareaktoreita. Sulasuolareaktori teknologian kannattavuutta ja tulevaisuudennäkymiä tarkastellaan. Lisäksi havaitaan olemassa olevia ongelmia sulasuolareaktorin kehittämisessä kaupalliseen käyttöön sekä seuraavia askelia näiden haasteiden päihittämiseksi. Tämänhetkisen tutkimustiedon ja olemassa olevan kirjallisuuden pohjalta tehtyjen johtopäätösten perusteella kirjallisuuskatsaus antaa laajan kuvan sulasuolareaktori teknologian nykyisestä kehitysvaiheesta ja analysoi sen tulevaisuutta energiantuotannossa.

SYMBOLS AND ABBREVIATIONS

Abbreviations

CMSR	Compact Molten Salt Reactor
FHR	Fluoride Salt-Cooled High-Temperature Reactor
HTR	High-Temperature Reactor
IMSBR	Indian Molten Salt Breeder Reactor
ITMSF	The International Thorium Molten Salt Forum
IMSR	Integral Molten Salt Reactor
LMFBR	Light Metal Fast Breeder Reactor
LWR	Light Water Reactor
MCSFR	Molten Chloride Salt Fast Reactor
MOSART	The Molten Salt Actinide Recycler and Transmuter
MSR	Molten Salt Reactor
ORLN	Oak Ridge National Laboratory
SmAHTR	Small Advanced High Temperature Reactor
SM-MSR	Small Modular Molten Salt Reactors
SSR	Stable Salt Thermal Reactor
SSR-W	Stable Salt reactor Waste Burner
TAP	Transatomic Power
TMSR	Thorium Molten Salt Reactor
TMSR-LF	Thorium Molten Salt Reactor, Liquid Fuel
TMSR-SF	Thorium Molten Salt Reactor, Solid Fuel
TRISO	Tri-Structural Isotropic

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Abstract

Symbols and abbreviations

1 Introduction

World energy demand is growing each year, but to slow rapid climate change emissions from the energy sector need to reduce significantly and as soon as possible. The challenge with reducing emissions from the energy sector is that the majority of the world's energy comes from burning fossil fuels, which contribute significantly to global emissions. Thus, research into low emission energy sources is important if we want to reduce emissions from the energy sector, while still meeting the rising global energy demand.

Fission of high energy density nuclear fuel inside a nuclear reactor core has been a viable source of low greenhouse gas emission energy since the 1950s, but politics and lack of public support for nuclear power has led to decline in research and construction of nuclear power plants in the past three decades. However, researchers in the field of nuclear power hope that increasing pressure to find solutions for reducing global emissions and new Generation IV reactor designs will gain governmental and public support.

Molten salt reactors were nuclear fission reactors that use molten salt mixture as coolant and, or fuel (Serp et al., 2014, p. 319). Molten salt fuels were first studied in the 1940s when at the height of World War II, the United States wanted to build a nuclear-powered aircraft, which can fly long ranges without refueling (Rosenthal MW, Kasten PR and Briggs RB, 1970, p. 1-2). After World War II, the Atoms for Peace program was launched to shift focus away from nuclear weapons manufacturing and towards energy production. The first molten salt reactor was developed in the 1960s at Oak Ridge National Laboratory (ORNL) in Tennessee, the United States. The MSR program at ORNL originates from the Aircraft Reactor Experiments, which was the earliest study of molten salt fuels. The Molten Salt Reactor Experiment at ORNL demonstrated the feasibility of the molten salt cooled breeder reactor technology, but during the run of the experiment at ORNL which ended in 1969 the experimental reactor logged ten thousand operating hours using Uranium-235 and Uranium-233 as fuel. After which, the laboratory prepared to build a Thorium fuelled slow breeding MSR. Research into molten salt reactors continued at ORNL until mid-1970s after which the program was cancelled due to challenges in the reactor designs that needed addressing. (World Nuclear Association, 2021.)

Research on molten salt reactor stalled after the 1970s because funding and talent in nuclear power reactor research was directed towards the development of the liquid metal fast breeder reactor (LMFBR) which requires less development effort than the MSR (Serp et al., 2014, p. 311.) In past ten years new interest in the research and development of molten salt reactors has emerged. “There is now renewed interest in the MSR concept in Japan, Russia, China, France and the USA” (World Nuclear Association, 2021). Updated research and modern technology in the Generation IV MSR designs could solve the problems faced by earlier MSR designs.

1.1 Objectives of Research

This research attempts to identify the challenges that molten salt reactors (MSRs) are currently facing and what needs to be done to overcome the challenges. The research will also examine the variety of diverse types of molten salt reactors under research to determine if any of these technologies show promise for use in commercial energy generation. The goal of this thesis is to present an updated view of molten salt reactors, through analysing the current developments and limitations that the MSR technology is facing. From the research it is possible to gain a broader understanding of the subject and awareness of new applications of MSRs that could produce commercial clean energy in the future. Due to rise in energy demand and the need to reduce emissions from energy production, future generations will be at the mercy of research and technological advancements made today. MSRs can be a part of that future.

In the past ten-years research on molten salt reactors has gained more interest. Many research institutions and companies worldwide have begun to develop their own molten salt reactor technologies. The hope is that Generation IV MSRs will be safer and more efficient nuclear power reactors than currently operational models. But molten salt reactors still have limitations that need solutions before this technology can be considered for commercial use.

1.2 Scope of Research

Research is done by reviewing relevant scholarly publications and information provided by scientific agencies and institutions. Literature review is conducted by searching for existing literature on research topics, evaluating the sources, and compiling and analysing information to answer the research questions. The literature search is conducted using LUTPub and Scopus databases and some basic information is acquired from agency and institution webpages. The literature review establishes an overview of the current knowledge on the research topics, which is used to identify gaps in existing research and to analyse the future perspectives of MSR technology and research.

This thesis is a literature review that investigates the outlook and challenges of molten salt reactor technology. A wide range of MSR designs are under development by national and independent research projects. To begin, an overview of Generation IV reactors including thorium fuelled MSRs and small modular MSRs, introducing their benefits, and development goals is given in section 2. Follower by a look at the challenges MSR technology and research is facing in section 3. Section 4 will analyse the feasibility and outlook of MSR technology and highlight areas of further research required to solve the current challenges of MSR designs. Economic, social, and political factors are left outside the scope of this research because the focus is mostly on physical and technological aspects. This research will give the reader an overview of the current state of MSR developments and the challenges that need to be overcome to make the technology realistic option for the future energy generation.

2 New Developments in Molten Salt Reactor Technology

Research funding and talent is directed away from MSRs in the 1970s because the technology requires more technological development to overcome its technical and design challenges than other fast breeder reactor types (U.S. Atomic Energy Commission Division of Reactor Technology, 1972, p. 3-4). After decades, MSR research is resurfacing. This section will overview the most significant new developments in MSR research.

2.1 MSR Technology Overview

Molten salt reactors are a type of nuclear fission reactor similar in design to currently operational light water reactors (LWRs) in which the primary coolant, and in some designs the fuel, is a molten salt mixture. MSRs are categorized to liquid fuelled and solid fuelled reactor designs. In liquid fuelled reactors the fissile material is dissolved in molten salt. Solid fuelled reactors use solid coated fuel pellets, like those used by High-Temperature Reactors (HTRs) but the core is cooled with low-pressure molten salt. The Fluoride Salt-Cooled High-Temperature Reactor (FHR) is the most common type of solid fuelled MSR. MSRs have a higher operation temperature (up to 700-750 °C) and operation pressure near atmospheric pressure, unlike other LWR designs that operate at lower temperatures but much higher pressures. (Serp et al., 2014, p. 309.) The general design of MSR systems is illustrated in Figure 1.

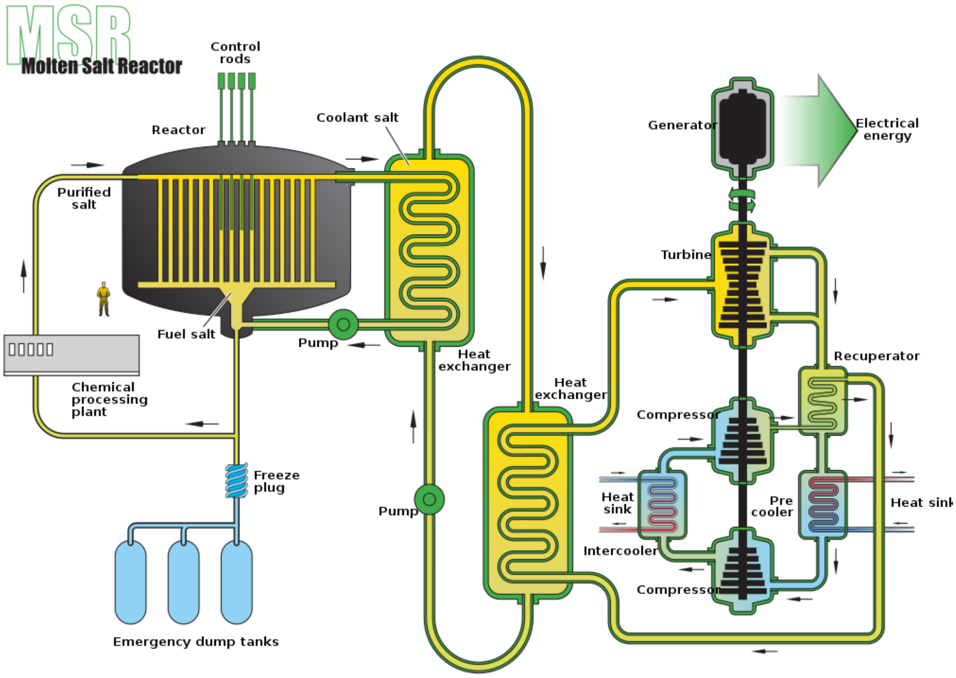


Figure 1. MSR reactor design (US Department of Energy, 2002)

Depending on the desired use, for example breeder reactors and actinide burners, liquid fuel in MSRs is a homogenous mixture of fissile elements like UF_4, PuF_3, and/or fertile elements (ThF_4) in thorium fuelled reactors, actinides, and fluoride-based coolant salts (Serp et al., 2014, p. 309). Fission occurs inside the fuel salt in the core, and the heat is transported to a secondary liquid-salt coolant via an intermediate heat exchanger that is connected to steam turbine loop where thermal energy is converted to kinetic energy and converted to electricity in the generator.

The thorium fuel cycle is often associated with liquid fuelled MSRs. Because the mass number of thorium (^{232}Th) is six units lower than that of uranium (^{238}U), transmuting thorium to the first transuranic element requires more neutron captures than in the uranium-plutonium (U-Pu) fuel cycle. Although any fissile material may be used to fuel MSRs, the use of thorium as a fertile element allows for breeding with a thermal spectrum and is thought to be more efficient than the U-Pu fuel cycle in terms of reducing the formation of extremely radiotoxic transuranic elements. However, thorium does not have any fissile isotopes like fissile isotope ^{235}U found in natural uranium. Fission in thorium fuel must be started up using fissile elements from the uranium fuel cycle. (Serp et al., 2014, p. 309.)

2.2 Renewed Interest in Molten Salt Reactors

MSR technology is attractive because it offers potentially safer, more efficient, and sustainable form of nuclear fission. Because of the high volumetric heat capacity and boiling point of the molten salt coolant, MSRs can operate at high temperatures which improves reactor efficiency and at atmospheric pressure which eliminates safety concerns associated with high pressure steam. MSRs have a high thermal coefficient which slows down the nuclear reaction allowing the reactor to be self-regulating, and higher fuel burn up than in reactors using a solid fuel which leads to better use of resources. The ability to drain the fuel from the core if the reactor is damaged and the low operation pressure, make the MSR a potentially safer reactor design than currently operational reactor designs. The efficiency of MSRs is higher because they can breed fissile fuel in uranium and thorium fuel while online, eliminating the need to shut down for refuelling. (Serp et al., 2014, p. 309.)

The advantages of reactors using molten salt coolants and fuel over other nuclear fission reactor types, and the need to develop low emission reliable energy sources has sparked worldwide interest in MSR technology and its potential applications. National and private research institutions and projects are developing their own Generation IV MSR reactors in Japan, Russia, China, France, the USA, and the UK (World Nuclear Association, 2021). In the next sections the most significant developments in MSR technology will be discussed. Overview of the MSR concepts discussed in the paper is shown in Table 1.

Table 1. MSR concepts under development (Hongjie Xu, 2018; IAEA, 2016; IAEA, 2020; Transatomic Power, 2015; World Nuclear Association, 2018)

Reactor Name	**Reactor Type**	**Power (MWth)**	**Operation Temperature** (°C)	**Fuel, Salt**	**Lifetime (years)**
Kairos Power FHR	Solid fuelled	320	550–650	Ceramic fuel, $NaNO_3$ - KNO_3	20 (vessel)/ 80 (plant)

Terrestrial Energy IMSR	Liquid fuelled thermal	440	620-700	UF^4, Fluoride	56
Moltex Energy’s SSR	Liquid fuelled fast	300–2500	525-590	UF^4, Fluoride	60
Transatomic Power MSR (TAP)	Liquid fuelled thermal	1250	650-700	UF^4, Fluoride	30
FUJI	Liquid fuelled thermal	450	565–700	ThF_4-$^{233}UF_4$, $^7LiFBeF_2$	30
Elysium Industries’ MCSFR	Liquid fuelled fast	110–2700	650–750	U-Pu, Chlorides	15–40 (core)
TMSR-LF	Liquid fuelled thermal	395	650–700	ThF_4-$^{233}UF_4$, $^7LiFBeF_2$	unknown
IMSBR	Liquid fuelled fast	1900	700	ThF_4-UF_4, LiF	unknown
MOSART	Liquid fuelled fast	2400	700–800	ThF_4-$^{233}UF_4$, $^7LiFBeF_2$	40
Thorcon Power MSR	Liquid fuelled thermal	557	565–700	UF_4, NaF-BeF_2	80
Seaborg Technology’s CMRS	Liquid fuelled thermal	250	700-900	Spend nuclear fuel, Flouride	60
Copenhagen Atomics Waste Burner	Liquid fuelled thermal	100	600-700	Spend nuclear fuel, Flouride	3-5

SmAHTR	Liquid fuelled thermal	125	700-1000	Coated Uranium particles, FLiBe	60

2.3 Generation IV MSRs

Generation IV reactors are nuclear power reactors that the GenIV International Forum believes can be developed for commercial energy generation. The goals of Generation IV reactors are to improve sustainability, economics, and safety of nuclear power reactors. (GIF, 2013.) Molten salt reactors are among the most promising Generation IV nuclear power reactor types. Currently, several types of MSR designs are being developed by many nations and enterprises pursuing MSR technology commercialization.

Many Generation IV MSR reactor designs are considered small modular molten salt reactors (SM-MSR). The aim of SM-MSR is to apply the safety and efficiency benefits of MSR technology to smaller more economical designs. The main goal of many SM-MSR designs is to lower the cost and time to build a nuclear power reactor.

Despite many modern design concepts proposed in the past decade, many of them are only research projects, and it is unclear which are realistic concepts for future energy generation. All claims made by companies on their web pages should be examined critically. This section gives an overview of the major ongoing development projects in MSR technology without commenting on the realistic outlook of designs. The outlook of MSR technology will be discussed in section 4.

2.3.1 Kairos Power FHR

In partnership with Oak Ridge National Laboratory, Kairos Power has designed a fluoride salt-cooled high temperature reactor (FHR), shown in Figure 2. The concept reactor will be built and researched at East Tennessee Technology Park in Oak Ridge, Tennessee. The reactor operates at high temperatures and utilizes 20% enriched tri-structural isotropic (TRISO) particle fuel in pebble form with online refuelling. Secondary circuit salt is nitrate salt with sodium nitrate to potassium nitrate in the weight ratio of 60:40, which feeds a steam generator. The safety features include a passive shutdown system as well as the decay heat removal system. (Kairos Power, 2020.) The Kairos Power FSR is designed to be cost competitive with natural gas while also providing long-term savings in operation costs. The unique reactor is designed to have flexible energy output and to operate with minimal maintenance and lifetime costs, resulting in dispatchable electricity that boosts grid reliability and security. The reactor can be combined with renewable energy sources to provide clean supplementary electricity when renewables cannot meet the electricity demand. (IAEA, 2020)

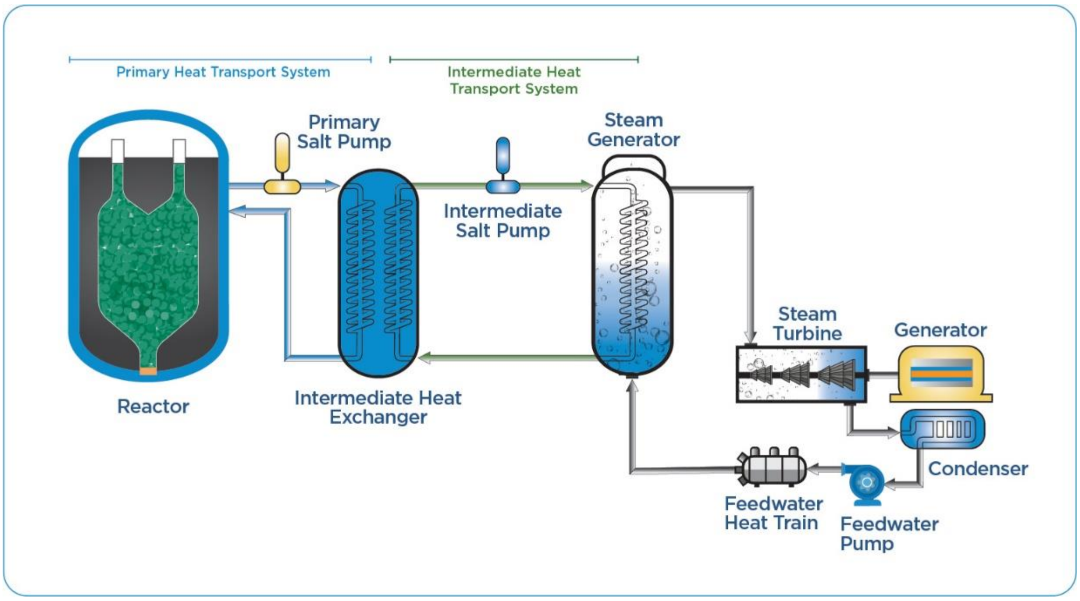


Figure 2. Kairos Power FHR (Kairos Power)

2.3.2 Terrestrial Energy IMSR

The integral molten salt reactor (IMSR) by Terrestrial Energy has just started phase 2 of the Canadian Nuclear Safety Commission's pre-licensing vendor design review process (Terrestrial Energy, 2018). The plant is designed to accommodate a variety of loads. The reactor parts are designed to be manufactured modularly in a semi-automated factory line and can be transported in trucks to the plant site. The principal reactor parts are sealed modules that can be interchanged by accessing the core. (IAEA, 2020.) The core's expected lifetime is seven years, with a net efficiency of 45%. Like currently operational nuclear reactor models, the Terrestrial Energy IMSR will use low enriched uranium in the core (Terrestrial Energy, 2018). Terrestrial Energy promises "combination of high safety, high energy output, simplicity of operation, versatility and cost-competitiveness necessary for broad and near-term commercial deployment" (Terrestrial Energy, 2018). The reactor is "walk-away" safe meaning reactor cooling and radioactive containment safety systems do not require "operator action, electricity, or externally-powered mechanical components". The high level of safety is achieved by combining MSR technology with an internal vessel auxiliary cooling system. (IAEA, 2020.) The IMRS design is shown in Figure 3.

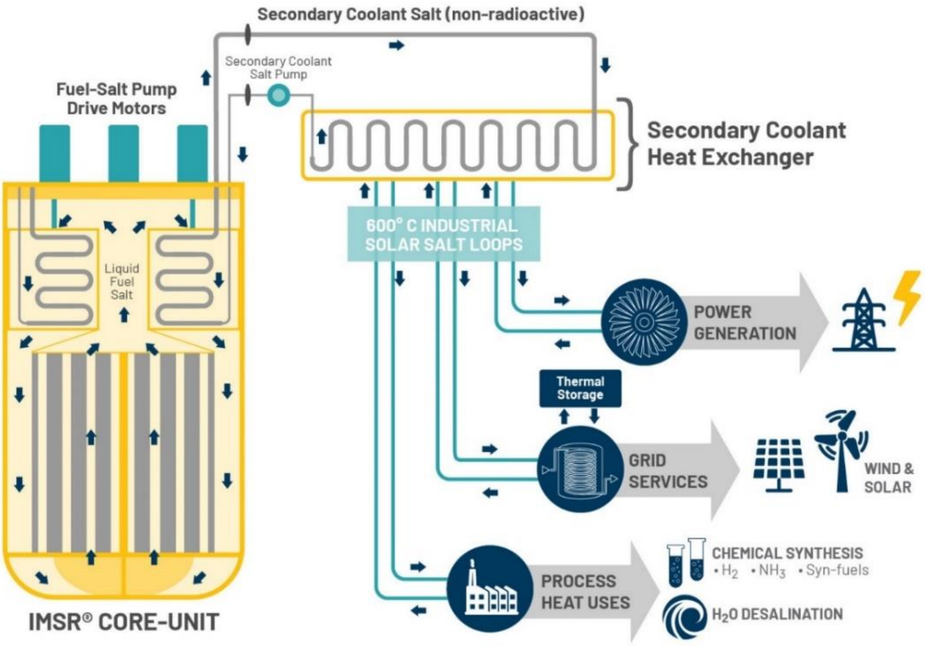


Figure 3. IMSR layout (Terrestrial Energy)

2.3.3 Moltex Energy SSR

Moltex Energy's stable salt reactor (SSR) design features an assembly layout like operational pressurized water reactors, but traditional fuel assemblies are replaced with fuel shells that contain molten salt fuel. The reactor uses plutonium fuel extracted from the spend uranium fuel that is processed to a stable salt fuel. Regular pumping equipment can be used to circulate core coolant salt because shells protect from contact with radioactive fuel salt. Due to the fuel salt being contained the challenges associated with the interactions of neutronics and thermohydraulics of flowing fuel salt are eliminated. Redox control aims to protect the materials in contact with fuel and coolant salt from corrosion. (Energy, M., 2018.) Decay heat removal and core cooling following shutdown is secured by air flow that provides natural convection. Moltex announced in 2018 that its stable salt reactor waste burner (SSR-W) has started operation testing in New Brunswick, Canada. (Moltex Energy, 2018.) Before 2030, the first reactor is expected to be ready for commercial use (World Nuclear Association, 2018). The reactor is designed for countries that have existing nuclear power plants that can provide fuel for the SSR. The SSR has high actinide burn up, which means that the waste fission products have short half-lives. (IAEA, 2020.) The design includes energy GridReverse molten salt heat storage that can supplement electricity to the grid during peak demand when renewable sources are not meeting the electricity demand. (World Nuclear Association, 2018.)

2.3.4 Transatomic Power Single-Fluid MSR

Transatomic Power (TAP) is a new US company that is partially owned by Founders Fund and is working on a single-fluid MSR that uses 1.8 percent enriched uranium fuel or the whole actinide components of spent LWR fuel. The TAP reactor features a small core that is feasible due to an efficient zirconium hydride (ZrH) moderator and a lithium-fluoride based fuel salt that contains uranium-fluoride (UF4) and actinides. When compared to a graphite moderator, the ZrH moderator produces much more neutrons in the thermal range, allowing the reactor to generate electricity from low-enriched uranium or spent LWR fuel. The ZrH moderator allows for about 96 percent actinide burnout due to a lower thermal spectrum than graphite. Batches of fission products are removed from the core, and new fuel is added without shutting down the reactor thus improving the efficiency and economics of the reactor. Natural convection is used to remove decay heat from the process. In 2016, Transatomic Power made exaggerated claims on the predicted actinide burn-up of their MSR design in MIT Technology Review. As a result, TAP declared in September 2018 that it will suspend operations and make its research data open source. (Transatomic Power, 2015; World Nuclear Association, 2018.)

2.3.5 FUJI MSR

The FUJI MSR is a graphite-moderated near-breeder that runs at high temperatures using thorium/uranium-fluoride (ThF4-UF4) fuel salt and salt coolant. It consumes plutonium and actinides, and refuelling occurs in batches. (Serp et al., 2014.) As well as electricity production, the high exit temperature of the FUJI MSR can be used for the heat source of desalination plants and hydrogen production (IAEA, 2020). The International Thorium Molten Salt Forum (ITMSF), located in Japan, is working on it with Japanese, Russian, and US research cooperation. It is based on the Oak Ridge MSBR, and a small modular version of the FUJI reactor has been constructed for research purposes. (Serp et al., 2014.)

2.3.6 Elysium Industries MCSFR

The Molten Chloride Salt Fast Breeder Reactor (MCSFR) is a design by Elysium Industries based in the United States and Canada, which uses chloride salt as fuel. It runs at near-atmospheric pressure. The primary and secondary fuel salts transport heat to steam generators. It can be easily constructed in a variety of sizes as shown in Figure 4. Research is done on reactors ranging from 10 to 3000 MWth. (Elysium Industries, 2015.) The small modular design of the MCSFR is designed for domestic use. All reactor components are designed to be mass produced with low costs. (IAEA, 2020.) It can run on spent light water reactor fuel or spent uranium-plutonium fuel. Fission products are removed in batches when the reactor is online. The design has a unique passive safety feature that can freeze the core in the case of a reactor accident. The reactor has negative temperature and void coefficients. (Elysium Industries, 2015; Word Nuclear Association, 2018.)

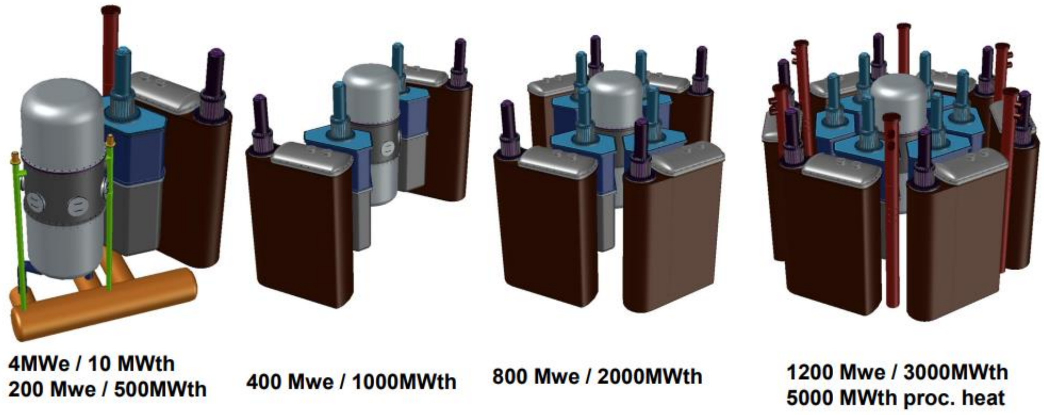


Figure 4. Elysium Industries MCSFRs (Thorium Energy Alliance, 2019)

2.3.7 Thorcon Power Modular Reactor

Thorcon Power is designing a highly modular facility with reactors buried below. The complete facility can be produced in blocks on a shipyard-style assembly line, with just block installation required on the site. The block design is shown in Figure 7. The modular design will make maintenance and replacement of individual reactor parts easier. The reactor's primary loop and reactor vessel has been designed to be changed and refurbished in a specific recycling facility every fourth year. Like in many other MSR designs, in the event of an accident the liquid fuel in the Thorcon MSR can be passively drained. (IAEA, 2020.) The first plant is expected to be ready for commercial use by the end of 2025. In 2017, Indonesia conducted a pre-feasibility study that included the Thorcon MSR as a possibility in the country's 10-year energy transition strategy. (Thorcon Power, 2017.) The Thorcon MSR concept is suited for developing nations with unreliable power grids and a black start capacity, meaning that the reactor can be started without any eternal electricity supply (Stevenson, 2018).

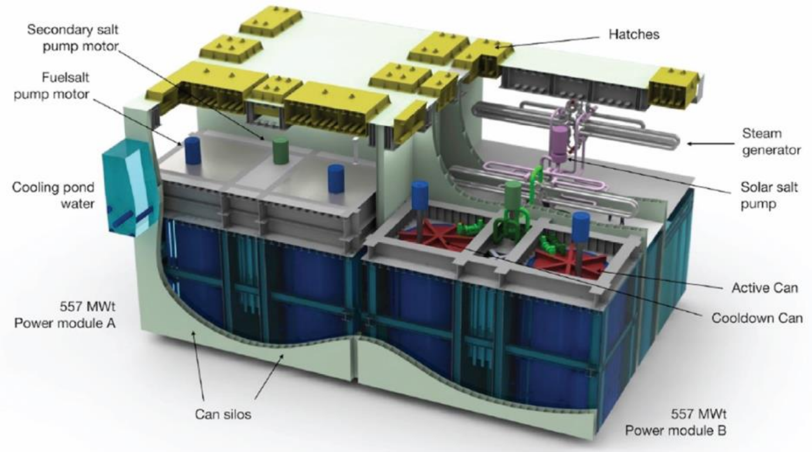


Figure 7. Thorcon modular reactor design (Thorcon Power)

2.3.8 Seaborg Technology CMSR

The Seaborg Technology’s compact molten salt reactor (CMSR) is a single salt, a thermal spectrum, ultracompact molten salt reactor that can run on conventional uranium nuclear fuel or a mix of spent nuclear fuel and thorium. The core exit temperature is 700°C, although it can reach a temperature of 900°C in some applications. A unique, liquid moderator substance makes the reactor design very compact. The CMSR has built-in safety mechanisms that eliminate the need for active intervention to manage the reactor’s safety systems. The CMSR is completely modularized and designed for mass production. It is made up of modules manufactured in instalments which are brought to the construction site where the reactor is assembled. The components that are in contact with the fuel salt and moderator are housed in the core unit. After 12 years, the fuel will be emptied, and the core unit will be retrieved, cooled, and returned to a central location for recycling. The reactor will run on the same batch of spent nuclear fuel for the duration of its lifespan. According to the IAEA, “the CMSR is in the conceptual design phase with development work focusing on reactor physics, material, and corrosion studies”. The engineering design can be seen in Figure 8. (IAEA, 2020.)

Our Compact Molten Salt Reactor, the CMSR, is safe, significantly smaller, better for the environment, and inexpensive even compared to fossil fuels.

Figure 8. Seaborg CMSR design concept (Seaborg Technologies)

2.3.9 Copenhagen Atomics Waste Burner

The Copenhagen Atomics waste burner is a waste burning, single fluid, fluoride salt based, a thermal spectrum, molten salt reactor with heavy water moderation. The Copenhagen Atomics Waste Burner is designed to breed more “fissile materials than in consumes” using a build in breeder. It converts fissile transuranic waste from the uranium cycle of currently operational nuclear reactors to start-up products of the thorium-based cycle. All principal parts of the reactor are contained in a sealed 12-meter-long shipping container that is encased in a frozen thorium blanked. The waste burner will be an additional module for nuclear power plants with fuel reprocessing capability. (IAEA, 2020.)

2.3.10 Small Advanced High Temperature Reactor

The Advanced High Temperature Reactor (AHTR) is a project at Oak Ridge National Laboratory in the United States that is focusing on molten salt coolant research. One of their research projects is a small modular MSR called SmAHTR, the design shown in Figure 9. The SmAHTR is a smaller variant of the AHTR, with a capacity of 125 MWth and it can produce over 50MWe. With FLiBe as the main coolant and three integrated heat exchangers, the operation temperature is 700°C. It can be transported by truck because it is nine meters long and 3.5 meters wide. It uses a fuel of tritium-sulphite particles in graphite blocks or fuel plates, which are 20 percent enriched uranium. Depending on the fuel composition, the refuelling frequency is 2.5 to 4 years. Auxiliary loops that run to convection cooled heat exchanger ensure passive decay heat removal. The reactor's secondary coolant is FLiNaK. Later generations will use materials under development to achieve operating temperatures of 850° to 1000°C. (IAEA, 2016; World Nuclear Association, 2018.)

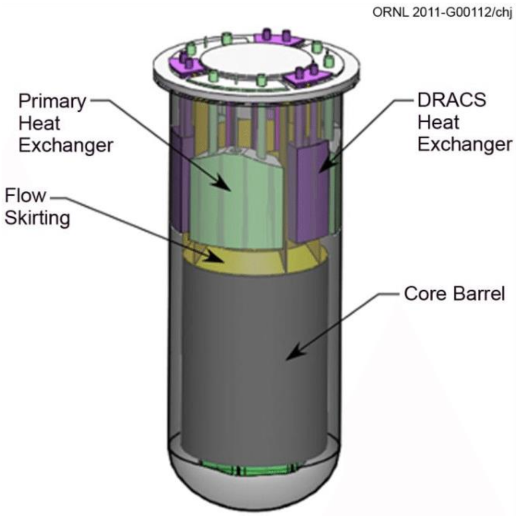


Figure 9. SmAHTR design (ORNL, 2011)

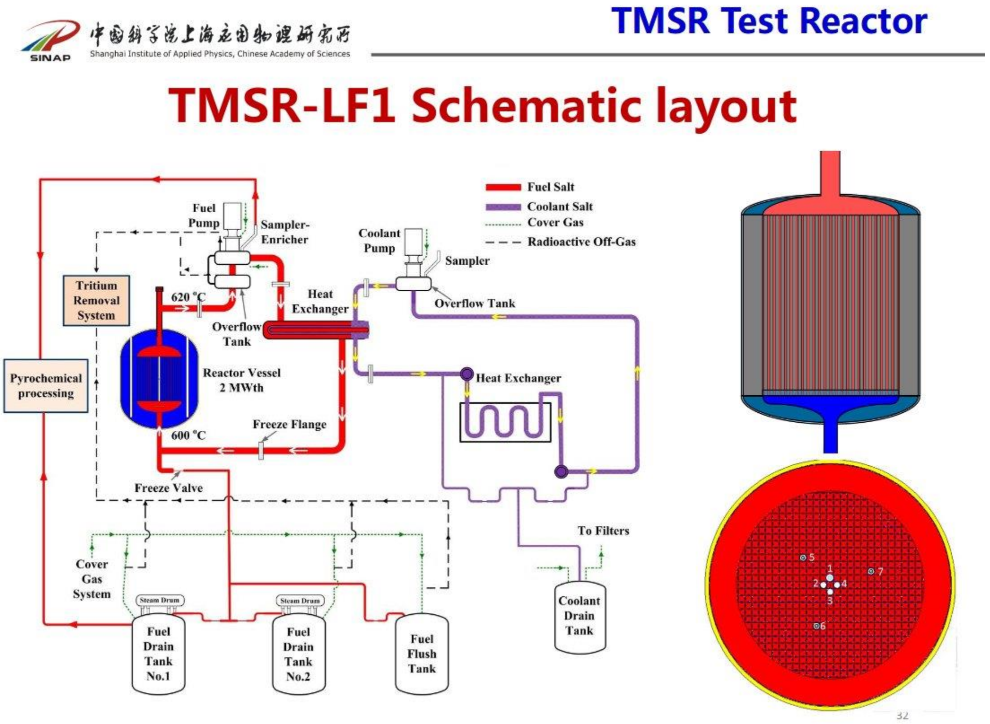
2.4 Thorium Fuelled MSR

One of the most promising MSR designs under development is the thorium fuelled molten salt reactor. Currently, China is evaluating a prototype thorium fuelled MSR that can become the first molten salt reactor to commercially produce electricity to the grid. Thorium fuelled MSRs promise clean and safe energy through fuel breeding without the risk of nuclear accidents or producing weapons grade plutonium.

In the Earth's crust, thorium is four times as abundant as uranium. Because thorium ore is extractable by open mining, thorium mining is easier than uranium mining. (OECD, 2015.) The thorium fuel cycle produces fewer actinides than uranium fuel, lowering the spent fuel's long-term radioactivity. As a nuclear fuel, thorium offers many appealing qualities. The thermal conductivity of thorium dioxide (ThO_2) is better in comparison to UO_2. It has a smaller thermal expansion and produces less fission gases. (Mathieu et al., 2006, p. 664-665.) The lack of a fissile isotope in natural thorium is a disadvantage. The thorium fuel consists of the fertile isotope ^{232}Th (^{230}Th 0.02 percent), and it is only fissile with fast neutrons. It operates at a faster neutron spectrum than ^{238}U which means it is best suited for thermal spectrum reactors because they convert ^{232}Th to fissile ^{233}U efficiently. Furthermore, a huge quantity of depleted uranium would ensure a long-term fuel supply for fast reactors using thorium fuel. Thorium fuel could increase reactor power efficiency and improve breeding, resulting in better resource use. To utilize thorium fuel cycles in practice, further research is required. (Anantharaman, Shivakumar and Saha, 2018, p. 119-121.)

China has risen to the forefront of MSR research due to significant investment from the Chinese government, which is increasingly investing in the technological development of sustainable and low emission energy generation solutions. The Chinese Academy of Science launched the “Thorium Molten Salt Reactor Nuclear Energy System” program in 2011 to develop the thorium molten salt reactor (TMSR) over the next two decades. The TMSR project is currently researching two prototypes of thorium molten salt reactors, a solid and a liquid fuelled one. (Serp et al., 2014, p. 314.)

China is working on two thorium fuelled molten salt breeder reactor designs. One for solid fuel (TMSR-SF) and the other for liquid fuel (TMSR-LF). The project is developing technologies using ultrafine graphite and nickel super alloys to improve corrosion control in the TMSR. In 2020, the construction of the first operational MSR test reactor TMSR-LF1 finished. The design of TMSR-LF1 is illustrated in Figure 5. It will demonstrate the thorium cycle in MSRs, and the research findings will be used to develop the succeeding 168 MWe demo reactor, which is expected to be finished by 2030 and capable of burnup of up to 330 GWd/tTh. (Hongjie Xu, 2018.)



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TMSR Test Reactor

TMSR-LF1 Schematic layout

Figure 5. TMSR-LF1 layout (SINAP, 2018)

India is developing its own TMSR technology. India hopes that its abundant natural thorium resources will ensure its long-term energy security. The Indian Molten Salt Breeder Reactor (IMSBR) design is created by the Indian Academy of Sciences in 2015. (Vijayan et al., 2015, p. 539.) The IMSBR is in the third stage of development, despite India’s significant investment in MSR development, the reactor requires significantly more research before it can be operational. A research project in Russia is focusing on liquid fuelled fluoride-based systems by developing the Molten Salt Actinide Recycler and Transmuter (MOSART), shown in Figure 6. MOSART is designed to finish the actinide fuel cycle and fuel the MSR exclusively with transuranic waste from spent fuel from Russia’s operating water-water energetic reactors. (Serp et al., 2014, p. 314.)

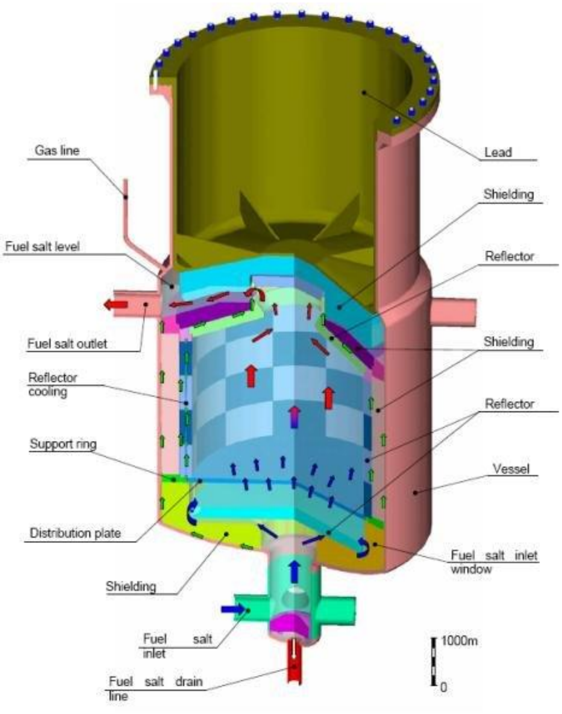

Figure 6. MOSART design (Gen IV International Forum, 2018)

3 Challenges with Molten Salt Reactor Technology

Molten salt reactor research stalled in the early 1970s because other nuclear reactor designs were further developed and had less technical challenges. Current research projects are using 21st century technology and scientific advancements to solve many of the technical challenges MSR researchers faced in the sixties. However, MSR technology still has challenges it needs to overcome before the technology is ready for commercial use.

3.1 Material Challenges

In comparison to conventional light water reactors, materials utilized in MSRs need to be developed and produced so they can tolerate high temperature and radioactive fuel salts. The response of materials to radioactive molten salts are unclear, and more research is needed to standardize materials that can be used in contact with molten salt fuel. Because MSRs function at near-atmospheric pressures, mechanical durability to withstand high pressures is not a significant concern. However, components must be engineered to always ensure the integrity of a highly radioactive primary loop with liquid fuel.

Material qualities must be evaluated at high operating temperatures, up to 900°C. Thermodynamic expansion and heat gradients are substantial in MSRs, limiting the lifetime of materials. Steel alloys in commercial use are prone to corrode in molten fluorides, making them unsuitable materials for MSR components. Chemically passive metals like gold, nickel and tin can withstand highly corrosive environments and could be suited for MSR components in contact with corrosive salts, but they are expensive, and a less abundant resource making construction of large structures difficult. Noble metal plating could offer an inert covering to protect the body of a less noble material from corrosion. (Singh et al., 2019, p. 223-228.)

In molten fluorides and chlorides, salt purity has considerable influence on corrosion rates because pure forms of fluoride and chloride are less corrosive than their very corrosive gas forms. To make molten salt corrosion experiments and comparisons easier, standardization is required. Impurities are a greater problem in single cycle reactors because when the fuel salt is treated, gaseous and non-soluble fissile products are only partially removed. (Serp et al., 2014, p. 315.) When soluble fission products stay in the salt, they can cause corrosion, especially when considerable heat gradients are present because corrosion accelerates at hot temperatures, and most alloys can only withstand temperatures up to 750°C (Ignatiev et al., 2013, p. 244). However, corrosion concerns may be solved with the right materials, redox monitoring, and management. (Serp et al., 2014, p. 315.)

Comprehensive studies to establish the best materials for molten salt reactors considering corrosion resistance and economical cost, have not been performed. Only few component level corrosion studies have been conducted using molten salts, even with the most researched fluoride salts. The vessel, primary and secondary loop pipes, heat exchangers, steam generating system, valves, and pumps are all critical components that require further material testing to fill current knowledge gaps before MSR technology can become feasible for commercial use (Singh et al., 2019, p. 222).

3.2 Safety Features

The safety of MSRs is examined and compared to that of traditional solid-fuelled LWRs. MSR designs aim to make the reactors safer than currently operational LWRs. Some features of MSRs that can improve their safety are that they do not reach high enough temperatures for meltdown, and they primary system operates at a low operating pressure, close to atmospheric pressure, even at hot temperatures, requiring no expensive containment or highly pressurized hot water. Chemical reactions, mechanical failures leading to radiation exposure of the environment, or explosions are less of a safety risk in MSRs than in currently operational LWRs. A comparison between LWR and MSR safety features is made in Table 2. MSR safety technology provides solutions to safety concerns that exist with other solid-fuelled LWRs, as well as eliminates the factors that caused accidents at Three Mile Island, Chernobyl, and Fukushima, and reduce the chance of catastrophic failures leading to severe nuclear accidents. (Elsheikh, 2013, p.64-69.) The safety concerns in MSR technology are not linked with the reactor design but are related to radioactive accountancy and licencing of liquid-fuelled reactors.

Table 2. Comparison of LWR and MSR safety features (Elsheikh, 2013)

Utility	**LWR**	**MSR**
Cooling water	Emergency water core cooling system	Unnecessary because of the fuel training system for emergency core cooling
Heat removal	Decay heat removal system	Decay heat removal system
Shut down systems	Control rods Boric acid injection	Control rods Fuel salt draining Fuel salt composition adjusting system

Radioactive material confinement (layers of defense)	1. Pellet 2. Cladding 3. Pressure vessel, pipes 4. Containment 5. Reactor building	1. None (liquid fuel) 2. None (liquid fuel) 3. Reactor vessel, pipes 4. Primary system confinement 5. Reactor building

Solid-fuelled reactors and liquid-fuelled reactors have unique needs regarding reactor safety. In the case of meltdown in MSRs, these measures include emptying the liquid fuel into tanks to avoid the reactor going critical, passively cooled tanks, limiting excess reactivity by on-line fuel processing and/or continuous fuelling. The existing regulatory framework was created for solid fuels. For liquid fuelled reactors, corresponding regulatory standards must be established. Adequate safety analysis, using current technologies, is necessary, followed by appropriate studies on the current safety concerns of MSRs. (Elsheikh, 2013, p. 69.) Since the radiation signatures from the use of thorium fuel cycle differ from the signatures of uranium fuel cycle, complications will arise when applying radiation safety procedures that are not adapted to thorium fuel. The current safety inspection methods like fuel pellet accounting and bulk radioactive material accounting from beginning to end of the nuclear fuel cycle, are based on ensuring the safety of currently operational nuclear reactors that use solid form of uranium/plutonium-based fuel. The bulk accounting approach and related tools have been developed for enrichment, and fuel manufacturing of solid uranium fuel. Bulk accounting procedures cannot be applied directly to liquid fuelled MSRs. (Kovacic et al., 2018, p. 1.)

MSR fuel is a homogeneous mixture of fuel, fission products, actinides, and coolant salts in a liquid form. Safeguards that take into account liquid molten salt fuels do not exist. Because MSR fuel is not contained in assemblies, item-based inventory and visual accountability of the salt fuel is not possible. Some MSR designs include online fuel processing, in which a portion of the radioactive material can be removed when the reactor is running. In addition, salt fuel is a high-temperature and radioactive solution, making developing safe measuring procedures and instruments difficult. (Kovacic et al., 2018, p. 6.)

MSR designs that use thorium fuel cycle will have different safeguarding needs than reactor designs that use other fuel cycles. The removal of protactinium from the reactor might result in the generation of pure ^{233}U, posing a safety hazard in the reactor or fuel processing unit.

There is the possibility of misusing the reactor by changing the fuel salt composition to increase ^{233}U production. (Kovacic et al., 2018, p. 7.) Overall, regulatory standards for the MSR need to be established, as well as quantitative safety analysis and thorough evaluation of possible accidents using simulations (Elsheikh, 2013, p. 69).

4 Analysis of Future Prospective

MSRs have performed well in feasibility studies compared to other Generation IV designs (Mohsin, Qureshi and Ashfaq, 2019, p. 6). The practical operation principle of MSRs was validated by the first experimental reactors at ORNL (World Nuclear Association, 2016). The concept of MSR design has been established during this experiment and modern technology and innovation is advancing MSR technical development. Licensing and material compatibility are the two major challenges in molten salt technology development. Currently, solid fuel reactors provide the basis of the licensing structure for new reactors (Mohsin, Qureshi and Ashfaq, 2019, p. 6.) This necessitates the implementation of new policies for liquid fuelled reactors (Elsheikh, 2013, p. 69). MSR technology is constantly developing due to significant international research interest. MSRs are being studied further in nations such as the United States, Russia, China, Japan, and France (Mohsin, Qureshi and Ashfaq, 2019, p. 6).

Generation IV MSR development aims to commercialize a nuclear power technology that has improved efficiency, sustainability, safety, and economics. Projects like the Chinas TMSR-LF1 test reactor and MSR research done by the ORNL, Moltex Energy’s concept and Thorcon Power concept are in advanced development phases and produce promising results in feasibility studies of energy generation using MSR technology. Reactor concepts by Terrestrial Energy, Elysium Industries, and Thorcon Power are constructed of modular parts that can be easily transported, replaced, maintained, and mass-produced cutting construction and maintenance costs and time. If the challenges related to MSR materials and radioactive material accounting are solved modular MSR reactors are a viable option for generating low emission energy efficiently, sustainably, and safely in the future. Reactor concepts by Kairos Power, Moltex Energy, and Thorcon Power are designed to have flexible energy output making them a lower emission alternative for natural gas to generate peak load electricity when renewable sources cannot meet the electricity demand. Considering the demand for low emission energy solutions to supplement renewable energy sources, these MSR concepts could fill that gap in the energy system.

Only time will tell if MSRs will be part of future energy production. Due to the variety of independent and national developers in MSR technology and international cooperation between research institutions, the technology is constantly developing. With 21st century technology and science many of the problems in MSR technology researchers faced in the 1960s and 70s can be overcome. Still some major challenges like material corrosion in MSRs remains unsolved, despite companies developing MSRs predicting long lifetimes for their reactor designs and few of them addressing the problem of material corrosion. A concern that exists with all nuclear power plants is the handling of the radioactive waste. Although most Generation IV MSR designs have higher fuel burn up than currently operational nuclear power plants and some have incorporated fuel recycling solutions, a solution for storage and processing of radioactive waste is needed. The waste management solutions of many MSR designs remain unclear and need further research.

There has been a lack of research on which of the existing safety measures can be used for MSRs, which could be modified, and what new measures need to be created. Research that combines safeguarding concepts and methodologies, as well as technological development, with knowledge of the various fuel cycle and reactor alternatives has not been conducted. Given that the liquid fuel cycle is significantly different from solid fuel cycles, special attention should be paid to how nuclear material inventory can be performed considering the various MSR designs and fuels, as well as what nuclear material inventory methods and technologies need to be developed to ensure the safety of MSR technology.

The prospects of MSR technology do not only rely on engineering and research to make it feasible for commercial use, but many other factors will decide if MSRs will ever be a part of commercial energy production. Political, economic, and social factors determine the funding and policies that will decide the fate of most research projects. Significant funding is needed to build test plants to establish the feasibility of the technology in practice and regulatory policies need updating to consider the variation in reactor designs and fuels they use.

5 Conclusion

The research set out to investigate the current state of MSR technology, challenges it is facing, and to analyse the outlook of the technology. Through an overview of the current development in the field of MSR research an understanding of different technological developments in Generation IV MSR designs, including thorium fuelled MSRs and small modular MSRs was achieved. The outlook of MSRs in the commercial energy generation depends on many factors, but the feasibility of the technology relies on researchers solving the current challenges in MSR development. The two major challenges in the MSR development that need additional research are preventing material corrosion in materials in contact with fuel and coolant salts and establishing procedures and licencing that is specific to liquid fuels to ensure accurate accounting and safeguarding of radioactive materials in liquid fuels. Many Generation IV MSR designs show promise in improving the efficiency, sustainability, safety, and cost competitiveness of nuclear power plants. When commercialized MSRs can provide low emission base or peak load electricity to lower emissions from energy generation and ensure future energy security.

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