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A general overview of generation IV molten salt reactor (MSR) and the use of thorium as fuel

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ABSTRACT

The molten salt reactors (MSRs) make use of fluoride salt as primary cooler, at low pressure. Although considered a generation IV reactor, your concept isn't new, since in the 1960 years the Oak Ridge National Laboratory created a little prototype of 8MWt. Over the 20th century, other countries, like UK, Japan, Russia, China and France also did research in the area, especially with the use of thorium as fuel. This goes with the fact that Brazil possess the biggest reserve of thorium in the world. In the center of nuclear engineering at IPEN is being created a study group connected to thorium reactors, which purpose is to investigate reactors using thorium to produce 233U and tailing burn, thus making the MSR using thorium as fuel, an object of study. This present work searches to do a general summary about the researches of MSR's, having as focus the utilization of thorium with the goal being to show it's efficiency and utilization is doable.

1. INTRODUCTION

As the world searches for new forms to substitute fossil fuel. We have a lot of possible candidates for it, the nuclear energy is one them [1]. Within the nuclear energy, the upcoming generation IV(Gen IV) reactors is it's future. It's design and purpose are of great interest around the world, specially since thorium [2], which is a possible candidate for the Gen IV fuel, is all around the world. Not only have the capacity of being more available than uranium, but also have advantages compared to it.

The Gen IV reactors goals are sustainability, safety and reliability, economic competitiveness, proliferation resistance and physical protection [3]. How they are attained depends on the technology used. There is a total of six reactors types which use different technology. They are Very High Temperature Reactor (VHTR), Molten Salt Reactor (MSR), Gas-cooled Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), Supercritical Water-cooled Reactor (SCWR) and Sodium-cooled Fast Reactor (SFR). It's deployment is planned to be between 2020 and 2030.

Our reactor of interest is the MSR. The first MSR reactor was called Molten Salt Reactor Experiment (MSRE) [4] it was made by Oak Ridge National Laboratory (ORNL) in the 1960s. It operated from 1965 to 1969 and was a prototype of 8MWt. The main purpose was to show that MSRs could operate reliably, safely and maintained without much difficulty. Then after it shut down, the molten salt technology was forgotten. Until recently that started to gain attention as a Gen IV reactor.

2. MOLTEN SALT REACTOR

The MSR is a Gen IV reactor [5], which main concept is to use fuel, it can be uranium, thorium or plutonium, dissolved in the molten salt and reprocess it make it usable again. To maintain the salt in liquid state it runs at low pressure and high temperature. An adequate fluoride salt can be dissolved in a mixture of LiF-BeF_2 (FLiBe)) to separate the uranium from the thorium in fluoride form. The actual interest is using liquid fuel since it have the possibility to make a breeder reactor if using thorium as a fuel. But the fuel can be solid or liquid so there is a lot of different concepts and difficulties to make it viable to produce electricity. And the effort to make it usable can be see from researches around the world.

2.1. Operation of the MSR

A basic MSR works with fluoride salt as a coolant. The choose for fluoride salt can be seen from it's advantages [6]. The FliBe is a common choice for the fluoride salt. The choice for lithium and beryllium lies in the fact that they possess some of the lowest cross section for neutron capture. This way they also benefit the neutron economy in the reactor. The FLiBe uses a mix of both lithium-fluoride (LiF) and beryllium-fluoride (BeF_2) to lower the melting temperature. In the case that the LiF is 66.6% and BeF_2 is 33.3%, a ratio of 2:1, the melting temperature is 479°C which is much lower than 845°C the LiF melting temperature. Having a high freezing temperature is a safety advantage because the FLiBe is resistance to radiation damage and the beryllium content increases the neutron moderation. It also makes impossible for the release of fission products to the atmosphere be it the fuel solid or liquid. And for last the FLiBe volumetric heat capacity is 4680 kJ/(m^3K) and the water is 4180 kJ/(m^3K). So FLiBe like the water have low rate of evaporation.

The use of molten salt brings advantages like neutron economy and moderation, negative reactivity coefficient, high temperature without pressurization and others. How to maintain the high temperature is one of the engineering problems that MSR possess, be it during normal operation or maintenance.

A scheme [7] for the MSR is show below:

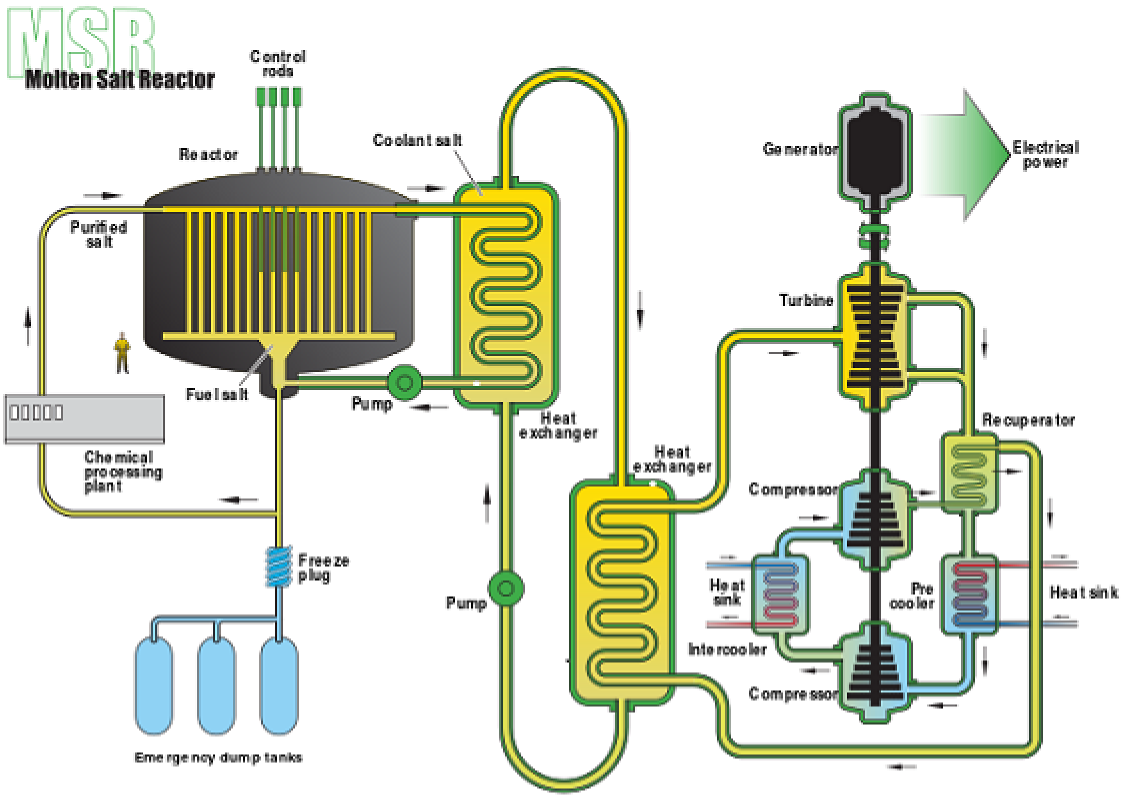

Figure 1: A basic MSR scheme

From the scheme we can see the basic flow of the MSR and some of the security measures. The operation without worrying about details is basically the molten salt flows through the reactor, then goes to the heat exchanger to provide the heat which makes the turbine move and generate electricity. After passing through the heat exchanger, the molten salt goes to a chemical plant where it's purified and then returns to the reactor.

As said before the fuel can be solid or liquid. The usage of solid fuel, makes the MSR a fluoride salt-cooled high-temperature reactor (FHR). The FHR are reactors that doesn't use the salt as a fuel but just as a coolant. The usage of liquid fuel is specially interesting with the use of thorium. That's why normally we call the reactors that use liquid fuel as liquid fluoride thorium reactor (LFTR). Both the FHR and LFTR have a lot of different concepts and technologies. Some of them are going to be discussed in the next sections.

2.1.1. Advanced high temperature reactor

The Advanced High Temperature Reactor (AHTR) is a concept MSR made by ORNL [8] that uses a solid fuel so it's a FHR. It uses a coated-particle graphite-matrix fuel cooled with molten salt in it's core. One of the things that makes the AHTR different is the capability of producing H_2 as well by using the heat from the reactor. They have similarities with the gas turbine-modular helium reactor(GT-MHR) and pebble-bed modular reactor(PBMR). In practically everything be the reactor core physics, general core design and fuel cycle. The choice for the salt is because of the neutron absorption and scattering cross sections are low, specifically below the water. And the graphite-moderated core have properties like long neutron lifetime, slow kinetics and thermal neutron spectrum characteristics similar to the GT-MHR.

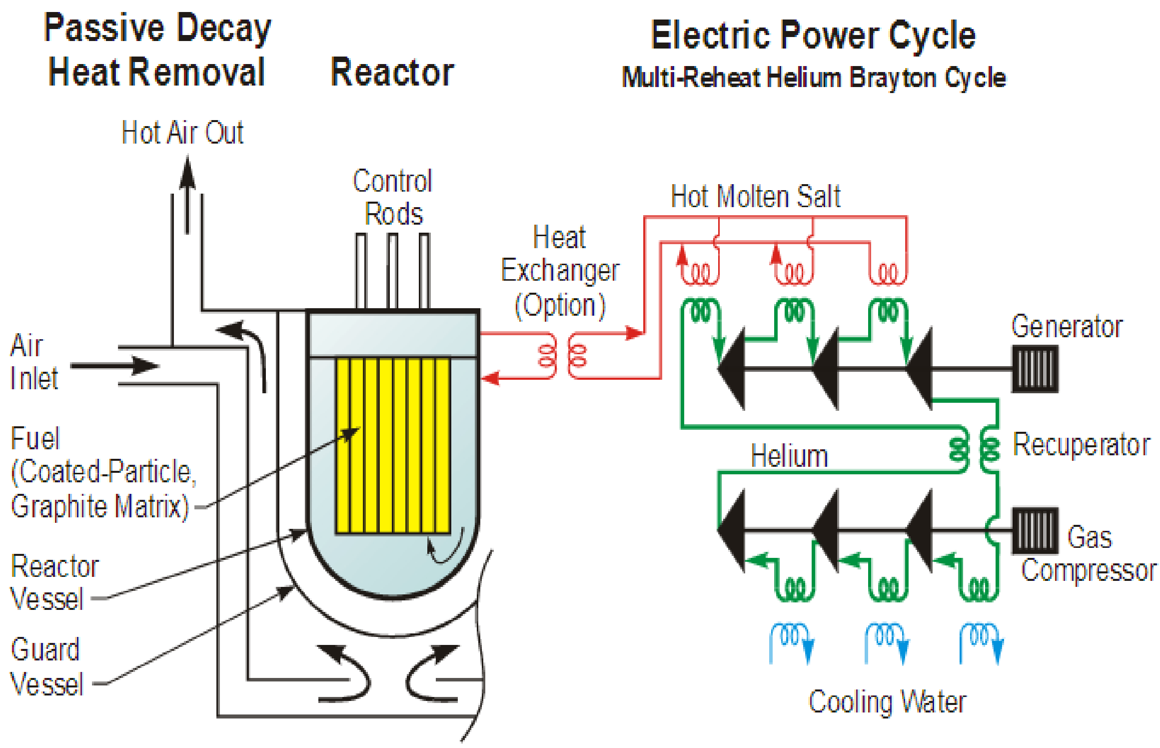

Figure 2: An AHTR scheme for electricity production

As said before it's a concept so there are a lot of challenges to make it viable in practice. There is one variation for the AHTR which is the Small Modular Advanced High-Temperature Reactor (SmAHTR) [9]. The SmAHTR is the actual tendency for AHTR future considering the fact that research about AHTR stopped in 2006 at ORNL.

2.1.2. Small modular advanced high-temperature reactor

As said in the previous section the SmAHTR is a variation of AHTR and FHR. It's concept is newer compared to the AHTR [9] and is supposed to deliver 125MWt. It's goals is to be capable of being easily transported and assembled at remote sites to deliver electricity, while being affordable and safe. The design of the SmAHTR is based on the safety philosophy of several small modular reactors. For it to be possible it uses a integral design, that means the reactor vessel contains all the primary components and the core itself. Similar to the AHTR, the SmAHTR is cooled with molten salt, coated-particle-fueled, graphite-moderated and operates at high temperature(700°C) with low pressure. And utilizes a passive decay-heat removal.

2.1.3. Integral molten salt reactor

The Integral Molten Salt Reactor (IMSR) is designed and developed by the Terrestrial Energy. The plan is to produce 400 MWt, hence it can also be called IMSR400. The IMSR is based on the ORNL SmAHTR so it uses a integral reactor design and a small modular molten salt fuelled reactor [10]. The IMSR core-unit is a vessel that is sealed, with the reactor core, heat exchangers, integrated pump and shutdown rods. And can be replaced at the end of it's life-time (7 years). A scheme for IMSR as a whole can be seen below:

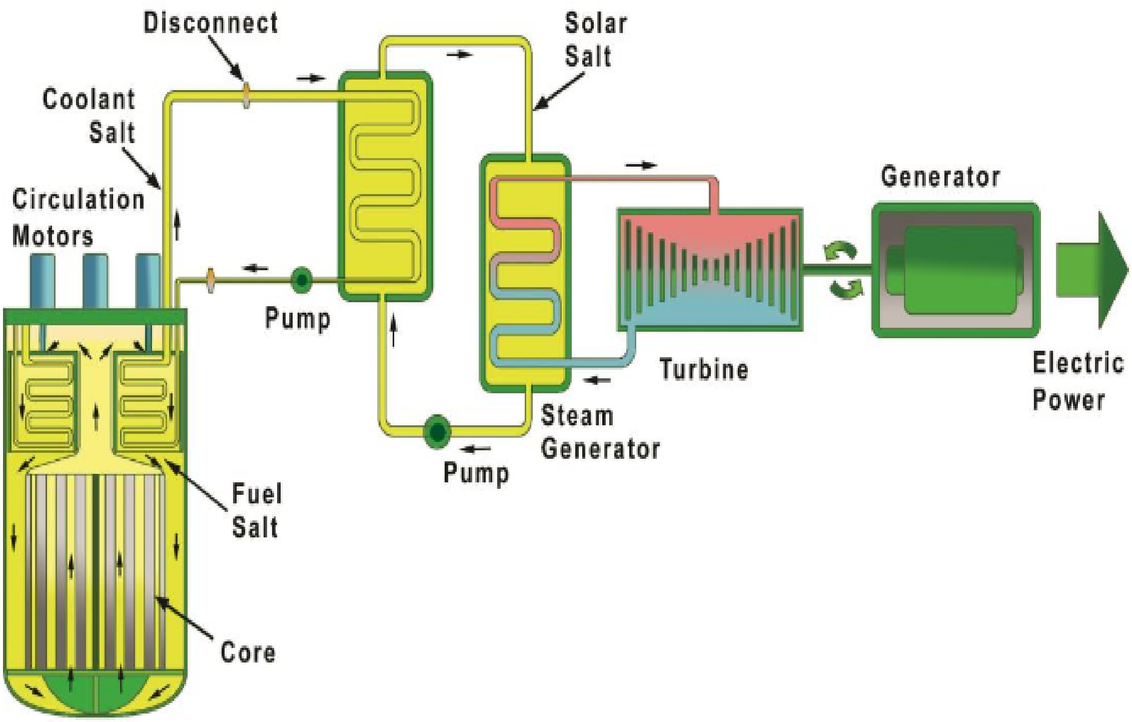

Figure 3: An IMSR scheme for electricity production

From the scheme above, we can see that there are two loops. One is the coolant salt loop, it gains heat from the IMSR core-unit then transfer the heat gained to the other loop which is called solar salt loop. The IMSR core-unit have the fuel salt as coolant, the fuel can be uranium fluoride, plutonium fluoride, thorium fluoride or a mixture of these. The salt in the coolant salt loop is also a fluoride salt but without the fuel and last the solar salt is a type of nitrate salt.

Since the IMSR is a Gen IV reactor, it achieves the necessary safety by the use of the molten salt, inherently stable nuclear core, the integral design and the fully passive backup core and containment cooling systems. The features cited makes the IMSR independent from operator intervention, powered mechanical components, cooling injection and support to things like electricity supply.

2.1.4. Stable salt reactor(SSR)

The stable salt reactor (SSR) is being made by Moltex Energy a company from UK. The SSR is a fast reactor without moderator [11], this way it's possible to destroy higher actinides like plutonium, americium and curium. It uses solid fuel. The design makes possible for continuous refuelling capability which allows the reactor to run indefinitely without shutdown and improve it's economic efficiency with reducing stress on components from the thermal cycling. A design outline for the SSR can be seen from the image below [12]:

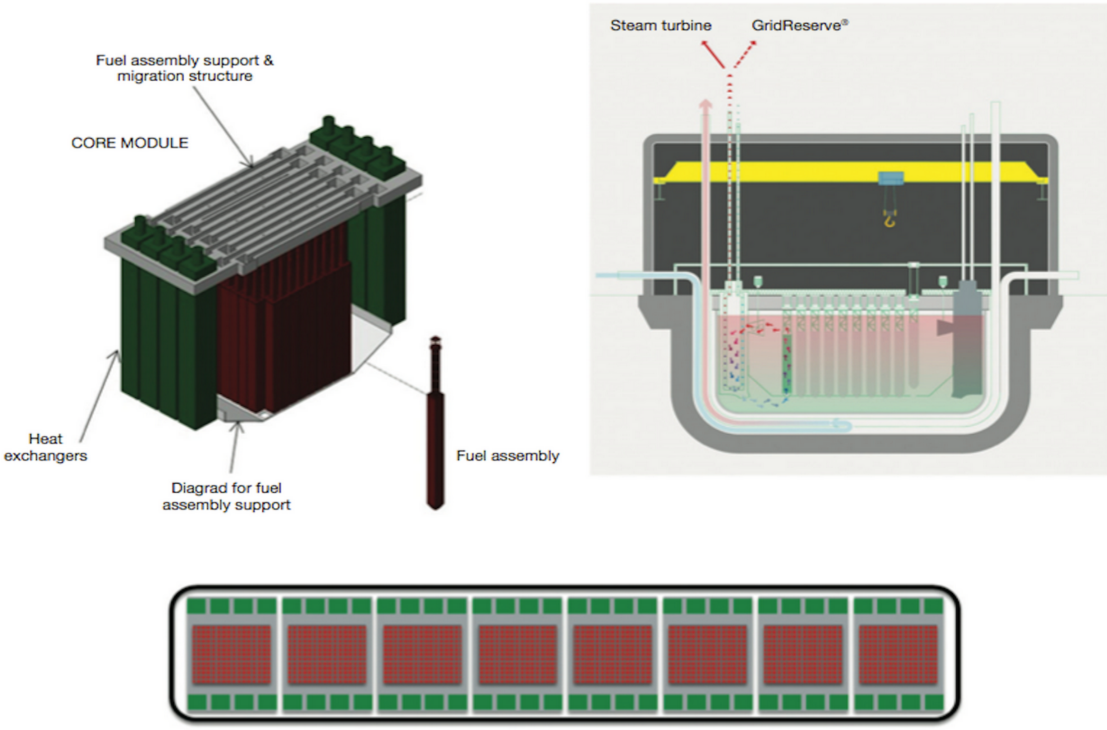

Figure 4: Basic design outline for the SSR

The rectangular core is one of the things that make the continuous refuelling capability to be viable. The fuel assemblies just migrate across the core in adjacent rows. Then fresh fuel assemblies are dropped at the end of row and spent assemblies are removed from the other end. The fuel assemblies are tubes made from zirconium containing uranium chloride salt.

The coolant system makes use of two coolants similar to the IMSR. The reactor controls are very simple and makes use of temperature and neutron sensors around the core, control blades in case of emergency shut down and reactivity is controled by the refuelling system. So the safety is obtained by the coolant system, reactor control and low pressure.

2.1.5. Thorium molten salt reactor

The Thorium molten salt reactor (TMSR) is being developed by the China Academy of Sciences [13]. It's aim is to develop energy from thorium and non-electric application of nuclear energy during the next 20-30 years. The choice for thorium comes from the fact, China doesn't have reserves of uranium and meanwhile thorium has larges reserves in China. There are two types one is the TMSR-SF(Solid-Fuel) and TMSR-LF(Liquid-Fuel). The TMSR-SF is optimized for high-temperature based hybrid nuclear energy application. And the TMSR-LF is optimized for the use of thorium and pyroprocess. They are doing test reactors and called TMSR-SF1 and TMSR-LF1.

The TMSR-SF1 is a FHR it produces 10MWt. And it's purpose is to verify the passive heat removal capability, temperature control, training of the reactor operator, investigate stability and safety and other things. It makes use of Tristructural-isotropic (TRISO) fuel, the core is a conventional pebble bed and uses a passive residual heat removal. Like other MSRs it uses two loops, the coolant for the first loop is FLiBe and for the second coolant is a mixture of LiF-NaF-KF (FLiNaK).

The TMSR-LF1 is a LFTR and produces 2MWt reactor. The purposes is to test online pyroprocessing, online refueling and continuous gas removing, to investigate stability and safety in the operation. Do operation with Thorium-Uranium (Th-U) mixed fuel and experiment of Th-U conversion. It uses FLiBe as a coolant and the core design is simple. So it's possible to have negative temperature feedback, low excess reactivity and permits to use an appropriate amount of Thorium, to verify the ^{233}U/Th fuel cycle.

2.1.6. Indian molten salt breeder reactor

The Indian molten salt breeder reactor (IMSBR) is being developed by Bhabha Atomic Research Centre (BARC) [14]. They have major goals for the IMSBR. Some of the goals are electrical power of 850 MWe, reactor design based on the ^{233}U/Th fuel cycle, a breeding ratio sufficient for self-sustaining and high efficiency in power conversion system around 45%. The others are more of details of the reactor itself and won't be cited here. A scheme for the IMSBR can be seen below [14]:

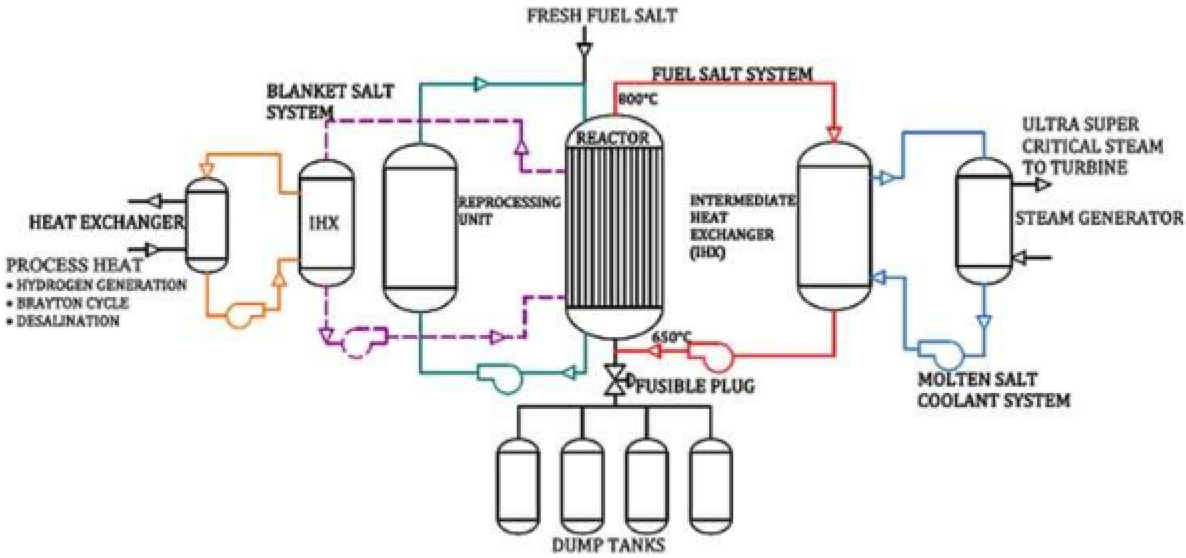

Figure 5: Scheme for the loop-type IMSBR

Two versions of the IMSBR are being designed. One design is based on the loop-type concept and the other is a pool-type concept. The selected blanket salt is the LiF-ThF_4 with a certain amount of UF_4 that depends on the reactor requirement.

2.2. Use of Thorium as Fuel

As we can see from the previous sections, there are a lot of different types of MSR that can use the thorium as a fuel. The possibility of using thorium is because of it's reserves around the world and thorium fuel cycle. The TMSR is an example of why thorium having reserves around the world is an advantage. The thorium fuel cycle can be open or closed [15]. The first step of both cycle are to convert the ^{232}Th into the ^{233}U. It's done when ^{232}Th, a fertile material, capture a neutron followed by two beta decays. Then they differ, details aside, the open cycle doesn't recycle the ^{233}U and the close does.

The open cycle, also called once-through fuel cycle, basically avoids the difficulties that come from the reprocess of the ^{233}U based fuels. One application of this cycle could be the incineration of weapon-grade plutonium (WPu) in combination with the use of thorium in light-water reactors (LWRs) of Russian WWER-1000 type to burn and not breed ^{239}Pu.

The closed cycle basically reprocess the thorium fuel to recover the ^{233}U and fabricate ^{233}U/Th fuel. One of the advantages for this cycle, is the possibility of the creation of a breeder reactor. That means it's possible to create a self-sustainable reactor, if giving the reactor an initial fuel to begin the cycle. The close cycle for uranium and thorium can be seen below [16]:

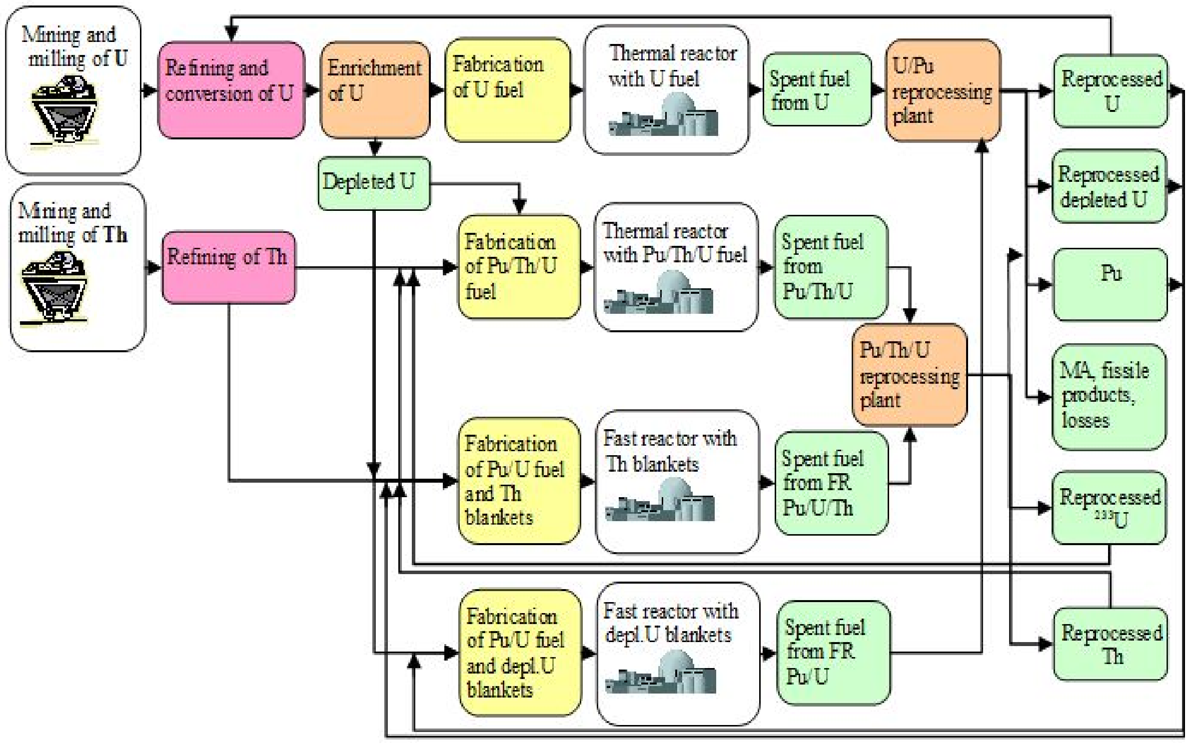

Figure 6: Closed fuel cycle based on thermal and fast reactors using thorium and/or ^{233}U

Considering the Gen IV objectives, most of the different types of MSR are gonna make use of the thorium closed fuel cycle. Aside from those cited in the previous sections, there are others MSRs that uses thorium as fuel. Like the Fuji MSR, thorcon MSR and Fiber LFTR, for example. The use of thorium as a fuel is physically possible and already happened in some reactors like Fast Breeder Test Reactor (FBTR) by India and even the MSRE [15]. And the fact most of the MSRs are breeder reactors makes it attractive for the Gen IV goals. But the MSR as a whole still needs research before being economically viable for electricity production and/or hydrogen production.

3. CONCLUSIONS

The MSRE already showed us that the MSR technology with thorium as a fuel is possible. And the fact that countries like China, India, USA, UK and others are doing research towards the viability of the MSR via different concepts with thorium as a fuel. Makes it one of the technologies capable of changing the way the world produces energy and view the nuclear energy as a whole. Not only to be known by disasters like Chernobyl and Fukushima, but as an efficient, safe and sustainable way of producing energy.

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