Molten salt reactors

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Molten salt reactors (MSRs) is an area of growing interest in sectors both private and public. Many advocates of MSRs talk of their potential to deliver safer nuclear power, bringing to the world energy sustainability without the generation of CO2 emissions and at a market-competitive price. Molten salt reactors are characterized by the use of fluoride salts as coolant, in particular lithium-beryllium fluoride (FLiBe) salts. The salt is not dissolved in water, the salt itself in molten form is the coolant. FLiBe salts have excellent heat transfer characteristics. The molten-salt carries a similar amount of heat per unit volume of water, remain liquid up to 1400°C giving incredible safety margins and unlike water does not need pressurisation at high temperatures. FLiBe salts have a very low rate of evaporation, low neutron absorption cross section, are transparent as a liquid and are very resistant to radiation damage on account of their ionic bonds. FLiBe salts as reactor coolant can be used in two ways – in a reactor with solid fuel or in a reactor with liquid fuel. Solid fuel, salt cooled reactors are known as FHRs (Fluoride High-temperature Reactors) or AHTRs (Advanced High Temperature Reactors). The operation of a FHR would not be dissimilar to PWRs with the need for regular refuelling and modest levels of burn up in fuel assemblies. However, due to FLiBe’s higher operational temperatures, FHRs have a higher thermal efficiency. The lack of pressurisation means the absence of a costly primary containment (the boiler) or a large secondary containment for steam capture in the event of core venting. The fact that the salt solidifies at 459°C means LOCA (loss of coolant accident) event may not be as severe for small pipe ruptures. Also the high boiling point of FLiBe means there is substantial margin between the reactor operational temperature and boiling temperatures that might cause a LOCA within hot channels. Liquid fuel, salt cooled reactors are known as MSRs (molten salt reactors) or LFRs (Liquid Fluoride Thorium Reactors). For MSRs, the fuel (²³³UF₄, ²³⁵UF₄ or ²³⁹PuF₄) is dissolved in the primary coolant itself. Having the fuel dissolved provides some advantages. Fission products such as ¹³⁵Xenon can be out-gassed and removed during operation and fuel reprocessing and refuelling can occur whilst the reactor is running. The ability to constantly remove fission products means a much higher rate of burn-up can be achieved (> 50%) and the removal of fission products means less decay heat to contend with after reactor shut down. The fact that both the fuel and beryllium moderator are in liquid form results in them readily expanding at high temperatures, giving the MSR a highly negative reactivity thermal coefficient that prevents a run-away chain reaction as the core temperature rises. However a fuel in solution also means the primary coolant salt becomes highly radioactive, complicating maintenance procedures and the chemistry of the salt must be monitored closely to maintain a chemically reduced state to minimise corrosion. Another advantage of the liquid fuel molten salt design is that it allows the thermal breeding of ²³³U from ²³²Th in a liquid form that is easily processed. ²³²Th neutron capture will produce Protactinium (²³³Pa) by beta decay which must be removed as it is a neutron-absorbing ‘poison’. The chemically removed Protactinium will then further beta decay into ²³¹Uranium which would then be used as fuel in the MSR reactor. Thorium is extremely plentiful relative to ²³⁵U and could hold the key to truly sustainable zero carbon emission energy. The list of advantages for molten salt reactors and thorium fuel is impressive. Pioneering work at Oak Ridge National Laboratory from the 1950’s to 1970’s demonstrated the basic advantages of MSRs and their compatibility for burning ²³³Th. The MSR experimental program was shut down for national security and political considerations in preference for support of the Integral Fast Reactor which bred ²³⁹Pu. The emergence of China and India as regional powers has put the spotlight back on thorium and molten salt reactor design. Driven by the need for secure and sustainable carbon neutral energy sources, both China and India have become interested in MSRs and thorium research. In the United States, there are moves to revive research in molten salts to be used in AHTRs and the British are poised to restart reactor construction with a possibility of reviving British fission reactor research. Various countries are also interested in the thorium fuel cycle including Russia, France, South Africa, Japan, Norway and the Czech Republic. Molten salt reactors, in the form of AHTRs could offer all countries a form of nuclear power superior to current reactors; in terms of safety, reliability, economy, deployment and waste disposal.

Keywords: molten salt reactor; liquid fuel reactor; FLiBe; Gen IV; passively-safe; thorium; fuel breeding; energy sustainability.

1. Introduction to molten salt as reactor coolant.

Molten-salt-reactors are characterized by the use of molten salts for reactor primary coolant and are very different from the light water which cools most of the world’s pressurized water reactors (PWRs). The primary advantage of molten salt over pressurized water for reactor coolant is its inherent safety of high boiling temperature and high volumetric heat capacity which prevents adverse cooling conditions due to coolant boiling and fuel elements overheating. One particular salt, lithium/beryllium Fluoride known as FLiBe remains liquid without pressurization up to a temperature of 1400°C (2552°F). This far exceeds the 315°C operational temperature of most PWRs which must hold the water coolant under a pressure of 150 atmospheres to prevent boiling. The replacement of water with molten salt for primary coolant can significantly increase the operational safety of nuclear reactors.
The suitability of molten salts for reactor coolant lies in its unique set of thermodynamic, solvent and radiation resistance qualities. A basic FLiBe salt is composed of 66.6% \(^7\)lithium-fluoride (LiF) and 33.3% beryllium-fluoride (BeF\(_2\)). The reason for mixing the two halide salts is to reduce the melting temperature of pure \(^7\)Lithium Fluoride from 845°C to a melting point of 459°C in a 2:1 ratio \(^7\)lithium/beryllium fluoride eutectic mixture. Naturally, with a melting temperature of 459°C, careful attention must be paid to the design of a molten-salt cooled reactor, so that the coolant does not freeze during normal operation or during maintenance. However having a high freezing-temperature coolant is also advantageous from a safety perspective because the salt serves as a barrier to atmospheric fission product release for either a solid fuel, (whereby the fuel is encapsulated in a cladding), or a liquid fuel reactor, (whereby the UF\(_6\)/ UF\(_4\) fuel salt is dissolved into the coolant salt itself). Furthermore, the ionic bond of the FLiBe salt gives the coolant a resistance to radiation damage, while its beryllium content enhances neutron moderation. The elements beryllium and \(^7\)lithium possess some of the lowest neutron capture cross sections out of all fluorine salts, benefiting the reactor’s neutron economy. FLiBe’s volumetric heat capacity at 4680 kJ/(m\(^3\)K) is similar to water and exhibits a very low vapour-pressure which means simply a low rate of evaporation. The thermal conductivity of FLiBe is similar to water, making primary cooling systems less prone to the thermal shocks experienced by sodium-potassium (NaK) cooled fast reactors.

In 1959, the US evaluated three liquid core concepts as detailed in AEC Report (TID-8505) [1]. The conclusion was that the Molten Salt Reactor had the highest probability of achieving technical feasibility, taking into account the fact that molten fluoride salts have:

(a) a wide range of solubility of uranium and thorium,
(b) are stable thermodynamically and do not undergo radiolytic decomposition,
(c) have a very low vapor pressure at operating temperatures, and
(d) do not attack the nickel-based alloy piping used in the circulating salt system.

From a nuclear engineering perspective, the attraction of using FLiBe salt as primary coolant is a product of its ease of containment, neutron economy and moderation, superior heat capacity, negative reactivity coefficient and high operational temperature without pressurization.

### 2. Solid-fuel molten salt reactors and liquid-fuel molten salt reactors.

Molten salt cooled reactors can burn either a solid fuel or liquid fuel. Solid fuel, molten salt cooled reactors of the type currently pursued by USA’s Department of Energy (DOE) are known as FHRs (Fluoride-cooled High-temperature Reactors) or AHTRs (Advanced High Temperature Reactors). The favourable aspect of solid fuel / molten salt cooled reactors over a liquid fuel reactor is the cladding of the solid fuel adds an extra barrier to fission product release. The solid fuel cladding serves as primary containment with the molten coolant serving as secondary containment. The salt will freeze and immobilize the fission products in the event of a reactor ‘SCRAM’. Finally, the reactor vessel and reactor building serves as a third level of containment. Such defense-in-depth qualities are important considerations for the future of passively safe advanced reactors. One drawback of solid fuel compared to liquid fuel MSRs is that fuel burn-up will remain at the modest levels of current PWRs because solid fuel structurally degrades upon irradiation which limits their complete burn-up. Whereas liquid fuel reactors have the potential to achieve much higher rates of burn-up.

Liquid fuel molten salt reactors have the fuel salt (such as UF\(_6\), UF\(_4\)) dissolved directly into molten coolant salt, creating a homogenous mixture and is thus known as a homogenous reactor. Recently, liquid fuel molten salt reactors have simply been called Molten Salt Reactors (MSRs), Thorium Molten Salt Reactors (TMSRs) or Liquid Fluoride Thorium Reactors (LFTRs) which are a particular type of molten salt reactor that burns \(^{233}\)U bred from the fertile material \(^{232}\)Th.

\(^{235}\)U and to a lesser extent \(^{239}\)Pu are the commonly used fuel for today’s nuclear reactors. Studies into burning \(^{235}\)U have been carried out in the past but have not been widely adopted. Currently the use of \(^{233}\)U bred from thorium is gaining interest on account of its abundance which is 4 times that of naturally occurring uranium. Thorium-bred U-233 fuel and liquid-fuel molten salt coolant are separate technologies which work well together. Although there are many options for the use of thorium and FLiBe in reactor design, a LFTR with thorium fuel breeding coupled with a fuel-reprocessing facility is recognised by many as the ultimate utilisation of all technologies, giving the best safety, burn-up, potential actinide burning, thermal efficiency and waste-disposal characteristics relative to many current and contending Gen IV reactor designs. In terms of breeding ratio, LFTRs cannot compete against sodium cooled fast reactors but this is counter-balanced by sodium’s reduced inherent safety when compared to FLiBe, because sodium is chemically very reactive. Also sodium fast reactors are optimised to breed \(^{239}\)Pu which limit their widespread deployment due to proliferation issues; whereas LFTRs are optimised to breed \(^{231}\)U which is more difficult to weaponise on account of \(^{233}\)U containing trace amounts of Thallium-208 that emit high energy gamma radiation making it difficult to handle and easier to identify.
On paper, LFTRs and MSRs can match or better the safety, economy, compactness and sustainability of current third and three-and-a-half generation PWRs like the Westinghouse AP1000 or Areva’s EPR. The caveat is that there is still a substantial amount of research and engineering work to be done to bring the potential of MSRs to fruition. ORNL successfully ran an 8MW(thermal) experimental-MSR but have yet to build a MSR breeder to produce $^{233}$U from thorium. Future work includes the testing of MSR operation at very high temperatures (~1000°C) which would increase the reactor’s thermodynamic efficiency and the evaluation of reactor material degradation at high temperature / high neutron fluence environments. To investigate this and all other associated technologies, including chemical processes for online fuel-reprocessing (pyro-processing or otherwise), will take substantial resources and time.

India and China are countries that have started the commitment of such resources as driven by their increasing demand for energy. The Chinese government have committed $350 million USD over five years for initial TMSR development. Chinese research will be centered at SINAP – Shanghai Institute of Nuclear Applied Physics, a branch of the Chinese Academy of Science with a target date for TMSR power-reactor deployment in 2032. In India, thorium research at the Bhabha Atomic Research Centre is embodied within a comprehensive plan of multiple reactor types that will breed and burn thorium fuel in separate reactors.

3. Thorium.

Thorium, existing naturally as $^{232}$Th, is a fertile element that can be transmuted into $^{233}$U when exposed to fast or thermal neutrons.

$$n + ^{232}_{90}Th \rightarrow ^{233}_{90}Th \xrightarrow{\beta^- (\lambda=22\text{min})} ^{233}_{91}Pa \xrightarrow{\beta^- (\lambda=27\text{days})} ^{233}_{92}U$$

As a solid fuel, $^{232}$Th / $^{233}$U can be fabricated into mixed-oxide-fuel (MOX) or tri-structural isotropic (TRISO) fuel to be bred and burnt in PWRs or AHTRs. As a liquid fuel, ThF$_3$ and UF$_3$ can be dissolved into a mixture in a single fluid MSR (otherwise known as the homogenous design). Alternatively, $^{232}$Th and $^{233}$U can be dissolved separately, with the $^{232}$Th dissolved in a ‘blanket salt’ surrounding a core of dissolved $^{233}$U ‘fuel salt’ (known as the heterogeneous design). Due to $^{233}$U containing trace amounts of thallium-208 ($^{208}$Tl) emitting a high energy 2.6MeV gamma radiation, the ideal manner of $^{233}$U deployment is in simple fluoride salts dissolved into a liquid form. As pointed out by H. G. MacPherson, former deputy head of Oak Ridge National Lab (ORNL) working on the MSR project: “...the highly radioactive U233 used would have been extremely difficult to handle if it had had to be incorporated into solid fuel elements.”[2] At the dawn of the nuclear era, both the U-235 fuel cycle and the thorium-breed U-233 fuel cycle were equal candidates for reactor fuel [3]. However, once uranium reserves were found to be abundant and when it became clear that U-233 breeding created trace amounts of hard gamma emitters, U-235 became today’s preferred and only uranium fuel.

Fig. 1 MSRE graphite moderator.

4. TMSRs past and present.

The first fluid-fuel molten salt reactor at ORNL was known as the ARE (Aircraft Reactor Experiment). Built in the 1950s, ARE was designed to investigate the possibility of a nuclear-powered bomber, with the design using a beryllium oxide moderator circulating a fuel-laden, molten-salt coolant [4]. Dr. Alvin Weinberg, physicist, pioneer of reactor design and head of ORNL (1955-1973), understood that molten salt, with its superior volumetric heat capacity, allowed compact reactors to be built. When funding for the ARE program ceased, Weinberg secured alternate funding from the DOE to build a new experimental MSR (MSRE) and continued research until 1973, when the program was cancelled by the Nixon administration. The 8MWth MSRE operated between 1965 and 1969 with 9000 full-power hours driven by dissolved U-235 and 4160 hours by dissolved U-233 see figures 1 & 2. While operating the MSRE, ORNL engineers and scientists demonstrated the essential features of the MSR - a negative reactivity thermal co-efficient, ease of operation & safety, fluorine salt chemical stability and limited salt corrosion of Hastelloy-N alloy, thus qualifying the MSR design for further development. Details on the success of the 8MW MSR test reactor are covered by Haubenreich [5] and MacPherson [6]. Plans for a Molten Salt Breeder Reactor (MSBR) were underway in 1970 but the design study remained on the drawing board after the MSR program was terminated in 1973 when US efforts were focused on the sodium-cooled fast-breeder reactor.

After the cessation of TMSR research at ORNL, things remained more or less dormant in the USA until recently, when molten fluoride salts were revived in the Advanced High Temperature Reactor (AHTR) concept. The 1500MWe AHTR studied at ORNL and INL is designed to use FLiBe coolant with solid fuel plates. ORNL is also working with UC-Berkeley, MIT and Uni. of Wisconsin on a 410MWe Pebble Bed Molten-Salt reactor. Additionally, a small modular fluoride salt coolant reactor called SmAHTR (125MWh, 40MWe) is being studied by ORNL. The three concepts AHTR, PB-AHTR and SmAHTR are all part of a sub-$10million/year study on AHTRs.

Recently Forsberg et al. published a strategy for the use of FHRs in the US [8]. FHRs have the ability to use an Air-Brayton Combined Cycle (ABCC) system for the production of both base-load and peak-power. The ability to very quickly (50ms) produce peak power is an important consideration in the deregulated US energy market because peak power is extremely profitable. The ABC system works by using the FHR as the base-load energy provider which drives a jet-engine like (Air Brayton Cycle) turbine. At the back-end of this turbine is a methane 'afterburner' which fires during peak-times, giving extremely high efficiencies (50%+). The Air Brayton Combined Cycle option is unique to the FHR because only FHRs and TMSRs using molten salt can provide the temperatures necessary to drive the system. The report also covers the possibility of using the thorium fuel cycle in FHRs as considered by the UC Berkeley group with its 900MWh, 410MWe, pebble bed fuel design (figure 3).

![Fig. 3 Modular PB-FHR with Primary, Intermediate, and Auxiliary cooling systems shown. Graphics from [8].](image)
The use of solid-fuel is a pragmatic choice by ORNL et al. considering a liquid-fuel, molten core design would require a longer duration to validate and license by the American NRC (Nuclear Regulatory Commission) because a fluid fuel MSR entails many novel technologies that require testing, evaluation and qualification. This includes but not limited to:

1) the qualification of advanced reactor materials (eg. Hastelloy-N or even silicon carbide instead of the commonly used Zircaloy or Inconel in most PWRs). The materials will have to operate at a higher temperature and higher radiation environment compared to PWRs.

2) addressing the question of whether the MSR should be a ‘breeder’ (whereby the reactor creates more $^{233}$U fuel than it burns) or a ‘converter’ (whereby the amount of fuel created is less than the amount burnt). Then to evaluate optimal $^{233}$U breeder / converter scenarios for the MSR. Should the reactor be single fluid or two fluids? Should the fuel be highly enriched or ‘denatured’ (<20% enrichment) with effects on reactor size? What kind of neutron spectrum should be used: thermal, epithermal or fast-neutron? Should the fuel cycle be once-through (no reprocessing) or require periodic reprocessing?

3) Deciding upon a thermal or fast spectrum will affect the inclusion of a moderator. In thermal spectrum MSR designs, the moderator of choice is graphite. But graphite is prone to neutron damage and would typically require replacement every 4 years, increasing the amount of maintenance. Choosing a fast spectrum would remove the graphite moderator and simplify the design but will increase the rate of radiation damage in the containment vessel.

Question such as these are starting to be addressed by small international research groups, including: Moir, Forsberg, Petersen, Furukawa, Ignatiev, Mathieu, Ragheb, Holcomb, Hron, Luzzi, LeBlanc and others. [7-16] Dr. David Holcomb, reactor researcher at ORNL, admits that MSR and AHTR research will require some time to build momentum and should be consistently funded as a $10-million per annum program for at least a few years: to develop the basic technology, source enough suppliers and familiarise the NRC with the AHTR concept before a pilot plant can be built. CAS, SINAP have also recently signed an MOU and agreement for technology transfer with ORNL to share solid-fuel / molten-salt coolant reactor research information.

4.1 International developments in MSR and thorium research.

Internationally, there have been efforts towards MSRs and TMSRs: notably researchers in Russia at the Kurchatov Institute are working on the MOSART concept [10] for burning actinides. In France, there is interest in both a fast and thermal MSR, the thermal MSR being the AMSTER concept [17]. At Grenoble, CNSR is interested in a Th/Pu, U233/Pu, fast/epithermal breeder under the Gen IV reactor research initiative [18]. The Czechs are working with America’s DOE on molten-salt research [19] and have procured some of the original secondary-coolant FLiBe salt from the 1960’s MSRE program. The British, though active in reactor decommissioning and PWR fuel re-processing, are not currently engaged in fission reactor research. However interest in nuclear power in the UK is increasing after the recent announcement of UK’s approval for the future construction of Areva’s EPR by the Office for Nuclear Regulation [20]. A Japanese consortium by the name of ‘International Thorium Molten-Salt Institute’ (ITHMSI) is pursuing a thorium fuel cycle thermal breeder reactor called the Fuji MSR (200MWe). Both the Fuji and 10MWe mini-Fuji remain at a developmental stage. The Chinese are recent entrants in TMSR research (2011) identifying it as a ‘project of national priority’. The Indians are also interested in the thorium fuel cycle especially in the form of solid fuel to be burnt in PWRs [21]. Also interested in solid thorium fuel is Thor Energy, a private Norwegian company who for the past five years has been working towards a Thorium MOX fuel. South African company Steenkampskraal Thorium Limited (STL) are engaged in talks with a South African energy supplier to build a 100MWth high-temperature helium-cooled reactor, possibly fuelled with thorium pebble-bed fuel.

4.2 MSR and public awareness

One of the most well-known proponents for MSR technology is Kirk Sorensen. Sorensen worked as an engineer at NASA looking for energy solutions in deep space when he came upon a textbook for fluoride molten salt reactors. Motivated by the potential of this technology, he promoted awareness of LFTRs in public lectures some of which are available on YouTube [22]. Notable interviews with ex-ORNL engineers, Dick Engels and Syd Ball are also available [23]. In these videos, they spoke openly about their operational experience on the MSRE program and noted the MSR’s superior negative reactivity coefficient characteristic as well as its thermodynamic efficiency by operating at a very high temperature in a compact core. A recent journal publication on TMSRs is Ralph Moir and Edward Teller’s 2005 article in Nuclear Technology, titled: “Thorium Fuelled Underground Power Plant Based on Molten Salt Technology” [7]. Dr. Robert Hargraves, from the University of Dartmouth, further popularised the idea by co-authoring with Moir an article in the American Scientist, July-August 2010, titled: “Liquid Fluoride Thorium Reactors” [24]. Hargraves also published a book called “Thorium, energy cheaper than coal” in 2012 which makes the case for TMSRs. Dr. Jiang Mianheng, head of CAS Shanghai branch, partially attributes his awareness of TMSRs to Hargrave’s 2010 article as
quoted in his address at the Thorium Energy Conference in Shanghai 2012. Finally, a MSR-specific textbook on coupled neutronic-thermohydraulic simulations of the molten fuel was published in 2012 [15]. The increase in thorium fuel cycle and TMSR awareness is interesting considering it has been partially driven by social media and creative-commons licensed YouTube videos, partially by business interests and partially by activities in government labs and Gen IV design studies.

5. Summary of advantages and challenges for MSRs and LFTRs.

Advantageous characteristics of the basic molten-salt reactor include:

1) A reactor in which a ‘liquid core’ can burn a variety of fuels: $^{235}$UF$_4$, $^{239}$UF$_4$ or $^{239}$PuF$_4$. Fuel salt in the form of uranium fluoride or plutonium fluoride is dissolved in the molten salt coolant and undergoes fission in the reactor core.

2) Since the fuel is already molten in the primary coolant, there is no possibility of fuel meltdown. The primary coolant, its fuel and fission products can be easily immobilised in the event of a reactor ‘scram’ due to the salt’s high freezing (~458°C) temperature and low vapour pressure (evaporation rate). In the event of an emergency shutdown, the coolant can be drained into separate sub-critical holding tanks.

3) The fluoride salt is known as FLiBe; standing for Fluoride-Lithium-Beryllium. FLiBe has a melting temperature of ~458°C and a boiling temperature of ~1400°C. The primary coolant fuel salt has a molar composition of 70% $^7$LiF, 18% BeF$_2$ and a 12% mixture of $^{235}$UF$_4$, ThF$_4$ and ZrF$_4$. The secondary coolant salt responsible for driving the turbine generators is composed of lithium fluoride and beryllium fluoride only and has a 2:1 lithium to beryllium ratio (Li$_2$BeF$_4$).

4) FLiBe has a similar volumetric heat capacity and a similar thermal conductivity compared to pressurized water. The higher boiling point and lower vapour pressure of FLiBe means MSRs operate at higher thermal efficiencies, and the ability to operate without pressurisation compared to current water-cooled PWRs.

5) Unlike Na-K coolants of Fast Breeder Reactors, FLiBe will not violently react with water or burn in air.

6) Since MSRs do not require a pressurised primary-containment or a large secondary-containment building for steam capture as needed for PWRs, MSR reactor size and back-up safety systems can be reduced in volume and complexity.

7) Costly PWR fuel-bundle fabrication is unnecessary for liquid fueled MSRs, reducing operational costs.

8) With a molten core with liquid fuel, krypton and xenon poisons can be out-gassed and removed from the primary coolant during operation, avoiding the ceramic cracking and damage associated with UO$_2$ pellet irradiation.

9) A liquid fuel MSR works well when deployed in tandem with a reprocessing facility to maintain minimum fissile inventory in the core. Fuel reprocessing including refueling and waste removal can occur whilst the MSR remains at power (ie. on-the-fly reprocessing). Also, sufficiently low fission inventory in the salt can be maintained so that decay heat could be minimised after reactor shutdown.

10) Since the primary cooling loop operates at a high temperature (700°C - 1000°C), it is possible to use Brayton cycle turbines that are compact and have the potential to deliver 45% thermal-mechanical conversion efficiency.

Challenges to be addressed for liquid-fuel molten salts reactors with FLiBe:

1) The primary coolant loop will be highly radioactive due to fission products being in solution with the primary coolant salt. This will complicate maintenance procedures which would require the use of flushing salts and remote handling techniques.

2) Beryllium is chemically toxic.

3) Lithium-7 must be +99.99% pure and its isotopic separation from Lithium-6 is costly. Lithium-6 is unwanted for its transmutation into tritium upon neutron capture. The presence of tritium (an isotope of hydrogen) can degrade the structural integrity of the containment vessel.

4) Close attention must be paid to the chemical composition of the salt to maintain a chemically reduced solution for deterring uranium out-precipitation. The out precipitation of uranium would lead to solid uranium depositing on the bottom of the reactor vessel, causing local hot spots that may affect the integrity of the primary containment vessel. One manner of control is to vary the mixture of UF$_3$ to UF$_4$ during operations to maintain a slight excess of fluorine molecules.

5) As the fuel is burnt in the core, fission products will be produced. Each fission product and daughter decay products would react differently with the metal alloy containment vessel. More work needs to be done to understand the reaction between alloys and fission products.

6) The benefit of having a primary coolant with a high melting point that will ‘freeze easily’ to immobilize waste could result in some operational challenges. Some areas of the reactor that loose heat easily – eg heat
exchanger surfaces and long narrow tubing, must be sufficiently well designed so they don’t freeze over during reactor operation.

7) FLiBe salts have the ability to maintain a liquid form up to 1400°C, allowing the possibility for very high temperature operations. The metallic alloys containing the liquid thus become the system’s weakest link. To exploit FLiBe’s advantages, new metallic alloys or non-metallics (eg. C-Si) resistant to both high temperatures and radiation need to be developed and qualified.

Proponents of the MSR design often talk of using U-233, bred from thorium, as fuel. Characteristics of the thorium fuel cycle include:

1) U-233 breeding by Th-232 neutron capture. Fast or thermal neutron capture by Th-232 produces Th-233 (half-life 22min) beta decaying to Pa-233 (half-life 27days) and beta decaying again to U-233 (half-life 1.59 x 10^5 years) following the Neptunium decay series.
2) U-233 can be chemically separated from Pa-233 and Th-232 in contrast to costly U-235/U-238 isotopic separation.
3) From a nuclear non-proliferation stand point using thorium / U-233 is preferable. The breeding of U-233 contains trace amounts of a hard-gamma emitter: Tl-208. This makes U-233 difficult to handle and easier to detect.
4) The hard-gamma emitting decay products U-233 means they are difficult to handle and fabricate into dioxide pellet fuel. The use of U-233 is more straight-forward in MSRs which only require their dissolution in the primary coolant.
5) The thorium fuel cycle produces less long-life radioactive waste compared to the U-235/U-238 fuel cycle.
6) Thorium reserves are plentiful; its relative abundance is 4 times that of natural uranium and has the potential to supply earth’s energy demands for thousands of years.

6. Conclusion.

Current research into the thorium fuel-cycle and liquid-fuel molten salt reactors is led by China and India. The United States of America, which pioneered TMSR work, have embarked on an alternate strategy of using molten salt as the primary coolant of a solid fuel reactor. Conceptual studies of molten salt reactors are being conducted in France and Russia, with interests in a fast neutron spectrum MSR useful for the burning of actinide waste. The Norwegians, through the private research of Thor Energy, are making headway in the development of thorium MOX fuel for PWRs. Some nations such as Czech Republic, South Korea, China and the UK have interests in the thorium fuel cycle in subcritical Accelerator Driven Systems (ADS). AHTRs, MSR and TMSR technology holds great potential for improving reactor safety and energy sustainability. However, there are technological and regulatory challenges to overcome before a MSR / TMSR pilot plant can be built. The enormity of the TMSR project has driven countries to work together, SINAP are most notable for forming international collaborations, having already signed an MOU with America’s MIT and UC-Berkeley, the DOE and ORNL. Given molten salt’s superior heat transfer qualities and MSR’s potential advantages in safety, economy, modular compactness, enhanced non-proliferation qualities and energy sustainability, there are good reasons to pursue research in molten salt reactors.

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