

Report for the All Party Parliamentary Group on Thorium Energy

Thorium-Fuelled Molten Salt Reactors

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Summary

Thorium-fuelled Molten Salt Reactors (MSRs) offer a potentially safer, more efficient and sustainable form of nuclear power. Pioneered in the US at Oak Ridge National Laboratory (ORNL) in the 1960s and 1970s, MSRs benefit from novel safety and operational features such as passive temperature regulation, low operating pressure and high thermal to electrical conversion efficiency. Some MSR designs, such as the Liquid Fluoride Thorium Reactor (LFTR), provide continuous online fuel reprocessing, enabling very high levels of fuel burn-up. Although MSRs can be fuelled by any fissile material, the use of abundant thorium as fuel enables breeding in the thermal spectrum, and produces only tiny quantities of plutonium and other long-lived actinides.

Current international research and development efforts are led by China, where a \$350 million MSR programme has recently been launched, with a 2MW test MSR scheduled for completion by around 2020. Smaller MSR research programmes are ongoing in France, Russia and the Czech Republic. The MSR programme at ORNL concluded that there were no insurmountable technical barriers to the development of MSRs. Current research and development priorities include integrated demonstration of online fuel reprocessing, verification of structural materials and development of closed cycle gas turbines for power conversion.

1. Thorium

Thorium is a mildly radioactive element, three times as abundant as uranium¹. There is enough energy in 5000 tons of thorium to meet world energy demand for a year². Reserves of thorium are widely dispersed around the world with large deposits in Australia, the USA, Turkey and India. China also has substantial thorium reserves, especially within its rare earth mineral deposits in Inner Mongolia. In Europe, Norway has 132,000 tons of proven reserves, 5% of the world's total³.

Thorium is not fissile and therefore cannot sustain a nuclear chain reaction on its own. However, it is fertile, which means that if it is bombarded by neutrons from a separate fissile driver material (Uranium-233, Uranium-235 or Plutonium-239) or from a particle accelerator it will transmute into the fissile element Uranium-233 (U-233) which is an excellent nuclear fuel.

The thorium fuel cycle has been successfully demonstrated in over 20 reactors worldwide⁴, including the UK's 'Dragon' High Temperature Gas Reactor which operated from 1966 to 1973.

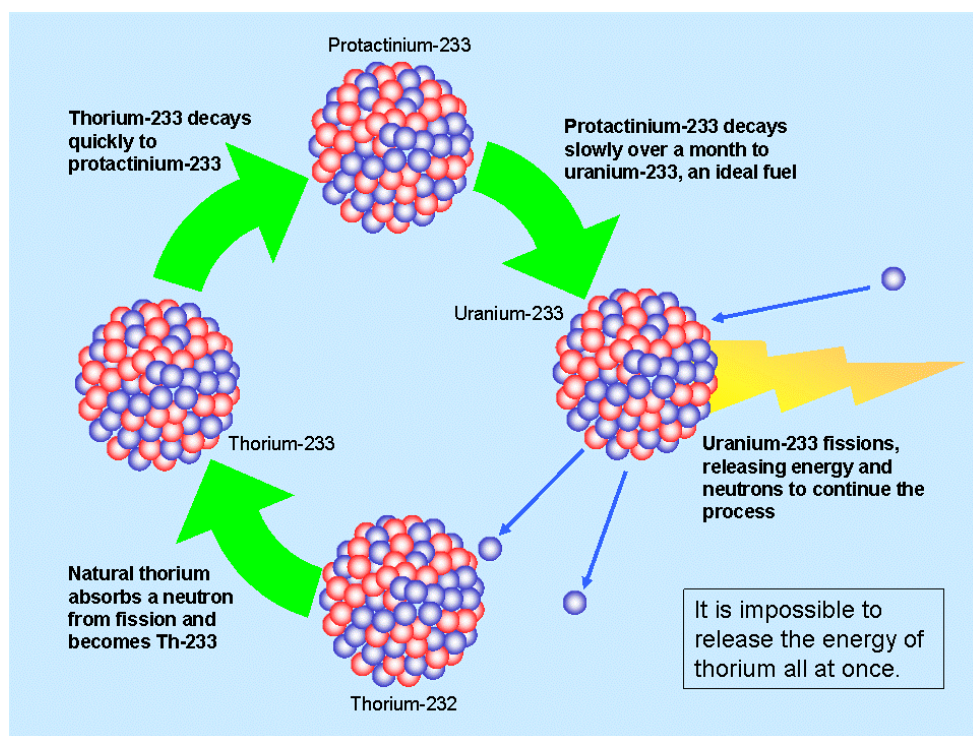


Figure 1: The Thorium Fuel Cycle

¹ World Nuclear Association website, '[Thorium](#)'.

² Thorium Energy Association, 'Towards an Alternative Nuclear Future', 2010, p.11.

³ Norwegian Ministry of Petroleum and Energy, 'Thorium as an Energy Source: Opportunities for Norway', 2008, p. 20.

⁴ For a full list of thorium-fuelled reactors see International Atomic Energy Agency, 'Thorium Fuel Cycle: Potential Benefits and Challenges', May 2005, p. 4.

2. History of the Molten Salt Reactor (MSR)

The first Molten Salt Reactor (MSR) was constructed at Oak Ridge National Laboratory (ORNL) in 1954 as part of the US Air Force's nuclear propulsion programme. The programme aimed to design and build a nuclear bomber that could fly continuously over the Soviet Union without having to land to refuel. The Aircraft Reactor Experiment (ARE) resulted in a 2.5MW reactor intended to power such an aircraft. The ARE used a molten fluoride salt as fuel (with uranium as the fissile component) and operated successfully for 100MW-hours over a nine day period at temperatures up to 860°C. Although the concept of a nuclear-propelled bomber was eventually abandoned, the successful testing of this first MSR laid the research foundations for the development of the technology for civil purposes.

From the mid-1950s under the directorship of Alvin Weinberg, ORNL began working on thorium-fuelled MSR power station designs. Initial work focussed on one-and-a-half fluid designs in which the fuel salt in the core contains both fissile and fertile material, while a surrounding blanket salt contains only thorium. As thorium is chemically similar to rare-earth fission products, it is hard to process out those fission products from the fuel salt without also removing the thorium. The early 1960s saw the development at ORNL of two-fluid designs which sought to overcome this problem by keeping the thorium separate from the fuel salt. To achieve this, the two-fluid designs employed a graphite barrier between the core and blanket salts. The separation of fluids necessitated complex plumbing design involving multiple graphite tubes.

During the life of the ORNL molten salt reactor programme the plumbing design problem was never resolved, and consequently single-fluid designs were prioritised. The Molten Salt Reactor Experiment (MSRE) which ran from 1965 to 1969 involved the construction and successful operation of a 7.4MW reactor fuelled by molten salts containing uranium and plutonium. The single-fluid 'kettle' design MSRE reactor ran without fault for the four year life of the experiment.

ORNL research in the 1960s also produced a design for a Molten Salt Breeder Reactor (MSBR) which would use thorium as the fertile component of the liquid fuel. The reactor would breed its own fuel by transmuting Th-232 into fissile U-233. The MSBR was conceived as a two-fluid design with a graphite moderator. In 1968, due to the development of Liquid Bismuth Reductive Extraction⁵, and in the absence of a solution to the two-fluid plumbing problem, the two-fluid design was abandoned. In 1972, ORNL proposed an 11-year, \$350 million development and construction plan for a demonstration MSBR. The US government's Atomic Energy Commission (AEC) rejected

⁵ This technique enables removal of rare earth fission products without also removing thorium in single-fluid systems. The technique works more simply and effectively in two-fluid systems.

the proposal, after carrying out its own assessment of the MSBR which cited materials corrosion and tritium control as major technical barriers to the reactor's development⁶.

In January 1973, the AEC withdrew funding for the MSBR programme. Despite this, small amounts of government funding were secured for intermittent work on the MSBR up until 1976 when the AEC finally cancelled the MSBR programme citing budget constraints. MSR research and development at ORNL had, in fact, demonstrated that the technical barriers cited by the AEC in their 1972 MSBR assessment could reasonably be expected to be overcome with continued work (See Section 7). It is likely that the ORNL MSR programme was cancelled because the US government had decided to divert all funding to the development of Liquid Metal Fast Breeder Reactors (LMFBRs)⁷. Work on LMFBRs pre-dated the MSR programme and considerable government money had already been invested in the technology. LMFBR research was taking place at numerous government laboratories, while the MSR was the sole interest of ORNL.

A very small research program on MSRs continued beyond 1976 focussing on proliferation-resistant designs. This period produced various designs for the Denatured Molten Salt Reactor (DMSR) including a simplified design without fuel processing known as the '30 Year Once Through Design'. This design runs on low-enriched uranium (U-235 or U-233 from thorium) unsuitable for weapons applications. The reactor would operate over a thirty-year lifespan with no need for removal of fission products or replacement of the graphite moderator.

The intergovernmental research and development organisation Generation IV International Forum (GIF) helped to revive interest in MSRs in 2002 when it chose the MSR as one of the six most promising nuclear reactor designs for future development. Established in 2001, GIF supports designs on the basis of sustainability, safety, economics and proliferation resistance. MSR work within GIF is led by the European Atomic Energy Community (EURATOM) and France, with Russia and the US participating as observers. China and Japan have also taken part as temporary observers.

⁶ Atomic Energy Commission (AEC), 'An Evaluation of the Molten Salt Breeder Reactor', September 1972, p. 52.

⁷ MacPherson, H G, 'The Molten Salt Reactor Adventure', Nuclear Science and Engineering, 1985, Vol. 90, pp. 374-380.

3. Key Safety and Operational Features of MSRs

Passive Temperature Regulation - The MSR's large negative temperature coefficient means that regulation of the reactor's temperature is passive. There is no need for control rods⁸ or an active cooling system. The molten salt expands as a result of the heat generated by fission, which slows the rate of fission. The reduction in fission heat cools the salt, which in turn leads to an increase in the rate of fission. In other words, as the reactor temperature rises, the reactivity decreases. The reactor thus automatically reduces its activity if it overheats. Conversely, if more power is required of the reactor, more heat is drawn out. The returning colder salt increases reactivity and power levels resulting in automatic load following.

An MSR can only overheat if the circulation of the molten salt is disrupted as a result of a loss of power, thereby preventing heat removal from the core. If that should happen, the build-up of excess heat melts a freeze plug of solidified salt at the bottom of the reactor, allowing the molten salt to drain into a separate tank. Once in the tank, the fission reaction stops and the liquid fuel cools down and becomes an inert solid mass. This is an entirely passive process requiring no external power source.

Low Operating Pressure - In a Light Water Reactor (LWR)⁹, water must be kept at high pressure¹⁰ to raise its boiling temperature. Most MSR designs operate at temperatures between 650°C and 750°C, while molten salt boils at around 1400°C, which means that reactor pressure remains at atmospheric levels, thus eliminating completely the risk of a pressure explosion. With no need for large pressure vessels and other elaborate containment structures, the cost and size of an MSR could be substantially less than an LWR.

If the ceramic fuel pellets in a LWR melt down, gaseous fission products can be released, and in the event of a steam explosion, these products can be carried and dispersed into the environment by wind and water. Given the low pressure in an MSR, if molten salt fuel should leak from the reactor, it simply spills onto the reactor room floor, where it solidifies on contact with the ground becoming an inert mass. The fissile fuel remains locked inside the mass and can be reused.

⁸ In a Light Water Reactor (LWR), control rods are moved in and out of the reactor core to control the level of reactivity. The rods are made of neutron-absorbing elements such as boron and hafnium. When the rods are inserted into the reactor, neutrons are absorbed and are thus prevented from splitting atoms. This decreases the amount of fission taking place. When the rods are removed the fission reactions increase.

⁹ The vast majority of nuclear power stations currently operating worldwide are Light Water Reactors (LWRs) which use solid uranium-235 (U-235) as the nuclear fuel.

¹⁰ Usually between 150 and 160 bar.

Benefits of Molten Salts - As fuel in an MSR is already in liquid form, it cannot melt down¹¹, as solid fuel rods in a LWR can. The liquid fuel can be quickly drained from the reactor and left to cool in dump tanks.

As molten fluoride salt is heavy, it cannot be dispersed by wind. In the very unlikely event of a terrorist attack or missile strike on the reactor, spilled fuel would only create a small contamination zone in the immediate surroundings of the reactor. To prevent leaching of radioactive material into soil or groundwater following a spill, MSRs can be built in protective bunkers which create an impervious barrier between any spill and the surrounding land.

Fission products which form stable fluorides remain in the salt in the case of a leak or accident, and in most MSR designs, insoluble or volatile fission products are continuously removed during operation.

Molten salts are effective coolants with high heat capacity which means that components such as pumps and heat exchangers can be compact.

Small Modular Designs Possible - MSRs can be small and modular (producing up to 300MW) which would suit power needs in remote locations, factories and military bases. Small Modular Reactors (SMRs) can be built in a central factory and assembled on site. It is also possible to combine SMRs to form a larger power station if required. A production line approach has the potential to generate economies of scale and result in quick delivery of a functioning reactor.

In addition, as MSRs do not require water to operate, they can be constructed near to or within urban areas, reducing the need for transmission infrastructure. MSRs could also be constructed adjacent to industrial sites so that waste heat from the reactor can be used for heat-intensive processes such as desalination, or the production of aluminium, cement, ammonia and synthesised fuels.

¹¹ A meltdown occurs when the core of a nuclear reactor overheats causing the solid fuel rods to melt and leak into other parts of the reactor. If a pressure explosion should then occur, the molten radioactive fuel (and toxic fission products) could breach all containment structures and be dispersed into the environment.

4. Types of MSR

4.1. Two Fluid MSRs

Interest in a two-fluid iteration of the MSBR, the LFTR, has grown over recent years underpinned by the campaign work of Kirk Sorensen of Flibe Energy¹², and the publication of popular science title 'SuperFuel: Thorium, The Green Energy Source for the Future' by US journalist Richard Martin¹³.

In 2008, a solution was proposed to the plumbing problem which led ORNL to abandon its two-fluid designs. Nuclear physicist David Leblanc has a patent pending on an alternative plumbing design which simplifies the complex series of graphite tubes separating the thorium blanket from the core present in ORNL designs¹⁴.

4.1.1. Case Study Design: Liquid Fluoride Thorium Reactor (LFTR)

The reactor core contains fissile fuel (U-233, U-235 or Pu-239 in liquid fluoride form) held in a graphite container which acts as a neutron moderator¹⁵. The core is surrounded by an outer vessel, the blanket, which contains thorium dissolved in a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF₂) known as FLiBe (see Fig.4). When the fuel in the core fissions, neutrons are released which penetrate the walls of the core and bombard the surrounding blanket of thorium causing it to transmute into U-233. The U-233 is transferred to the core and new thorium is added to the blanket.

The LFTR contains two separate piping loops. The first loop (see Figure 2, green loop) carries the irradiated liquid thorium into a decay tank where the U-233 can be moved to the inner core. The second loop transfers the heated U-233 molten salt from the inner core to the heat exchanger which drives a turbine which generates electricity. The U-233 salt is then transferred back to the reactor core to continue fissioning.

The amount of fuel the reactor breeds is equal to the amount that it consumes. To keep the fission reaction going, thorium must be added to the reactor at the same rate that it generates and fissions uranium.

The concentration of thorium fuel in the blanket can be adjusted at any time, which provides further control over the level of reactivity in the core.

¹² <http://flibe-energy.com/>

¹³ <http://superfuelbook.com/>

¹⁴ [US Patent Application 20120183112 - Molten Salt Nuclear Reactor](#)

¹⁵ To increase the chance that nuclear fission will take place, the speed of neutrons can be reduced so that they can be absorbed by the nuclei of a fissile material. The substance that brings about this reduction in speed is known as a neutron moderator. Common moderators include water and graphite. Molten salt itself also has a moderating effect.

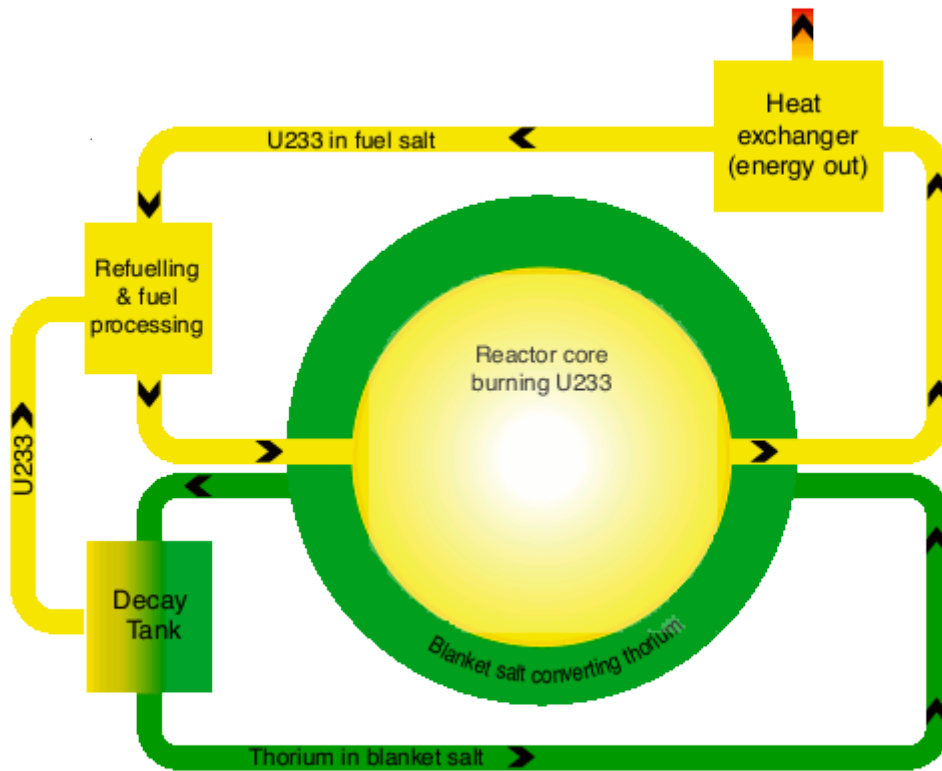


Figure 2. The LFTR fuel cycle. Image: www.thorium.klimabedrag.dk

Nuclear reactors produce two kinds of radiotoxic waste - fission products¹⁶ and long-lived transuranic elements¹⁷ such as plutonium. Fission products such as Xenon absorb neutrons and slow down the fission reaction, reducing the efficiency of a reactor. After a few years the solid fuel rods in an LWR are rendered unusable by the buildup of these neutron absorbing fission products, thus preventing the bulk of the energy in the fuel from being exploited. When this happens, the reactor must be shut down so that refuelling can take place. The hazardous spent fuel from a LWR must be safely stored for around 10,000 years.

As fission products can be removed from a LFTR during operation, the reactor can fission almost all of its fuel including its own transuranic products. This means that LFTRs produce almost no long-term waste and very little short-term waste, while achieving near total burn up of the fuel. For this reason, the energy produced by one ton of thorium in a LFTR is equivalent to that produced by 250 tons of uranium in an LWR (see Fig 3).

In a LFTR valuable fission products such as Xenon and Krypton gas can be removed and sold for medical, industrial and scientific research purposes. The molten salt fluid is pumped from the reactor into a chemical processing unit which separates the fission

¹⁶ When the nucleus of a fissile material undergoes fission, it splits into two smaller nuclei. These smaller nuclei are known as fission products.

¹⁷ All elements after Uranium in the periodic table are known as transuranics, and are characterised by their instability and propensity to decay into other elements.

products and transfers them to armoured storage casks. The small volume of fission products with no market value can be safely stored in casks, where most will become inert within 30 years. Only 17% of fission products from a LFTR have long half-lives and these will require safe storage for up to 300 years.

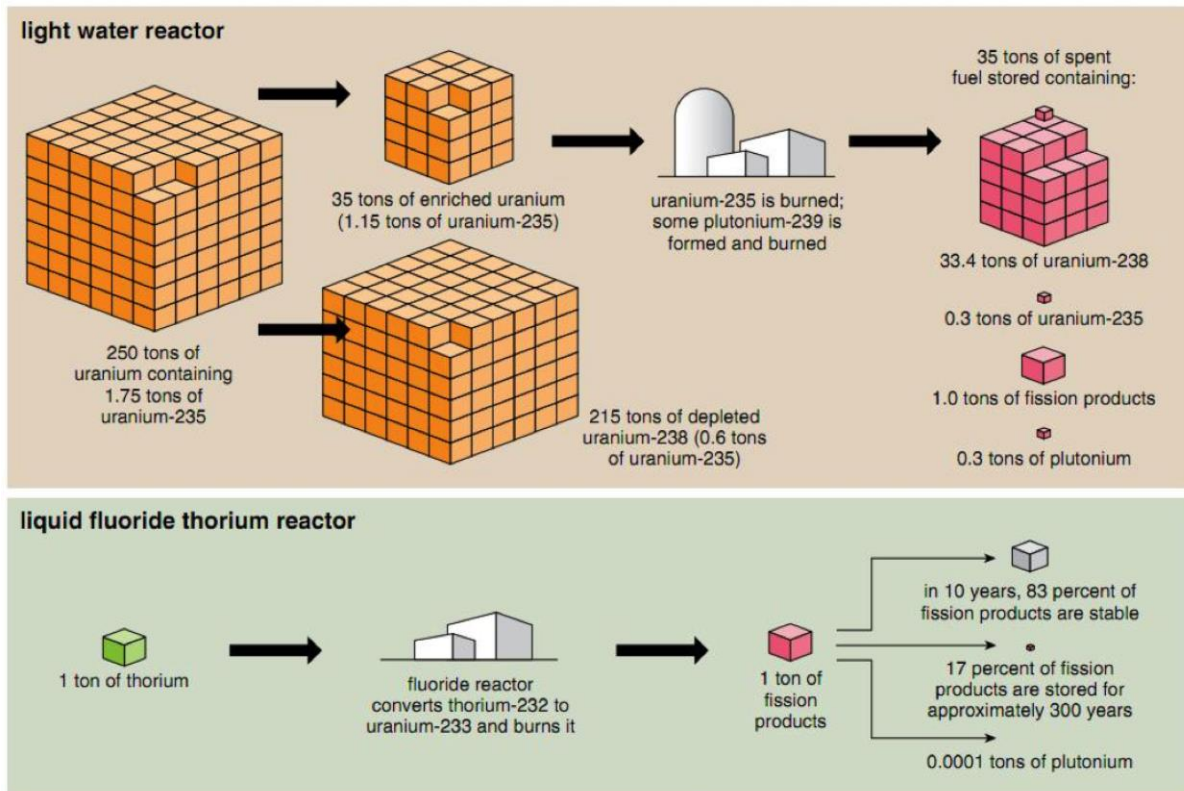


Figure 3. Comparison of Fuel and Waste Quantities from a 1GW LFTR and 1GW LWR. Image: Hargraves & Moir.

4.2. Single Fluid MSRs

Single fluid MSRs combine both fertile thorium and fissile material in one salt. The two MSRs constructed at ORNL were both single fluid systems. ORNL focussed on single fluid systems to avoid the plumbing complexities associated with two fluid reactors.

4.2.1. Case Study Design: Denatured Molten Salt Reactor (DMSR) '30 Year Once Through'

The DMSR was designed in the late 1970s at ORNL as part of a program to develop proliferation-resistant reactors. Denatured fuel contains fissile fuel diluted with at least 80% U-238 which renders the fissile component unsuitable for weapons applications. The DMSR is started from a mix of low-enriched uranium 235 and thorium contained in

a single fluid. Neutrons in the core fission the uranium and are absorbed by the thorium. This causes the thorium to transmute into U-233, which is then fissioned. The U-238 in the core also absorbs neutrons, transmuting into fissile Pu-239.

As the DMSR was designed for simplicity without continuous fission product removal, it does not make enough of its own fuel to self-sustain, so a fresh mixture of around 80% U-238/20% U-235 must be continuously added to the fuel salt. The DMSR is thus fuelled, at least partly, by uranium, but a majority of its energy would come from the thorium to U-233 chain.

The DMSR's graphite core is larger and thus less power dense than the earlier MSBR. This enables the graphite moderator to last for the lifetime of the reactor¹⁸.

Gaseous fission products and noble metals are continuously removed, but the remaining fission products are left in the molten salt for the full 30 year lifetime of the reactor. As there is no online processing of the salt, the DMSR cannot fission all of the uranium in the core, as the LFTR can. Despite this, the DMSR is a much more efficient burner of uranium than an LWR.

At the end of a DMSR's 30 year life, the salt can be removed and stored as waste, resulting in overall uranium usage one third the size than that of a LWR. Alternatively, the salt can be reprocessed to extract any useful uranium, before being stored, which results in a lifetime uranium usage one sixth that of a LWR. Plutonium and other transuranics can also be removed and recycled into the next batch of salt. This results in a very low long-lived waste profile comparable to that achieved by breeder reactors such as the LFTR.

Although the lack of continuous fuel processing reduces the fuel burn-up potential, it offers the advantage of much simpler research and development requirements compared to breeder designs such as the LFTR. ORNL believed that an operating DMSR could be developed in 15 years¹⁹.

¹⁸ Graphite deteriorates as a result of neutron irradiation. The MSBR and LFTR designs require periodic replacement of graphite because of their smaller, higher power density core designs.

¹⁹ Oak Ridge National Laboratory (ORNL), '[Development Status and Potential Program for Development of Proliferation-Resistant Molten-Salt Reactors](#)', March 1979, p. 108.

5. Thermal and Fast Spectrum Reactors

The terms 'thermal' and 'fast' refer to the speed of neutrons in a reactor. Thermal neutrons move at around 2000m/s, while fast neutrons move at around 9000 km/s. In the fast spectrum the fission cross-section (the probability that neutrons will fission fissile atoms) is small. When neutrons are released from fissioning atoms they tend to be travelling at high speed. In the same way that it would be hard to take a motorway exit if you were travelling at 300mph, so neutrons generally do not hit the target and split atoms when moving fast.

In the thermal spectrum, the speed of neutrons is reduced by the presence of a neutron moderator, thus increasing the fission cross-section. Common moderators include water, helium and graphite. Neutrons lose thermal energy when they bounce off the nuclei of the atoms in the moderator which slows them down. This process is known as thermalising.

Uranium consists of fissile isotope U-235 (0.7%) and fertile isotope U-238 (99.3%). With a thermal spectrum, even this natural uranium can support a chain reaction in reactors such as the CANDU or Magnox, while LWRs require only modest enrichment of 3% to 5% U-235 to operate. While operating they also produce and partially burn off Pu-239 produced when U-238 absorbs a neutron. In the thermal spectrum however, Pu-239 is an inefficient fuel, emitting on average less than two neutrons for every one absorbed. Conversely in a fast spectrum, while a far greater fraction of fissile material must be present, the Pu-239 produced from U-238 is a far more efficient fuel and can allow operation as a breeder where more fissile fuel is made than consumed. This is not possible for U-238 to Pu-239 in the thermal spectrum.

20 fast reactors have been built since the 1950s, accumulating 400 reactor years of operating experience²⁰. However, commercial roll-out of fast reactors has yet to occur due to technical and materials problems. The strong neutron flux in the fast spectrum corrodes reactor materials very quickly, so the success of fast reactors will depend on the development of new, more resilient construction materials. In addition, as it is less likely that a fission chain reaction will occur in the fast spectrum, a fast reactor needs 3 to 4 times as much fissile material to start up than a thermal reactor, which substantially increases start-up costs.

5.1. Thorium-Fuelled Molten Salt Fast Reactors

Unlike U-238, thorium can readily be consumed in its entirety in a thermal reactor. ORNL's MSR work focussed only on thermal spectrum designs, and the current Chinese MSR programme is also dedicated to thermal spectrum reactors. Several conceptual

²⁰ World Nuclear Association website, '[Fast Neutron Reactors](#)'.

fast-spectrum MSR (FS-MSR) designs are being worked on in France, Russia and the Czech Republic (see Section 6).

FS-MSRs may eventually offer certain advantages over thermal spectrum designs. Fuel reprocessing should be simpler in FS-MSRs as fission products do not capture neutrons as often in the fast spectrum as in the thermal spectrum, therefore reducing the quantity of fuel which needs to be processed. ORNL's two-fluid MSBR design required 400 litres a day of liquid fuel to be processed, while the fuel processing volume in the French MSFR design is ten times less at between 10 and 40 litres a day²¹. With this simpler processing requirement, the processing plant can be much smaller in an FS-MSR than in a thermal spectrum MSR. Also, because of the absence of a moderator in FS-MSRs, the problem of graphite deterioration is avoided²².

Unlike thermal spectrum MSRs however, no FS-MSR design has ever been built, and there are no plans anywhere in the world to build one. The current state of FS-MSR technology development is immature²³. As thorium can be fully consumed in the thermal spectrum, there are at present few relative benefits in developing thorium-fuelled FS-MSRs. In the long term²⁴, FS-MSRs could help expand the fissile resource base by enabling uranium-to-plutonium breeding, as well as consuming actinides from spent LWR fuel.

²¹ Sustainable Nuclear Energy Technology Platform (SNETP), Strategic Research Agenda Annex 'Molten Salt Reactor Systems', January 2012, p. 4.

²² In ORNL's MSBR design, the graphite moderator needs to be replaced approximately every four years. ORNL's later DMSR design extended the lifetime of the graphite moderator to thirty years.

²³ Oak Ridge National Laboratory (ORNL), 'Fast Spectrum Molten Salt Reactor Options', July 2011, p. 3.

²⁴ The French MSFR design team have developed a scenario envisaging commercial roll-out of MSFRs in the 2070s.

6. International MSR Research and Development Efforts

6.1. China

In January 2011, the Chinese Academy of Sciences (CAS) announced a 5-year government-funded \$350 million research and development (R&D) programme into thorium-fuelled MSRs. The Shanghai Institute of Applied Physics (SINAP) is coordinating the programme, which will be carried out at universities across China.

Two reactor designs will be developed simultaneously- a molten-salt cooled reactor known as a Fluoride-Salt-Cooled High-Temperature Reactor (FHR), and a thorium molten-salt fuelled and cooled reactor (TMSR). Development of the FHR is being prioritised as the technical challenges relating to this reactor are considered easier to resolve (see 6.1.1.). A 2MW research FHR is scheduled to be completed by around 2017. By around 2020, a 2MW research TMSR is scheduled for completion. For both reactor designs the intention is to follow up the 2MW research reactors with 10MW pilot reactors, and then 100MW demonstration reactors. Funding for these larger reactors depends upon the success of the initial 5-year programme. In the longer term, the programme aims to build both a 1000MW FHR and a 100MW MSR demonstration reactor in the 2030s.

The Chinese programme employs over 350 full-time staff and is the world's only comprehensive MSR R&D test facility, covering all aspects of MSR development including reactor design, high-temperature molten salt loops, pyroprocessing of spent fuel, safety and licensing, and high-temperature materials. The number of personnel involved in the programme is projected to grow to 750 by 2015 and 1500 by 2020²⁵.

6.1.1. Fluoride-Salt-Cooled High-Temperature Reactor (FHR)

Both the US and China are pursuing FHR programmes and are collaborating on the research and development effort. The US Department of Energy (DOE) started a multi-university research programme in January 2012 and US experts have been participating in a design review of the Chinese FHR design. US and Chinese research teams plan to independently develop predictive models to understand the behaviour of the Chinese design. There are also plans for US research students to work in China on the FHR programme. The US programme aims to develop a conceptual design for a 20MW test reactor and a pre-conceptual design for a 200-900MW commercial prototype reactor.

Molten-salt cooled reactors enjoy some of the safety and operational benefits associated with molten-salt fuelled reactors. As FHRs run at atmospheric pressure, large pressure

²⁵ Hongyie, Xu, '[TMSR Project at SINAP](#)', International Thorium Energy Organisation Conference, Shanghai, October 2012.

vessels are not required and unlike water-cooled reactors, there is no steam in the core which eliminates the risk of a pressure explosion. High operating temperatures mean that FHRs, like MSRs, can make use of efficient Brayton cycle gas power conversion. The high heat capacity of the molten-salt coolant means that the reactor can be compact and relatively cheap to construct.

In the pebble-bed FHRs favoured by the Chinese, the fissile fuel is contained within golf ball size pebbles, known as tristructural-isotropic (TRISO) fuel. The pebbles consist of a fissile fuel kernel surrounded by four layers of carbon and ceramic material. The layers retain fission products within the pebble and enable the pebble to withstand high temperatures without cracking, thus avoiding the possibility of meltdown. The pebbles are immersed in the molten salt coolant and move slowly upwards through the core. When they reach the top they are removed. If fissile fuel remains in them, they are reinserted at the bottom of the core. If they are spent, then they are transferred to secure storage facilities, and fresh replacement pebbles are inserted into the core. Operational experience with TRISO fuel has been developed over the past 20 years in Germany, China and the US. Production of TRISO fuel already takes place in China to fuel prototype high temperature reactors at Tsinghua University²⁶.

Given the relatively advanced state of FHR development, the US and Chinese research programs believe that FHRs will be commercially ready sooner than MSRs, perhaps within 20 years, and therefore priority is being given to FHR work, hence the projected three-year gap between the 2MW Chinese test FHR and the subsequent test MSR. The development of FHRs will benefit MSR development, as the R&D work on high temperature salt systems and the Brayton power conversion cycle is equally applicable to MSRs and represents about half of the R&D challenges relating to the development of the MSR.

6.2. France

The French National Centre for Scientific Research (CNRS) has funded a molten salt reactor programme at its Grenoble-based Laboratory of Subatomic Physics and Cosmology (LPSC) since 1997. The LPSC has developed a conceptual 3000MWth fast-spectrum MSR design known as the Molten Salt Fast Reactor (MSFR). The MSFR is a two-fluid core and blanket design, which can be started with an initial fissile load of U233, U235 or Pu239. The fast neutron spectrum allows unprocessed transuranics to be used as fuel, and reduces the daily fuel salt reprocessing volume to around 40 litres, as opposed to 400 litres in a LFTR, thus requiring only a small reprocessing structure. The design also ensures a strongly negative temperature coefficient, a feature integral to MSRs but found by the LPSC not to be present in ORNL's MSBR design.

²⁶ Tsinghua University, Institute of Nuclear and New Energy Technology website, '[HTR-10](#)'.

In 2008, the Generation IV International Forum (GIF)²⁷ chose the MSFR as their default MSR concept. Work on the MSFR has also received EU funding through the Evaluation and Viability of Liquid Fuel Fast Reactor Systems project (EVOL). The objective of EVOL is to produce a more detailed MSFR design by the end of 2013.

6.3. Czech Republic

The Czech government has funded MSR research at the Nuclear Research Institute Rez (NRI Rez), just north of Prague, since 1997. Between 1997 and 2003, NRI Rez's SPHINX (SPent Hot fuel Incinerator by Neutron flux) project focussed on a conceptual design for a Molten Salt Transmuter Reactor (MSTR) fuelled by plutonium and minor actinides recovered from spent LWR fuel.

From 2004 to 2008 the SPHINX project produced a conceptual, fast spectrum, thorium-fuelled MSR breeder design, with accompanying research covering theoretical and experimental work in materials, fuel cycle chemistry and molten salt thermohydraulics. SPHINX produced a new nickel alloy to replace Hastelloy-N, known as SKODA-MONICR. A separate project running from 2006 to 2011 covered reprocessing issues such as fluoride separation processes relating to the thorium-uranium fuel cycle and the separation of transuranics.

In September 2011, the US Department of Energy (DOE) announced a bilateral US-Czech nuclear research and development programme. The programme includes work on molten salt coolant. Coolant salt originating from ORNL is being tested at the Czech nuclear test facility at Rez. To contribute towards the joint effort, a consortium of Czech companies and institutions including NRI Rez are pursuing a three-year R&D project (ending 2015) into FHRs and MSRs, covering theoretical and experimental activities in reactor physics, fuel cycle processes, molten salt thermohydraulics and structural material development.

6.4. Russia

Russia's National Research Centre, the Kurchatov Institute, is pursuing the Minor Actinides Recycling in Salts (MARS) project, planned to run until the end of 2014²⁸. The MARS team have developed the conceptual Molten Salt Actinide Recycler and Transmuter (MOSART). This is a non-moderated, fast spectrum design using plutonium and minor actinides from spent LWR fuel as fuel to produce 2400MWt. It uses a sodium-

²⁷ GIF is an international project to coordinate research and development efforts on advanced nuclear reactor designs.

²⁸ MARS project funding for the period 2010 to 2012 amounted to 35 million rubles, equivalent to around \$400,000 a year.

lithium-beryllium fluoride salt chosen for its high solubility for actinides. MOSART has a peak operating temperature of 720°C.

A second design using thorium as fuel is being worked on. The Hybrid MOSART system is a fast spectrum two-fluid core and blanket reactor which would convert thorium into U-233 either to generate electricity directly, or to be extracted and used as fuel in an MSFR, as per the French design.

In 2011, the MOSART project team carried out studies on a variety of molten salt mixtures, as well as corrosion testing of nickel-based alloys²⁹. The team has developed a nickel-molybdenum alloy known as HN80MTY which has withstood tellurium corrosion at temperatures up to 740°C. The team believe that HN80MTY has resolved the corrosion problems associated with Hastelloy-N and that the alloy's 'corrosion and mechanical properties completely meet MOSART requirements'³⁰.

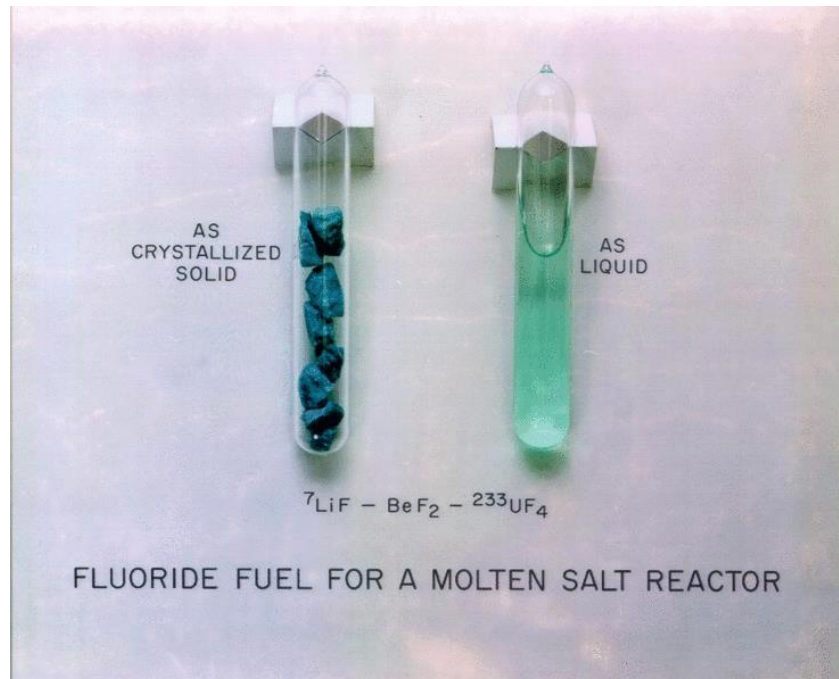


Figure 4. A comparison of solid and molten FLiBe salt. Image: Oak Ridge National Laboratory.

²⁹ Boussier, Hubert. Generation IV International Forum (GIF), '[Molten Salt Reactor System 2011 Status](#)'.

³⁰ Ignatiev, V. 'Critical Issues of Nuclear Energy Systems Employing Molten Salt Fluorides', Acsept International Workshop, Lisbon April 2010, p.20.

7. MSR R&D Priorities

7.1. Continuous Processing of the Fuel Salt

In order for a closed-cycle MSR such as the LFTR to successfully breed U-233, the fuel salt must be continuously processed to remove neutron-poisoning fission products. In addition, the U-233 produced must be separated from the blanket salt and transferred to the fuel salt. Towards the end of the MSR programme, ORNL recognised that they had much work still to do to demonstrate a continuous fuel processing system. Only small-scale experiments had been carried out and component development was still at an early stage. ORNL had, however, found 'no insurmountable obstacles' to progress in this area³¹.

ORNL had shown that U-233 separation could be achieved through a process known as fluorine volatility. The newly-created U-233 is transferred to a fluorinator where it is exposed to fluorine gas to form uranium fluoride which is then converted into a gas. This gas is exposed to hydrogen which converts the U-233 into a soluble form, after which it is transported to the fuel salt. This process was demonstrated during the MSRE, though ORNL made clear that further testing would need to be done to demonstrate fluorination on a continuous basis³².

Successful fission product removal experiments were also carried out at ORNL, but continuous extraction of fission products was not demonstrated. Xenon and Krypton gas are produced by the fission reaction, and if they are not removed from the reactor then they absorb neutrons which slows and eventually stops the chain reaction from taking place. The MSRE showed that both gases can be removed from the system by injecting helium into the salt, which absorbs the gases, and is then itself removed from the salt along with the trapped neutron poisoning gases. This process is known as sparging.

Rare-earth fission products were successfully removed from molten salt in multiple experiments at ORNL using the metal transfer method known as liquid bismuth reductive extraction³³. However, no large-scale testing was done. ORNL recognised that 'sound engineering tests of individual process steps' and 'relatively long-term and near full-scale integrated tests of the [reprocessing] system as a whole' would be necessary for future development of MSR technology³⁴. ORNL believed that the fuel processing system could be demonstrated within 15 years³⁵.

³¹ ORNL, '[Conceptual Design Study of a Single-Fluid Molten Salt Breeder Reactor](#)', June 1971.

³² ORNL, 1979, p.107.

³³ ORNL, '[Engineering Tests of the Metal Transfer Process for Extraction of Rare-Earth Fission Products from a Molten-Salt Breeder Reactor Fuel Salt](#)', February 1977.

³⁴ ORNL, 1979, p. 107.

³⁵ ORNL, 1979, p. 108.

Recent developments in electrochemical processing of molten salt fuel could provide new techniques to aid development of MSR fuel processing. Electroseparation methods such as anodic dissolution and cathodic deposition are being tested at the Nuclear Institute Rez in the Czech Republic. These methods may provide a means to separate lanthanides³⁶ from actinides, so that actinides can be fed back into the core for fissioning, while lanthanides are removed and stored as waste³⁷.

An additional challenge for the R&D effort relating to fuel processing is the form in which waste fission products will be stored. At present there is no proven process available to convert fluoride High-Level Waste (HLW) into a form suitable for safe storage. Potential methods are being developed to solve this problem involving both vitrification and crystallisation of the liquid waste³⁸.

7.2. Materials/Corrosion

When Oak Ridge MSR research funding was curtailed in 1973, one explanation given by the AEC was that corrosion in reactor materials presented a major technical difficulty for further MSR development³⁹. In fact, ORNL studies had demonstrated that the material of construction, nickel-based alloy Hastelloy N, had 'generally performed very well'⁴⁰. ORNL did encounter two problems with Hastelloy N for which likely solutions were found, though not fully tested.

Radiation Damage - Hastelloy N corrosion occurred during the MSRE as a result of neutron irradiation. When neutrons react with boron and nickel contained within the alloy, helium gas is produced which builds up and stresses the alloy, causing it to become brittle. Later Oak Ridge work showed that adding titanium to Hastelloy-N enables the alloy to withstand radiation much more effectively⁴¹. Extensive tests of the new alloy were cut short by the 1973 funding cut to the MSR programme.

Tellurium - The MSRE also established that the fission product tellurium corrodes Hastelloy N, causing cracking along the grains of the alloy. Oak Ridge later found that adding the soft metal niobium to the alloy reduced tellurium corrosion, though the studies were not carried out over long enough a period to conclusively demonstrate that the addition of niobium completely resolves the corrosion problem⁴².

³⁶ The 15 metallic elements from lanthanum to lutetium.

³⁷ Tulackova, R., et al. 'Development of Pyrochemical Reprocessing of the Spent Nuclear Fuel and Prospects of Closed Fuel Cycle.' *Atom Indonesia Journal* 33.1 (2012).

³⁸ Forsberg, Charles. 'Molten-Salt-Reactor Technology Gaps', June 2006, Proceedings of International Congress on the Advances in Nuclear Power Plants (ICAPP '06).

³⁹ AEC, 1972, p. 52.

⁴⁰ ORNL, 1979, p. ix.

⁴¹ ORNL, 1979, p. x.

⁴² ORNL, '[Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling](#)', July 1980, p.86.

Oak Ridge found that an alternative approach to the tellurium problem, controlling the oxidation potential of the salt, was also effective in reducing corrosion⁴³. Combining this approach with a titanium-enriched Hastelloy N could resolve the corrosion problem completely.

New Materials - Materials developed since the end of the ORNL MSR programme offer innovative ways of resolving difficulties with corrosion in MSRs, and could replace Hastelloy N and other nickel-based alloys as the main construction material for MSRs. New materials could also allow for higher operating temperatures, perhaps up to 1000°C. Higher temperatures would improve thermal to electrical conversion efficiency and enable process heat applications such as hydrogen and liquid fuel production.

Carbon fibre-reinforced carbon, also known as carbon-carbon (C/C), is a composite consisting of graphite reinforced with carbon fibre, and is already being developed for use in high-temperature reactors. C/C maintains its strength at temperatures up to 1400°C and is compatible with molten fluoride salts. This opens up the possibility of constructing MSR heat exchangers, pumps, piping and vessels out of carbon-carbon.

Technical challenges remain for carbon-carbons in high temperature nuclear applications. In very high temperature reactors (>1000°C), C/C may degrade when subjected to core level radiation, and, unlike metal alloys, C/C is potentially permeable, so composites with very low levels of permeability will need to be developed.

Silicon Carbide (SiC) is also a promising material for future high temperature nuclear applications. SiC has very high temperature and radiation tolerance⁴⁴ and can prevent oxidation in carbon-carbon if used as a coating. A SiC composite comprising silicon carbide fibre and silicon carbide matrix (Sic-Sic) could compete with C/C as a standalone material for high-temperature reactor components. SiC is already used in TRISO fuel.

Both Sic-Sic and C/C require the development of suitable joining technologies. Advances in laser joining could prove the solution⁴⁵. The Chinese MSR programme is currently testing C/C and Sic-Sic composites up to temperatures of 1000°C⁴⁶.

7.3. Buildup of Noble Metals

Noble metals formed as fission products do not dissolve in molten salt, and instead are deposited on the surfaces of components within the reactor. They produce large

⁴³ ORNL, '[Status of Tellurium-Hastelloy-N Studies in Molten Fluoride Salts](#)', October 1977.

⁴⁴ Ozawa et al, 'Evaluation of Damage Tolerance of Advanced Sic/Sic Composites after Neutron Irradiation', 2011, IOP Conference Series: Materials Science and Engineering Volume 18, Symposium 10.

⁴⁵ Hille, Lippmann & Hurtado, 'Electrically conductive ceramics and new joining technology for applications in HTR engineering', October 2012, Nuclear Engineering and Design, Vol. 251, p 222-229.

⁴⁶ Hongyie, Xu, '[TMSR Project at SINAP](#)', International Thorium Energy Organisation Conference, Shanghai, October 2012.

amounts of decay heat which can damage the heat exchanger. Noble metals need to be captured for an MSR to operate successfully.

These metals tend to accumulate on metal surfaces, so heat exchangers constructed from new materials such as carbon-carbon composites may be able to avoid harmful build up. Buildup can be encouraged in less problematic areas of a reactor, such as the salt clean-up system, by using coated carbon-foam matrices which absorb the noble metals. Research into the noble metal problem in molten salts was, until recently, an expensive undertaking, involving a test reactor or radioactive salt loop. The French national Laboratory of Subatomic Physics and Cosmology at Grenoble have developed cheaper non-radioactive test methods for molten salts, which will enable faster progress in resolving the noble metal problem⁴⁷.

7.4. Tritium Control

Tritium is a radioactive hydrogen isotope which is produced in significant quantities in MSRs as a fission product and also as a result of neutrons reacting with lithium in the fuel salt. Small quantities are routinely and safely released into the environment every day from existing nuclear power plants. However, in sufficient quantity, tritium can be hazardous to human health, so its release from nuclear power stations must be controlled. National nuclear safety bodies set limits on the amount of tritium that can be released into the environment.

At high temperatures in an MSR, tritium can pass through metal walls and potentially enter the power cycle, increasing the risk of uncontrolled release into the environment. To prevent this, tritium needs to be captured and isolated. The Oak Ridge MSR designs assumed a steam power cycle. Tritium reacts with steam to form tritiated water, and separating the tritiated water from non-tritiated water is complex. ORNL experiments demonstrated that tritium could be trapped in the secondary coolant if that coolant contained sodium fluoroborate. Later analysis has suggested that this would be a difficult and expensive option for isolating large quantities of tritium⁴⁸.

Alternative power cycles, such as the Brayton cycle, could offer the solution. Tritium can be trapped in and removed from gas in the Brayton cycle. Removal of tritium from helium gas has already been demonstrated cost-effectively in helium-cooled high-temperature reactors⁴⁹.

⁴⁷ Forsberg, 2006.

⁴⁸ Ibid.

⁴⁹ Ibid.

7.5. Power Conversion Systems

During the ORNL MSR programme, the Rankine steam cycle was the only proven method of converting heat to electricity. The steam cycle presented a number of technical challenges to MSR development including chemical reactivity of molten salts and water, the risk of salt coolant freezing because of the relatively low temperature of the steam cycle, and the tritium problem (see above 7.4).

The Brayton gas cycle, commonly used in jet engines, offers multiple potential advantages to the steam cycle in MSR applications. Tritium can be removed in the Brayton Cycle, and due to its high temperature operation, the Brayton Cycle also protects against the freezing of molten salt coolant. When coupled with a reactor outlet temperature higher than 700°C, Brayton also offers much greater conversion efficiency of thermal to electrical energy.

In an MSR attached to a combined or closed-cycle gas turbine (CCGT), heat is transferred from the molten salt coolant to gases such as helium, nitrogen, carbon dioxide or compressed air. The heated gas then drives a turbine which generates electricity. While steam cycle temperatures peak at around 550°C, gas cycles can operate above 1000°C. MSRs can produce outlet temperatures in excess of 650°C, with the heat transfer capacity of molten salt increasing with higher outlet temperatures. Therefore the combination of a high-temperature MSR and high-temperature CCGT maximises potential power conversion efficiency. CCGTs can be 50% more efficient than steam cycle turbines⁵⁰.

CCGTs have not yet been proven at a scale suitable for a power plant, though small-scale CCGTs have been successfully demonstrated, and large-scale prototypes are currently being built⁵¹. The FHR programs in China and the US (see above 6.1.1.) plan to bring FHRs with CCGTs to commercial level in 20 years. The US FHR program has opted to develop an air-Brayton combined-cycle system which enables process heat production, grid stabilisation and base-load and peak electricity output. These features may enable significant cost savings compared to current LWRs⁵².

⁵⁰ NASA, Juhasz et al, 2009, 'High Efficiency Nuclear Power Plants Using Liquid Fluoride Thorium Reactor Technology', Seventh International Energy Conversion Engineering Conference (IECEC), Denver, Colorado, August 2–5, 2009.

⁵¹ U.S. Department of Energy website, [SunShot Initiative](#).

⁵² Forsberg et al, 'Fluoride-Salt-Cooled-High-Temperature Reactors (FHRs) for Base-Load and Peak Electricity, Grid Stabilization, and Process Heat', Center for Advanced Nuclear Energy Systems, January 2013.

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