Department of Mechanical and Aerospace Engineering

Research in to a thorium reactor, thorium infusion and pressurized water reactor

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Signed:  Date: 23.08.2018

Abstract

The aim for this thesis is to research positives and negatives of the use of thorium and different infusion options. First looking in to the history of the nuclear reactors which is the basis of what has become the reactors we know today and the start and end of the molten salt reactor research and experiments from the 50s to the 70s/80s. After the history it is looked in to the technical data and how a pressure water reactor works, named the APR1000 using the conventional uranium fuel cycle, as well as the molten salt reactor conceptual design from 1971 using the th-u233 fuel cycle and the option of infusing thorium in certain amount in to the existing light water reactors together with other elements. To look in to the elements thorium and uranium first it is calculated the difference in the use of th-u233 and fuel containing just enriched u235 with fluoride salts in the molten salt reactor to see the difference in heat transferred, where the enriched uranium creates more heat. The second calculations looks in to the energy released from fission in the th-u233 cycle, where the u233 is fissioned, for therefore to calculate the energy released from the fission of Pu and U235 and then comparing those two to see how much potential energy is possible. The two has almost the same amount of energy released in the fission process for 1 kg of fuel, but the U233 has a higher potential chemical energy. After that it is looked in to the mining and waste management for the three different options, where the infusion of thorium is mostly the same as the thorium molten salt reactor but depending on if it needs uranium has the same mining as the conventional cycle and that it will not be a breeder. Otherwise the thorium doesn’t need mining since it is a bi-product from other mining operations, only natural uranium needs to be mined.

Acknowledgements

I wish to thank my friend Sigrid Irene Birkelund who sent me the first article on thorium that I ever read and tipped me about this interesting topic that I didn't know anything about beforehand. I also want to extend my gratitude to my supervisor Mr Cameron Johnstone for supervising my writing and Dr Paul Gerard Tuohy for advice and assistance.

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1. Introduction

Nuclear energy makes up around 11% of 2015/2016 energy generation in the world, but in the OECD countries the generation is 18.1%. This is 34 countries in an Organisation for Economic Co-operation and Development, including United Kingdom, United States and Norway.

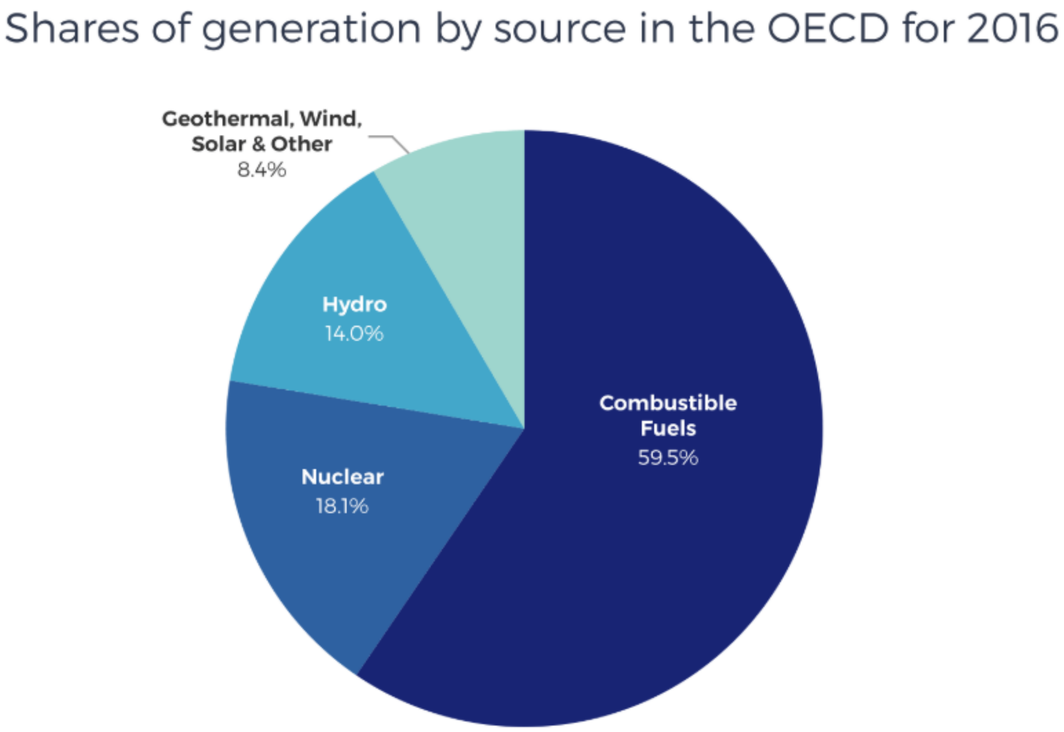

Figure 1: This show the type of energy generation used in the 34 OECD countries in 2016 in percentage

The demand for energy is increasing as the developing countries get better access to electricity and the world population is increasing, and therefore the need for finding new options for energy generation is present and will be more necessary in the future. Because of this the technology needs to be developed today before the need for electricity is to big.

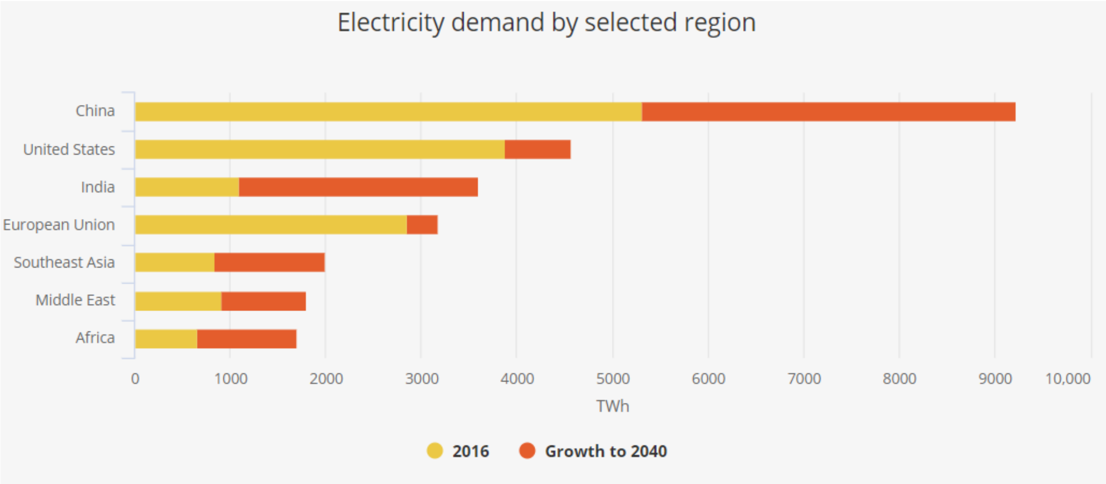

Figure 2: This show the predicted electricity demand growth from 2016 to 2040 in different areas and countries in the world

Reactors using uranium 235 is the option that is used the most today, but some of the reactors lifespan is running out and it is important to figure out if it is possible to use the existing ones and infuse thorium or make new reactors to replace the old ones.

Thorium is starting to become an important research field, both China and India are trying to figure out how to use it in a reactor, one of the most promising ones is the molten salt reactor which is a technology that was found in the 60's but stopped its development in favour of the uranium reactors we know today.

The research in to these molten salt reactors using thorium is still in the researching stages and the problems with it is that it needs to be go through experiments to learn more about how it will act when operating. Why hasn't it been done before if it is so good, is it actually possible and what is the feasibility and viability of it being used in the future is some of the things looked at in this thesis.

Overall aim and research question and objectives:

Aim: To identify the positive and negatives with using thorium in exiting reactors and MSR compared to uranium.

For first to understand why the technology and use of thorium isn't in use today the history of nuclear energy needs to be researched.

History/background:

1.1 Nuclear power:

First inn 1938 in Berlin the nuclear fission process was first recognised by Otto Hahn and Fritz Strassmann, but it had already begun being research in 1933 by Leo Szilard and Niels Bohr. Leo Szilard had back then patented the possible chain reaction of nuclear atoms for use in bombs. Niels Bohr was the one that found that Uranium-235 was the atom that could fission by low energy neutrons, his theory was the Liquid drop model where only the odd numbered isotopes could fission by low energy neutrons. But up until 1938 the research had been slow, but then when the war started the interest in nuclear reactions increased for use in warfare and the developments increased.

What they did was to bombard uranium with neutrons and saw that it was split in two, by the help of Lise Meitner and Bohr's liquid drop model.

The Bohr's liquid drop model, also known as just liquid drop model, was a theory on how nuclear fission took place, and was formulated by Niels Bohr. The reason why he called it liquid drop model was that he theorised the nuclear fission to mimic the way the molecules of a liquid drop would split, where the nucleus would split because of the positive charge inside it.

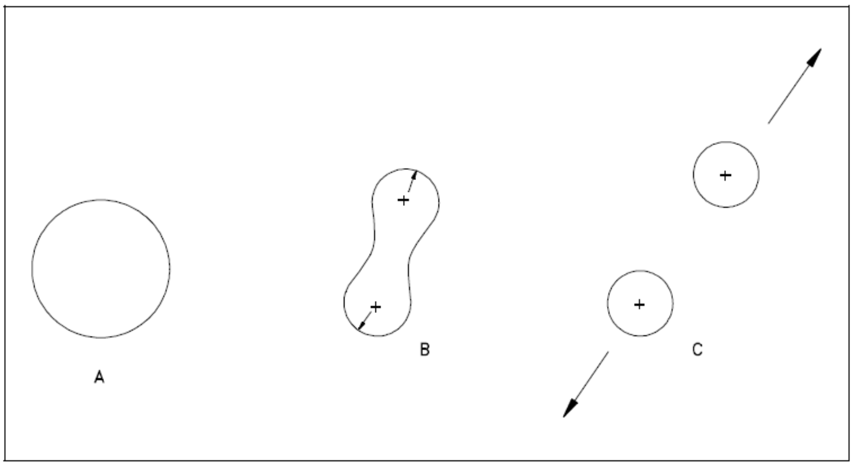

Figure 3: This is a picture of Niels Bohr liquid drop model and the first depiction on how a nuclear fission would occur

The nucleus is the centre of the atom, which is positively charged and consists of protons and neutrons, where the protons are the positive charged and neutrons have no charge. Around it is the electrons which is negative charged, and even though the electron is attracted to the protons they move so fast that they move in an orbit around the nucleus. The number of the protons in the nucleus defines which element the atom is, and the number of neutrons defines which isotope the atom is. So, the $^{235}_{92}U$ top

number is the nucleon number which is the protons + neutrons and the bottom one is the number of protons. This one has 92 protons and 143 neutrons. An isotope is then when the atom has the same number of protons and different numbers of neutrons, in this instance it is $^{238}_{92}U$ which has 92 protons but 146 neutrons.

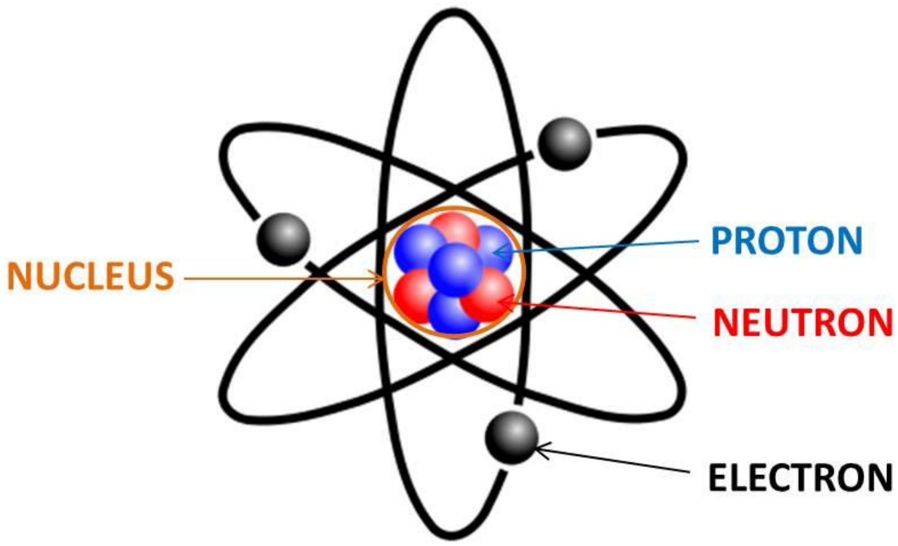

Figure 4: This show how what an element consists of, the nucleus which is the name of the core that consists of protons and neutrons together and electrons circling around the nucleus

The scientists used this theory to explain how an extra neutron had caused a vibration in the nucleus of the uranium and causing it to split in two.

Then the following year Lew Kowarski, Fredric Jolito and Hans von Halban discovered that this splitting of the uranium nucleus also released neutrons, which could indicate a possible chain reaction. Which Leo Szilard had patented in 1933.

Figure 5: This is the logo for the Manhattan Project, where the aim was to build bombs

Then in 1941 the Americans joined world war two and the following year they created the Manhattan project. The Manhattan project was a collaboration between scientists working in different universities to create nuclear bombs, where the material used was 239PU and 235U to be used for warfare.

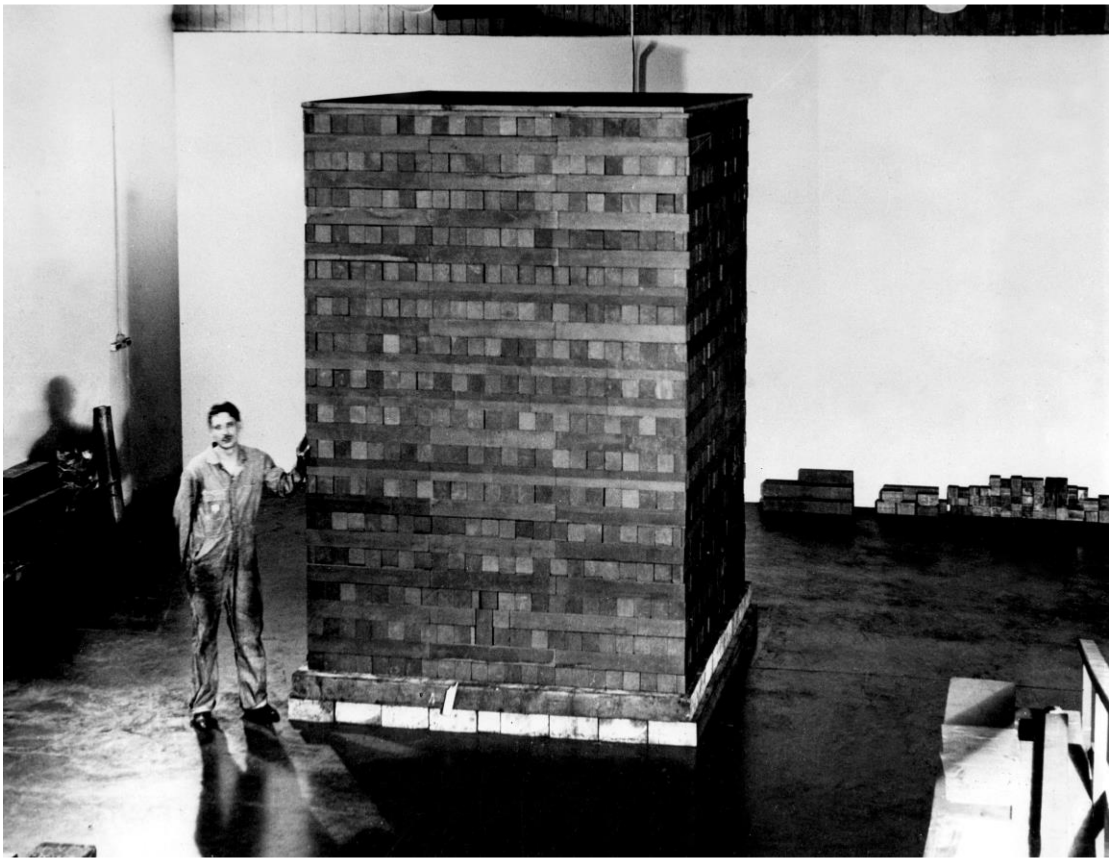

Figure 6: This show the 349 tonnes of graphite used in Chicago Pile-1

The first successful controlled and critical nuclear chain reaction and the creation of the first nuclear reaction happened in December of 1942, at University of Chicago, and was done by Enrico Fermi. This was called Chicago Pile-1. It consisted of 349 tonnes of graphite, 36 tonnes of uranium dioxide and 5 tonnes of uranium metal. This one had 2 watts power, and within two years they were able to scale it up to 250MW.

Later, the Manhattan project led to three bombs being created, one uranium bomb called Little Boy, one plutonium bomb called Fat Man, and the third one was never used. Little Boy and Fat Man was released over Hiroshima 6th of August 1945 and Nagasaki 9th of August 1945, both cities in Japan.

After the war the first commercial nuclear power plant was built in 1957 near San Jose, America, this was only a 5MW(e). Then based on this successful project there was built a 210MW(e) in 1959 in Illinois. Both of these were boiling water reactors. This is reactors where purified water is being heated by the fission and creates steam that again drives a steam turbine that generates electricity.

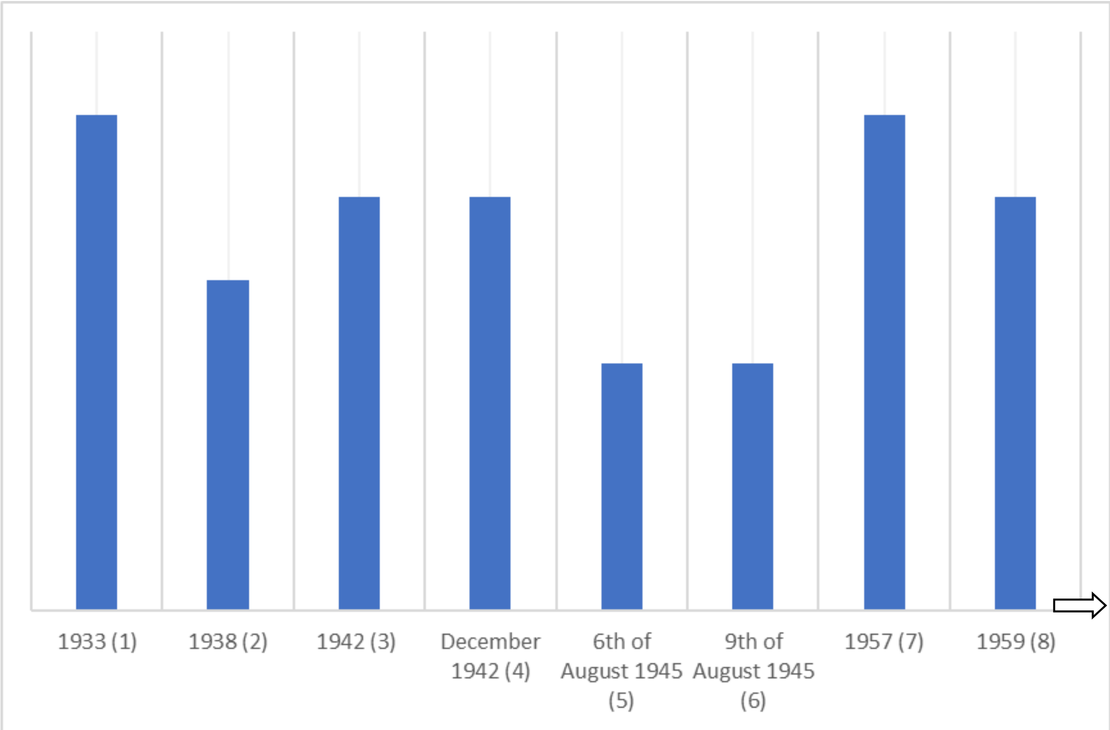

Figure 7: Key dates in the history of nuclear power, 1. Research in to fission of uranium and patented, 2. Fission recognised, 3. Manhattan project, 4. First successful controlled and critical nuclear chain reaction - Chicago Pile – 1, 5. Little boy - released over Hiroshima , 6. Fat man - released over Nagasaki, 7. First commercial nuclear power plant - 5MW(e), 8. 210MW(e) nuclear power plant

The statistics from June 2018 shows that the country with most operable nuclear powerplants is the US with 99 reactors and France is in second place with 58. The UK has the same as Ukraine, and that is 15 running nuclear powerplants.

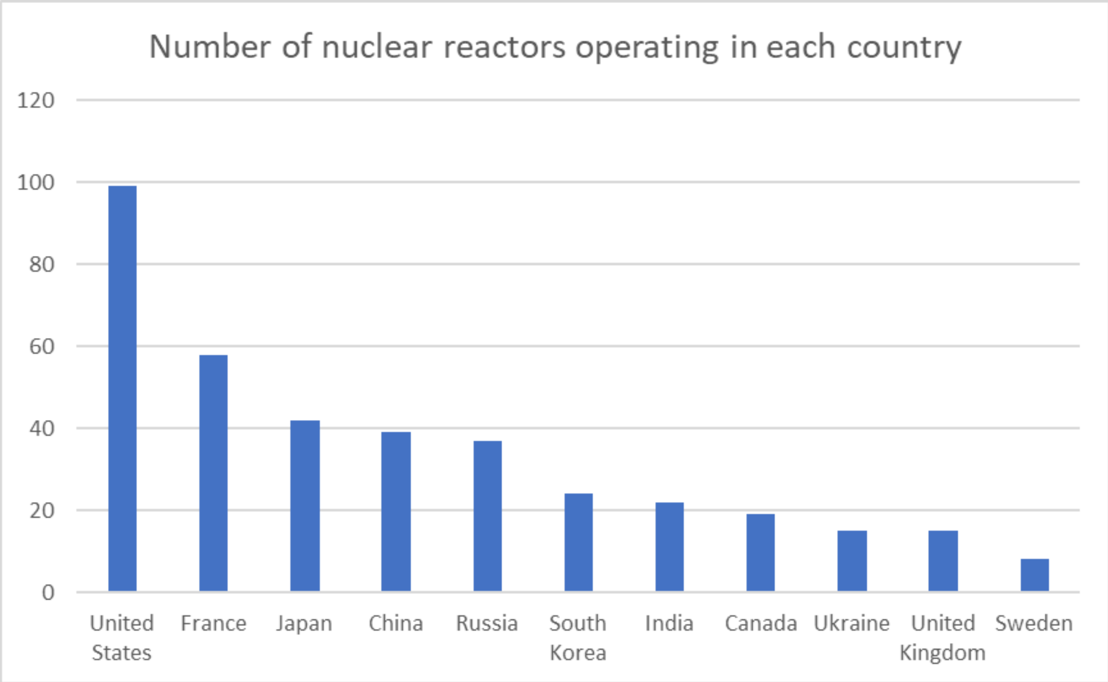

Table 1: Number of nuclear reactors in operation by country

This is top 11 countries in the world on how many reactors they have operating. As of February 2018 there is 449 operable nuclear reactors global.

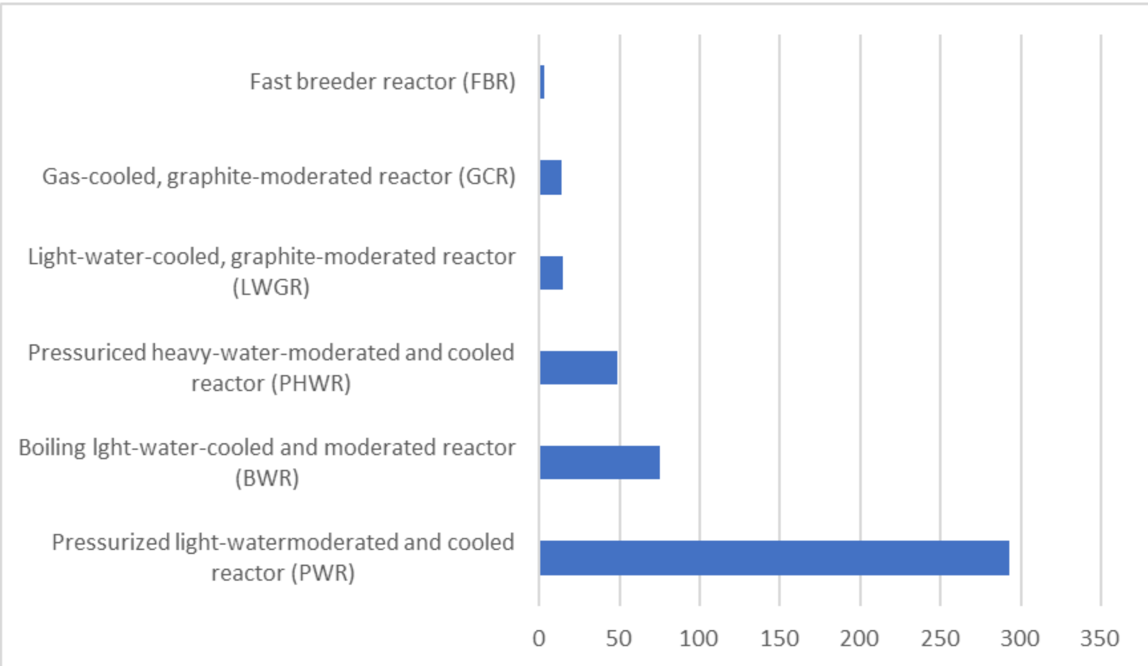

Table 2: number of operable nuclear reactors worldwide, by type where the most used is the pressurized water reactor

1.2 Molten salt reactor (MSR):

The start of the Molten Salt reactor was later than the uranium, it began in the late 1940's, when it was discovered that liquid fuel would have several advantages for nuclear powered airplanes, specifically in using a molten salt reactor in the US's program to try and power it using nuclear power. Then in 1947 the scientist doing experiments with MSR and molten-salt fuels (MSF) started to look at feasibility.

The scientists who started the research in to MSF wanted the program in Oak Ridge National Laboratory to start looking at mainly MSF, which they did in 1950. The program was on Aircraft Nuclear Pollution, and MSF had a lot of advantages since they have low vapor pressure even when it is super heated, high solubility for uranium (easy for uranium to dissolve in MSF), don't react violently to air or water, have reasonable good heat transfer, it is among the most stable chemical compounds, it is not damaged by radiation and is inert to some of the common structural metals (means that it will not react chemically to some of the common structural metals).

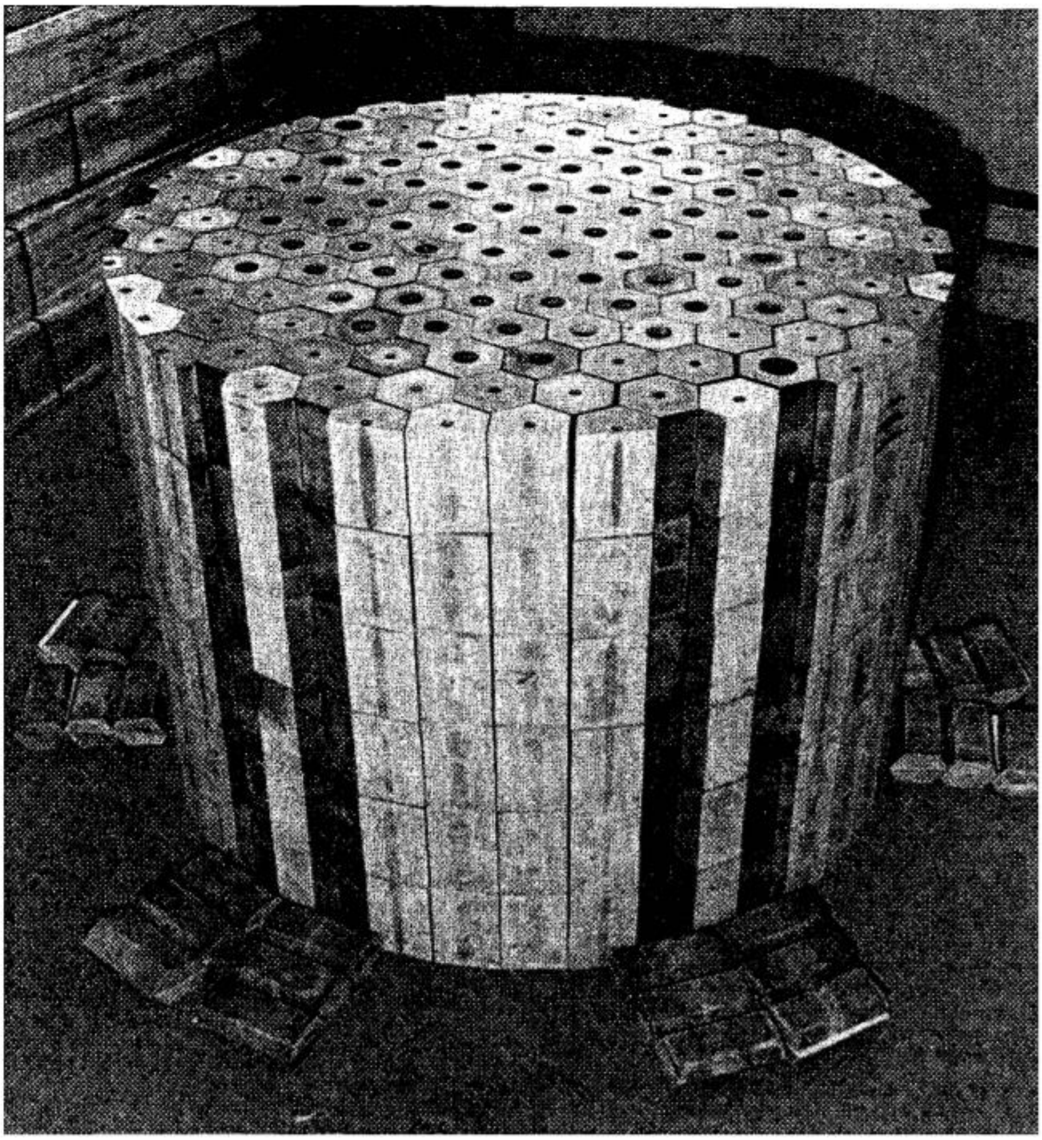

Figure 8: BeO moderator blocks used in the ARE

From this, a small reactor was built, and the Aircraft Reactor Experiment (ARE) was started. They looked in to the use of molten fluoride fuels for aircraft propulsion reactors and to see how stabile nuclear chemicals was in the circulating fuel system. They used a fuel salt containing NaF-ZrF_4-UF_4 and the moderator was BeO which is Beryllium Oxide, and the material used for the piping was inconel. The ARE was operated for 9 days at steady-state outlet temperatures going up to 1133K and was stable and self-regulating, this was 4 years after it was started in the Oak Ridge national laboratory. They did not have any chemical or mechanical problems.

Through all this research it was always known that MSR could be attractive for civilian power usage, not just as aircraft propulsion reactors, and in 1956 there was a group started by H.G. MacPherson to study the nuclear performance, technical characteristics and economics associated with molten-salt breeders and converters for commercial usage. This group worked for years and in the end ended up with that the best fuel to use was thorium with recycled 233U in a graphite-moderated thermal reactor. They concluded with that it would perform better than if they used 238U and recycled plutonium. They rejected a reactor which used salt also as a moderator because it did not make as good a thermal reactor as where the graphite moderator did. The group also looked at two types of graphite-moderated reactors, which was the single-fluid reactor and two-fluid reactor. The single-fluid reactor would have thorium and uranium in the same salt whereas the two-fluid would have them separated in to two different salts. The differences was that the single-fluid would be simpler to build and have lower power cost, but would not have the same breeding ratio as the two-fluid reactor, it would be less than 1.0 with the technology they had available. During the ARE they were able to demonstrate that it was possible to remove uranium from fluoride salts, and was called the fluoride volatility process, and was therefore available for partial processing of salts from either the two of the reactors.

In 1960 the conceptual design stage was in full swing, these design had the most emphasis on two-fluid reactors since it was a better breeder and had better nuclear performance, they also studied the single-fluid. Even though the ARE was running for 9 days fine, they needed to do more experiments to investigate some of the technology for the reactor more. The design of the Molten-Salt Reactor Experiment (MSRE) was then started in the same year.

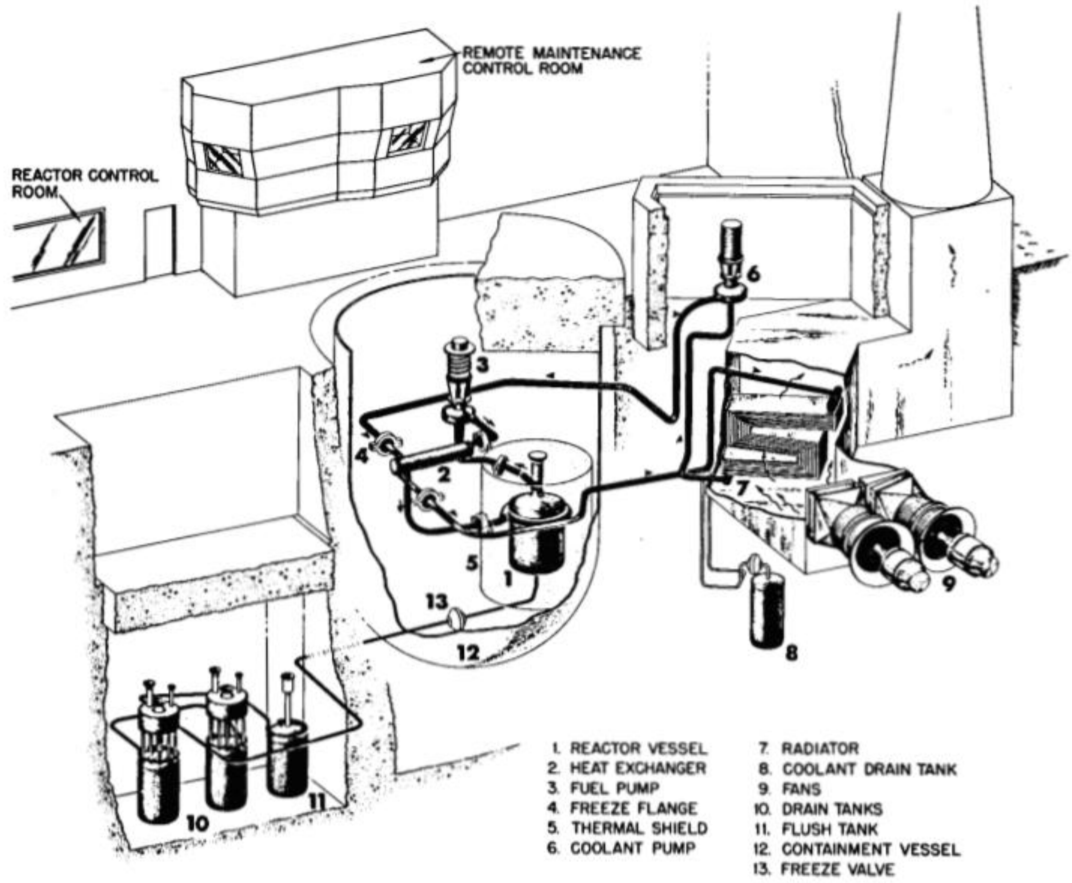

Figure 9: Flow diagram of the MSRE

The end result of the MSRE was a single-fluid reactor, but the fuel salt did not contain thorium, so it was more of a two-fluid breeder in that way, where the thorium was separated from the uranium in two different fuels of a two-fluid breeder.

The fuel salt was a mix of uranium 235, lithium-7, beryllium and zirconium fluorides and the moderator was unclad graphite. Where unclad means it has no protection layer. All the parts in contact with salts was made from nickel-base alloy, INOR-8. This was specifically made for the previous ARE for the parts in the reactor where the parts would be in contact with salt.

Then in 1962 the construction began and this reactor went critical for the first time in 1965, and operation at full power began in December of 1966. A 6 month successful run was completed in 1968. The molten fluoride fuel, which had the chemical composition LiF-BeF_2-ZrF_4-UF_4, temperature was higher than 920K for many months without any rust or corrosive attacks on the different parts, the same for the graphite.

They were also able to contain the gases and radioactive liquids safely that was created while running and the fuel was completely stable. They were also able to replace or repair equipment without overexposing maintenance personnel to radioactivity.

Then the second phase started, where they replaced the 235U with 233U, this was in August of 1968, and that same October it was made critical, and six days after going critical it was running at 100kW and was the first reactor to operate on 233U. Later the fissionable 239Pu. The reactor ended up being shut down in December of 1969.

During the MSRE it was also done chemical tests and research and they found a on-site way to separate rare earths from lithium fluoride and beryllium fluoride in fuel salts via vacuum distillation at temperatures near 1000C. After this it was focused on two-fluid breeders where the fuel would be fluorinated to separate the carrier salt from fission products and recover uranium. This is done by bubbling fluorine gas through the salt. But then in 1967 new experimental information and advances in core design cause the program at ORNL to change back to single-fluid breeder, because it showed that the fuel utilization could be almost as good as a two-fluid reactor and that it could possibly be better economically. And it was therefore they did experiments with a single fluid molten salt reactor.

Even though the MSRE was successful, in the early 1970s the program funding at ORNL was cut down, because the US wanted to invest more in the liquid metal fast-breeder reactor, the reasoning was that this reactor was well advanced in the 70's and the MSR still had a large amount of research, developments and tests still remaining to be done. They still continued the some of the program until early 1980s with making designs, and also proposed a new design that could solve the problems they had in the 70s, and this was called Denatured molten salt reactor.

There is no molten-salt reactors up and running, but there are several conceptual designs and under design globally.

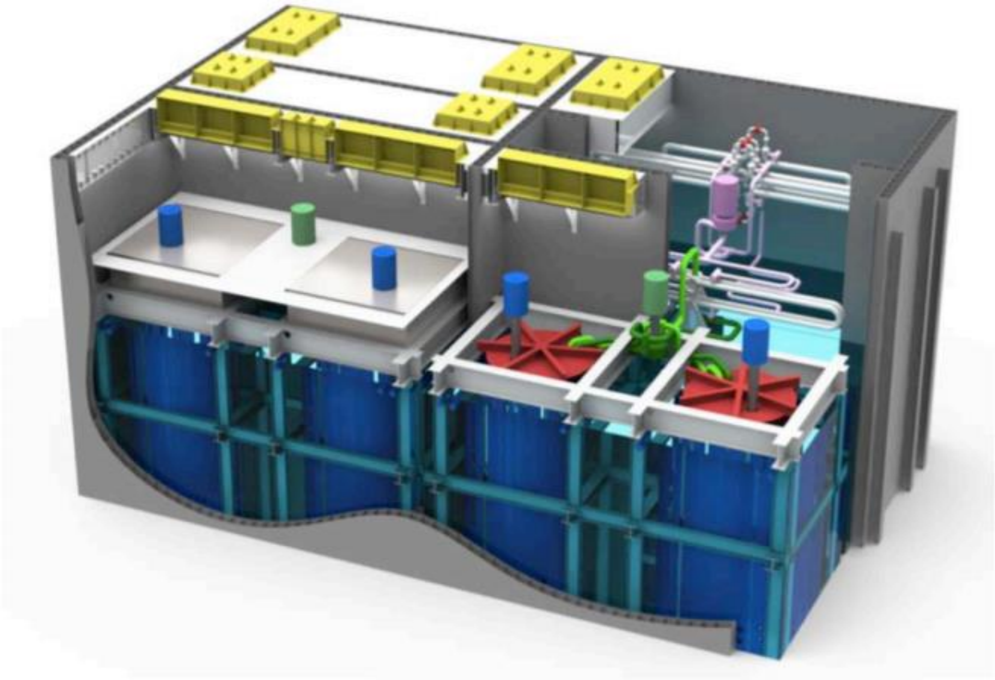

Figure 10:ThorCon conceptual design

One of the newer conceptual designs are the ThorCon. It is a MSR that is under design in the US and a scale up of the MSRE, and uses the same fuel as the 1971 conceptual design made by ORNL just with different mol % in the fuel of the different chemicals. NaF-BeF2-ThF4-UF4 → 76/12/9.5/2.5 is the new mol composition - 71.7-16-12-0.3 is the old mol composition, the new one have less thorium and more enriched uranium. The previous is less than 5% enriched uranium, and the new is 19.7% U235.

To try and increase the development of reactors a forum called Generation IV International Forum(GIF) was established around the 2000's. GIF is a collaboration of several countries who share research and development of six different reactor types to try and advance the technology and look at feasibility and performance capabilities. These are Molten salt reactor, gas -cooled fast reactor, lead-cooled fast reactor, sodium-cooled fast reactor, very high temperature reactor and supercritical water-cooled reactor.

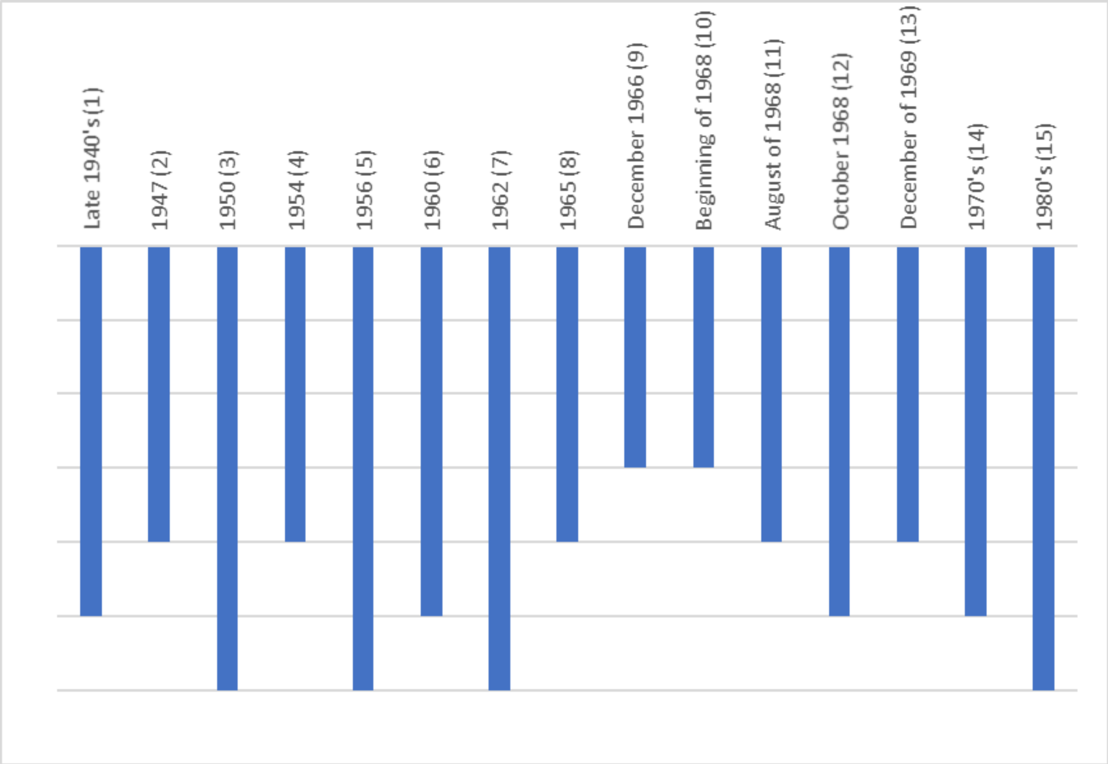

Figure 11: Key dates for the history of MSR, 1. Research in to liquid fuel, 2. Feasibility research of MSR and MSF, 3. ORNL started to look at MSF trough the ARE, 4. ARE operating for 9 days , 5. Study of nuclear performance, technical characteristics and economics associated with MS breeders and converters, 6. Conceptual designs, 7. Construction of a MSR using U235 in fluoride salts as fuel, 8. The MSR went critical, 9. At full power, 10. Completion of a 6 month run, 11. Replacing U235 with U233 in the fuel, 12. Went critical using U233, 13. Shut down of the MSRE, 14. Financial support cut down, 15. Shut down of the project and research completely

2. Technical data and how it works:

2.1 Nuclear reactor:

Nuclear reactors are either fission driven reactors or breeders.

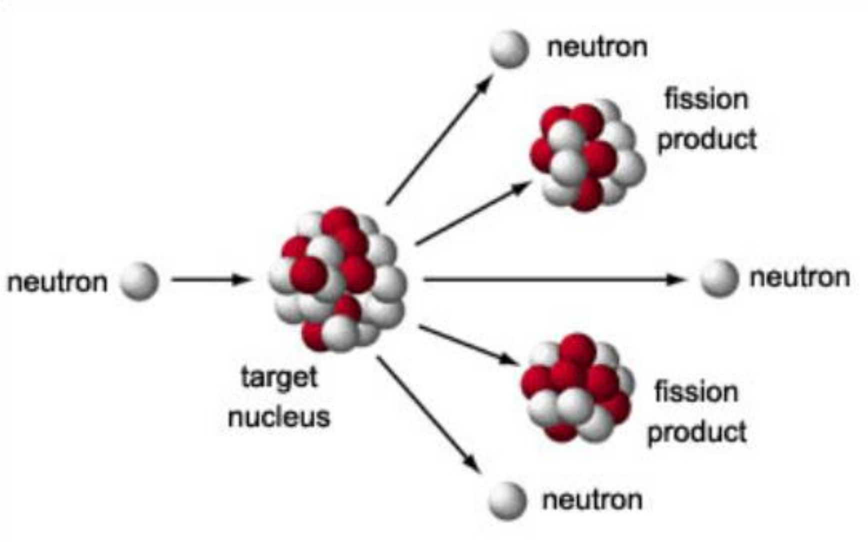

Figure 12: This show the fission process and the results after an element has gone through fission

The fission process is a chemical process where one element gets hit by a neutron and splits in to two new elements (and new neutrons) and the new elements also gets hit by the new neutrons created and splits again. This reaction is called a chain reaction and creates heat. The heat is used to heat up water to create steam that drives a steam turbine for then to generate electricity. The elements possible to use in a fission reactor is Uranium 233, U235 or Pu239, which is fissile isotopes.

The most standard nuclear reactor uses uranium 235 and 238 as fuel but some research suggests that thorium 232 is an option that can create just as much energy but with less space with pure thorium or use the current reactors but infuse the thorium in to the uranium fuel.

If companies want to create new reactors just for thorium the molten salt reactor (MSR) is the most promising. It can use both fluid and solid fuel.

The nuclear reactor most used today is the pressurized water reactor (PWR) also known as pressurized light water reactor. There is 293 of these running as of February 2018.

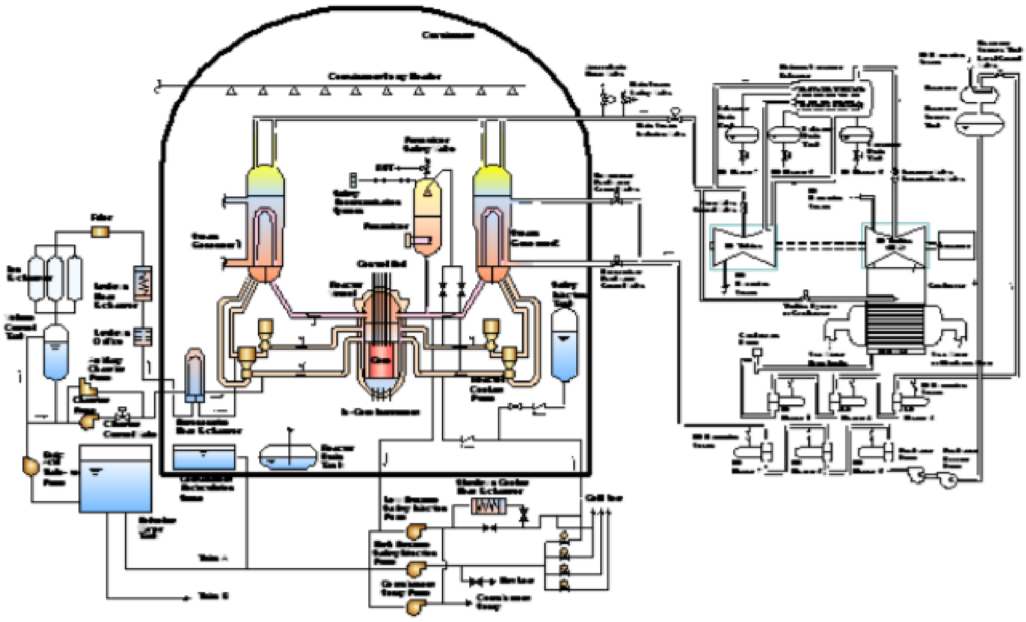

Figure 13: The APR1000 scheme of the primary components

The pressurized water reactor used for comparison in this thesis is the APR1000, (which is an improvement of OPR1000). It uses Gd_2O_3-UO_2 fuel rods. The Gd_2O_3 is gadolinium oxide and UO_2 is uranium dioxide, where the uranium is low-enriched uranium, and that means that the 235U content is 4%, the rest is 238U. Naturally the percentage is different than the one used in reactors, in the earths crust U235 is only 0.7% and the rest is U-238.

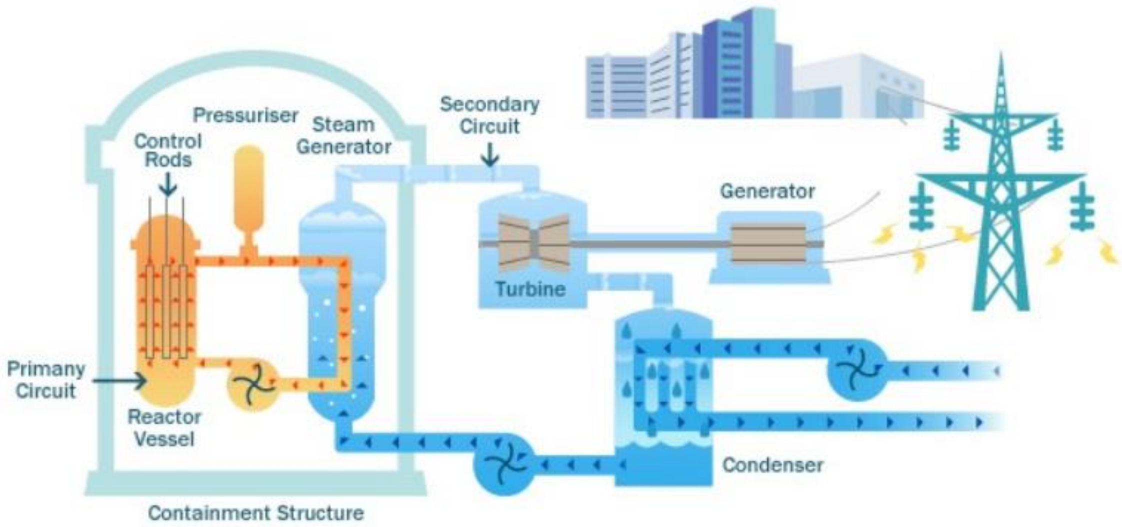

Figure 14: The primary components of a pressurized water reactor

The primary components of a PWR is the reactor vessel where the 235U fuel rods are, then pressurized water is passing through the reactor core to transport heat to the steam generator and works as a moderator to slow down the neutrons in the fission process. The reason for using pressurized water is that when water is under high pressure it will have a higher boiling point, so it will still be fluid at a much higher temperature. Therefore, the water running through the reactor which is under high pressure will stay fluid and not turn in to steam.

Then when this water reaches the steam generator heat transfer happens, cold water (also called feed water) comes in and gets heated by the warm water from the reactor and steam is then created, because the feedwater is not under pressure as the reactor coolant. This steam will then travel to the steam turbine where the steam is used to make the turbine run and creates mechanical energy from the thermal energy. This turbine is connected to a generator that transform the mechanical energy in to electrical energy.

After the steam has been to the steam generator it is discarded to the condenser, where it is cooled down by either a cooling tower or possibly a natural water source nearby, then becomes water again, for then to return to the steam generator as feed water.

This reactor has an overall efficiency of 35.5% (in general around 33-37% for nuclear reactors). The reactor heat is 2815 MW(thermal) and the netto energy generated is 1000MW(electrical). The gross energy generated is 1050 MW, but 50 MW is needed to run the reactor and therefore the netto energy generated is 1000 MW.

To maintain the efficiency of around 35%, around 1/3 of spent fuel gets replaced with fresh fuel about once each year, 18 months or some do every second years, depending on protocol. The APR1000 has a refuelling cycle of 18-24 months.

When this is done the fuel waste from the nuclear reactors have 96% of the original uranium content, where less than 1% is U235, and over half the original energy content. Therefore, a lot of companies do something called reprocessing to extract some of the recyclable materials to use as fresh fuel. This decreases the radioactivity and the use for new uranium fuel.

2.2 MSR:

The MSR is a breeder. The breeder starts with one element that absorbs the first neutron, which is called a fertile element, for then to create a new element trough decaying. U238 and Th232 are two such fertile elements.

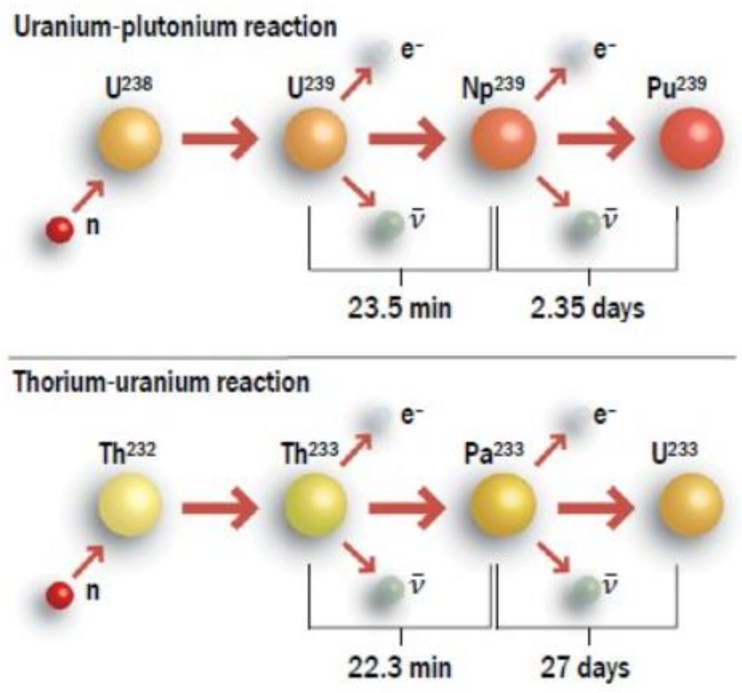

Figure 15: This show the fertile elements absorbing a neutron and how it decays to become a fissile element and the different decaying periods

U238 becomes Pu239 and Th232 becomes U233 through absorbing a neutron and the decaying process, and both these result elements are fissile. In the thorium fuel cycle the thorium that has absorbed a neutron needs to be extracted from the fuel and put in a separate containment part so it can decay to U233 and then it is put back in to the fuel where U233 is fissioned.

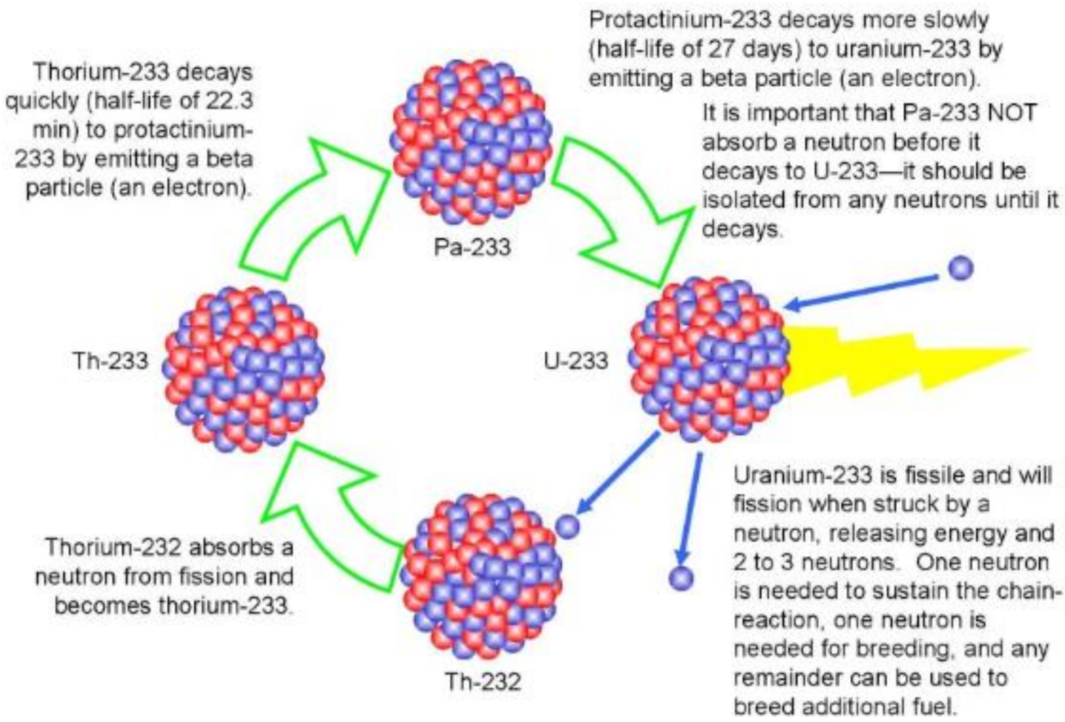

Figure 16: Th 232 fuel cycle more in depth

There are two different fuels used in the thorium molten-salt reactor, solid or liquid fuel, and generally the efficiency of a conceptual MSR system is estimated to be 45%.

The thorium molten salt – liquid fuel (TMSR-LF) used for this comparison is the conceptual design of a single fluid molten-salt breeder reactor using a liquid fuel from 1971, the fuel is LiF-BeF_2-ThF_4-UF_4. Lithium fluoride – Beryllium fluoride – Thorium tetrafluoride – Uranium tetrafluoride. The secondary salt is $NaBF_4$-NaF, Sodium tetrafluoroborate – Sodium fluoride.

The biggest problem with using fluoride salts is that it is corrosive and that means certain components needs to be replaced often and that there needs to be used a special kind of metal to slow down the corrosion prosses of the components that are in contact with the salts.

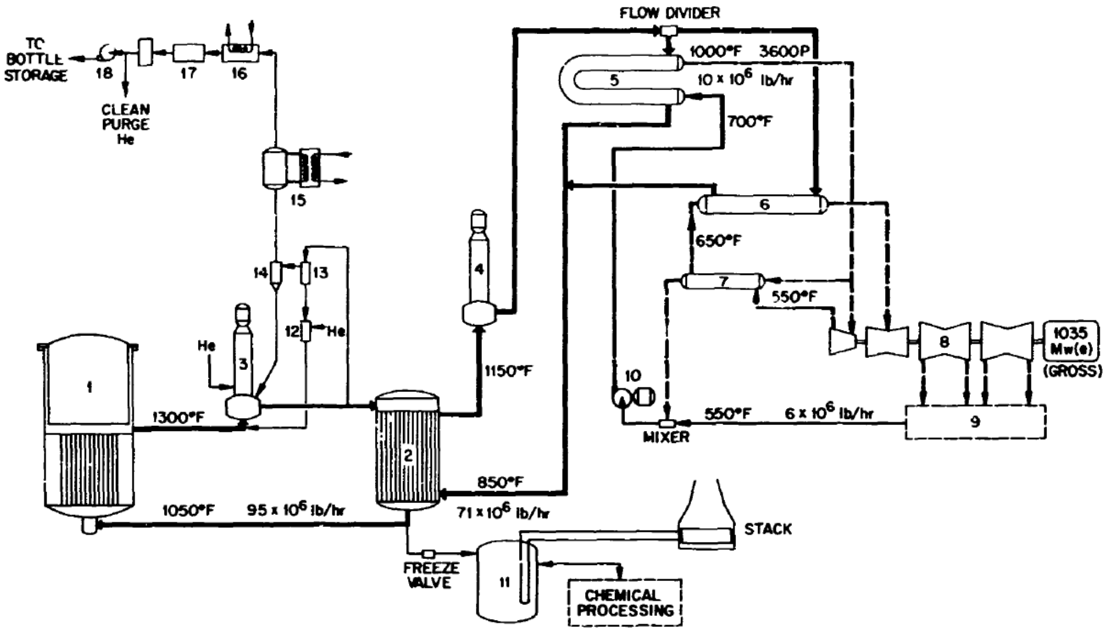

Fig. S.1. Simplified flow diagram of MSBR system. (1) Reactor, (2) Primary heat exchanger, (3) Fuel-salt pump, (4) Coolant-salt pump, (5) Steam generator, (6) Steam reheater, (7) Reheat steam preheater, (8) Steam turbine-generator, (9) Steam condenser, (10) Feedwater booster pump, (11) Fuel-salt drain tank, (12) Bubble generator, (13) Gas separator, (14) Entrainment separator, (15) Holdup tank, (16) 47-hr Xe holdup charcoal bed, (17) Long-delay charcoal bed, (18) Gas cleanup and compressor system.

Figure 17: Conceptual design study of a single fluid molten salt breeder reactor (ORNL-4541)

The primary components are the reactor where the graphite moderator is, and fission within that moderator raises the temperature of the fuel salt traveling through the reactor. Then the heated fuel salt travels to the primary heat exchanger where it exchanges heat with the secondary-salt in the second loop of the system. (point 1-2)

The second loop is where the secondary-salt goes from the heat exchanger for then to split in to two directions, one to the steam generator and one to the reheater. The salt transfer heat in these two places to heat the water so it becomes steam.

Then there is the third loop, which is the water/steam loop. Here the water is heated by the salt in the steam generator, for then to go down to the turbine, some of the steam not used goes back in to the preheater of the reheater for then to go to the reheater and back again to the steam generator. The steam that goes past the turbine goes in to the condenser where it is cooled down for then to be pumped back to the steam generator. This is a simplified version, there are more components overall.

This reactor have an calculate overall efficiency of 44.4%. The reactor heat is 2250 MW(t) and the netto energy created is 1000 MW (e), so 1000/2250 = 44.4%. The gross energy created is 1035 MW but 35 MW is used to run the generator. (In general around 45% efficiency for the MSR)

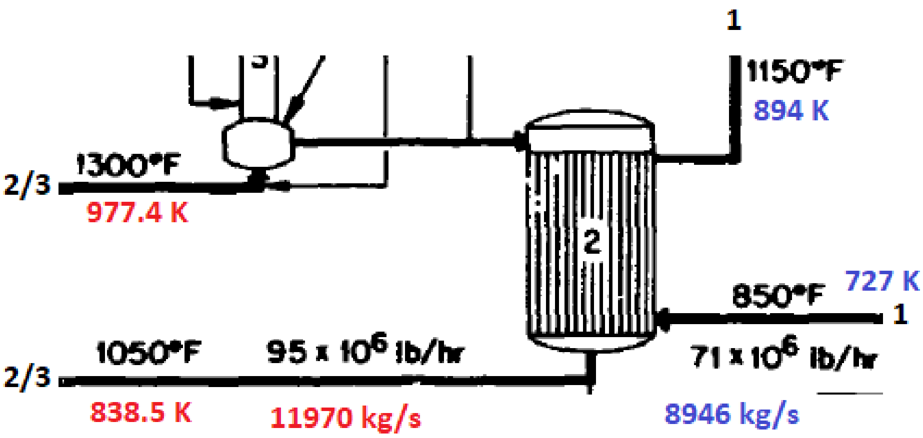

Figure 18: Conceptual design study of a single fluid molten salt breeder reactor (ORNL-4541)

The fuel in the MSR will double after 22 years, because it has a breeding ratio of 1.06. That means it produces more energy than it uses. The doubled fission product can then be used in a new reactor.

2.3 Infusion of thorium:

Last of the three options is the option of infusing thorium in to existing uranium reactors. Thor Energy is a company, based in Norway, looking in to and testing this option of implementing or replacing the conventional uranium cycle in nuclear reactors with thorium. They are a part of a consortium that supports a five year irradiation project and is done in close cooperation with the Norwegian Institute for Energy Technology (IFE). Irradiation is where something, in this case the fuel, is exposed to radiation, like gamma rays, and the irradiation test is to see what happens to the fuel while this happens.

They made a specially designed rig with six fuel rods containing different varieties of thorium fuel and was loaded it in to the reactor in April 2013.

They started a three-step program for different variations of thorium infusion or replacing the uranium cycle fully and just using thorium. The three steps are; adding thorium to the uranium cycle, supplementing thorium and plutonium to the uranium cycle and replacing the uranium cycle with the thorium-uranium 233 cycle.

The Thorium adding is where they would add 5-10% thorium in uranium oxide. Then the supplementing, thorium mox (MOX-mixed oxide fuel), which is 90%Th and 10% Pu, replacing the U-238 in the conventional uranium-mox fuel cuycle. The last one is to replace all of the existing uranium-mox fuel with thorium, where u233 is recycled.
The two first steps they say can be used in light water reactors. Light water reactors include the pressurized water reactor and boiling water reactor.

The difference between the pressurized and boiling water reactor is that instead of having pure water running through the core and transporting hot water to a steam generator like in the PWR the boiling water reactor creates steam in the reactor core itself.

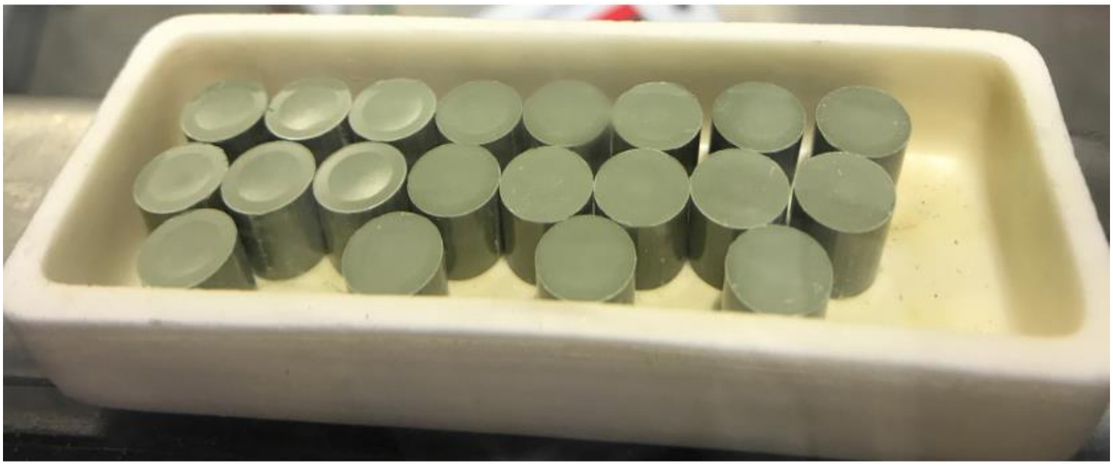

Figure 19: Th-MOX fuel pellets made by Thor Energy

In February of 2018 Thor energy together with IFE successfully produced th-mox fuel pellets, the reason they made fuel pellets was so it could be used in existing reactors. At OECD Halden they have a test reactor in a large cavern inside a mountain, where they inserted these fuel pellets in to two fuel pins and one with u-mox for reference, and for then to insert the fuel pins in to the test reactor. The irradiation is now under way. This is being tested with a focus on commercial deployment. This test reactor allows for continuous data collection while the fuel is operating, which can give data to show if it is safe to commercialize.

Figure 20: Holes at the top of the rig for sensors to be put trough and allows for continuous collection of data from the reactor at OECD

The reasoning for using th-mox, which is both thorium and plutonium, is that around the world it exists stocks of plutonium, and instead of using U-235 as the fissile driver, plutonium is used, and no new plutonium is created and can therefore use up the plutonium being stored around the world. By replacing the current uranium cycle with thorium-mox the nuclear reactors become safer, since thorium has a higher thermal conductivity and melting point, so it will not have a melt down as easily as the current reactors.

This seems like the only option that has gotten so far as to doing experiments, but the reactors will not be able to become breeders, and therefore use more fuel than it creates, unless tests show otherwise or more design changes is done.

3. Calculations:

Calculations are done to see the different quantities of heat transfer in the heat exchanger given different fuels in a single fuel system, but using the same secondary-coolant salt on the receiving side of the heat, which is then used to heat water. This is the design from 1971 conceptual design report by ORNL, the coolant is $NaBF_4$-NaF, Cp_1=1.507 kJ/kg K.

The two types of molten- salt fuel tested:

- Containing Th and U in one fuel – LiF-BeF_2-ThF_4-UF_4 Cp_2=1.357 kJ/kg K, which is the one suggested in the conceptual design report.
- Containing just U in the single fluid – LiF-BeF_2-ZrF_4-UF_4, Cp_3=1.967 kJ/kg K Which is the fuel composition used in the original MSRE

To find the heat transfer done by the fluids, the equation used is: $Q=\dot{m} \times Cp \times \Delta T$.

$\dot{m}$ is mass flow.

ΔT is the temperature difference.

First the two sides should equal each other, so $\dot{m}_1 \times Cp_1 \times \Delta T_1 = \dot{m}_2 \times Cp_2 \times \Delta T_2$.

Where:

$\dot{m}_1$ = 8946 kg/s , $\dot{m}_2$ = 11970 kg/s

Cp_1 = 1.507 kJ/kg k, Cp_2 = 1.357 kJ/kg K

ΔT_1 = 894 K – 727 K = 167 K , ΔT_2 = 997.4 K – 838.5 K = 138.9 K

This then gives:

8946 x 1.507 x 167 = 11970 x 1.357 x 138.9

2.25×10^6 kW = 2.25×10^6 kW

This means that there is no heat escaping in the heat exchanger and all of it is transferred to the secondary salt.

Then the fuel is replaced with the fuel containing just uranium to see how it will affect ΔT_1, assuming that everything except the Cp_2 changes to Cp_3 and ΔT_1 changes while using the same design.

$8946 \times 1.507 \times \Delta T_1 = 11970 \times 1.967 \times 138.9$

$8946 \times 1.507 \times \Delta T_1 = 3.27 \times 10^6$ kW

$\Delta T_1 = 242$ K

Changing the fuel to the one that only have uranium increase the temperature change on the other side by 45%, which may lead to higher quality in the turbine output.

The second calculation part is to see how much potential energy the two different fission processes can release.

The two different reactors use to different fission materials, PWR uses 235U 4% and the rest is the fertile 238U that decays to 239Pu and MSR uses 233U decayed from 232Th and some 235U just in the beginning (0.3%) to get the process starting.

To find how much energy each 233U and 235U release the equation $E=mc^2$ is used, where E is the energy released in J, m is the mass defect which is mass before minus mass after chemical reaction, and c is the velocity of electromagnetic radiation in vacuum.

The three reactions used here: (the results after the fission may vary in what type of elements it creates, this is one of the possible outcomes)

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n$$

$${}^{239}_{94}Pu + {}^{1}_{0}n \rightarrow {}^{134}_{54}Xe + {}^{103}_{40}Zr + 3\,{}^{1}_{0}n$$

$${}^{233}_{92}U + {}^{1}_{0}n \rightarrow {}^{137}_{54}Xe + {}^{94}_{38}Sr + 3\,{}^{1}_{0}n$$

(find the molecular weight X amounts of u and to find kg you multiply that number with the atomic mass unit 1u= 1.66×10^{-27}. So for 235 U it has a weight of 235.044 u = $235.044 \times 1.66 \times 10^{-27} = 390.173 \times 10^{-27}$ kg.)

The different elemental mass is in 10^{-27} kg:

Particle	Mass
$^{1}_{0}n$	1.675
$^{235}_{92}U$	390.173
$^{141}_{56}Ba$	233.917
$^{92}_{36}Kr$	152.597
$^{233}_{92}U$	386.846
$^{137}_{54}Xe$	227.274
$^{94}_{38}Sr$	155.899
$^{239}_{94}Pu$	396.823
$^{134}_{54}Xe$	222.282
$^{103}_{40}Zr$	170.859

Table 3: Element weight in 10^{-27} kg

The first reaction of U-235, mass before and after, where the lost mass is conformed in to energy:

$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$

390.173 + 1.675 → 233.917 + 152.597 + 3(1.675)

391.848 → 391.539

391.848 – 391.539 = 0.309 x 10^{-27} kg.

$E=mc^2$ → E== 0.309 x 10^{-27} kg x $(3 \times 10^8)^2$ = 2.78 x 10^{-11} J

is being released per U-235 atom fission.

In 1 kg U used in the PWR there would be 1kg/(390.173 x 10^{-27})kg = 2.563 x 10^{24} Number of U-235 atoms in 1kg if it was pure, but the enrichment in the fuel of the PWR is around 4%, so there would be just 4% of the U-235 atoms in 1 kg, that makes it = 1.025 x 10^{23} atoms of U-235 per kg U. The rest is U-238.

Therefore, there is a total chemical potential energy from the 4% of U235:

2.78 x 10^{-11} x 1.025 x 10^{23} = 2.85 x 10^{12} J

from the 4% U-235 in 1 kg U. (2.85 x 10^{12} J (/kg U) converted to 32.986 MWd/kg)

The rest of the fuel is then 238 U, which decays to 239Pu, therefore the calculations of that:

$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{134}_{54}Xe + ^{103}_{40}Zr + 3^{1}_{0}n$

The U-238 is fertile, so it takes one of the neutrons released from the U-235 fissions, and when it decays it becomes Pu-239 which is fissionable and releases neutrons and energy.

The mass before and after the reaction:

396.823 + 1.675 → 222.282 + 170.859 + 3(1.675)

398.498 → 398.166

Mass before – after: 398.498 – 398.166 = 0.332 x 10^{-27} kg.

Finding the energy released per fission of Pu-239: $E=mc^2$ → E= 0.332 x 10^{-27} kg x $(3 \times 10^8)^2$ = 2.99 x 10^{-11} J.

If we assume that the remaining of the U (96%) will all become Pu-239, then the total energy released will be: 2.42 x 10^{24} atoms/kg x 2.99 x 10^{-11} J = 72.358 x 10^{12} J/kg → 873.48 MWd/kg (96% Pu, 4% U235) Total for the two 4% of U235 and 96% U238 is: 906.466 MWd/kg.

This is the total potential if it was ideal. That means that the whole of the 4% of U-235 is being used, as well as that all of the U-238 is receiving a neutron so all of them decays and becomes Pu-239. The report of the APR1000 say it has a burnup of 54.1 MWd/kg.

Last is the MSR, where the thorium will decay to U-233, and there is a very small part (0.3 %) that is U-235 to get the fission process to start, then it is replaced by U233, so in this calculation it is after the U235 is used up so assumes all is U233.

$$ {}^{233}_{92}U + {}^{1}_{0}n \rightarrow {}^{137}_{54}Xe + {}^{94}_{38}Sr + 3\,{}^{1}_{0}n $$

386.846 + 1.675 → 227.274 + 155.899 + 3(1.675)
388.521 → 388.198
Mass before – after:
0.323 x 10^{-27} kg is the mass defect. Then how much energy is that:
= 0.323 x 10^{-27} x $(3x10^8)^2$ = 2.91 x 10^{-11} J.

1kg/(386.846 x 10^{-27})kg = 2.585 x 10^{24} number of atoms of U-233 in 1 kg. This gives: 75.224 x 10^{12}J per kg U-233. This equals: 870.65 MWd/kg.

If it is as said in the report that it has 1501 kg fission material at the beginning, and assuming that it is U-233, then that gives: 3.88 x 10^{27} atoms, which releases: 1.13 x 10^{17} J total = 31.39 x 10^6 MWh or 1.308 x 10^6 MWd from 1501 kg fissionable U233 material in the MSR.

4. Design life:

The design life of the APR1000 is given to be 60 years, but that one is not in operation and is still conceptual, but the OPR1000 is in operation several places, which have a design life of 40 years.

The conceptual design of the single fluid from 1971 have been given as 30 years, but a new conceptual design called ThorCon has an estimated design life of 80 years. Both of them are still just designs.

As for the infusion of thorium it all depends on how the fuel will react, but no actual number have been given.

5. Size and material usage:

The biggest difference in size is that the PWR needs a backup system as well as that the pressurized water needs more space to keep up the pressure needed for the water to stay liquid. The backup system is often diesel generators, that are supposed to run if something in the reactor doesn't work as it should.

The MSR doesn't need this since it is not working under very high pressure, and it is self-regulating, as well as having control rods that can be put in to the reactor core to absorb the neutrons created by the fuel running through the core, so it doesn't create more fissions. As well that the 232Th will absorb the neutrons and will take time for it to become fissionable as well that some of it is separated.

When the pressure or something happens in the PWR that doesn't keep up the cooling of the reactor liquid, the whole plant could explode.

The MSR would have a spike in temperature because of unregulated fission reactions but would then cool down and not be dangerous to anyone.

6. Mining and waste management:

6.1 Uranium:

Natural uranium is 0.7% U-235 and 99.3% U-238. For it to become a fuel that could be used in reactors or for other purposes, the percentage of U-235 needs to be increased, this is called an enrichment process.

But first the uranium needs to be mined, since it is in the ground. It is also radioactive, so there are several regulations in place to make sure the environment and people who works with it are safe, and the IAEA developed monitoring programs to make sure it is under control.

There are three different ways of mining uranium: open cut mining, situ leach mining (ISL) and heap leaching.

Figure 21: This show one of the conventional methods of mining uranium, also known as open cut mining

Open cut mining is the one we often associate with mining, which is where there is an oar of uranium close to the surface and overlying rock is removed and extracted and placed somewhere else to get to the uranium. These often have a mill where the oar is crushed, ground and leached to release the mineral particles. Leaching is a process, often using sulfuric acid, to dissolve the uranium from the other elements, afterwards it is chemically processed to recover the uranium.

The situ leach mining is where the uranium is dissolved in to groundwater and pumped up to the surface and sent to a treatment plant so that the uranium could be recovered.

The heap leaching is pretty much the same as situ leaching, but the heap leaching is used for an oar that has very low concentration of uranium, that means below 0.1%. The broken oar is irrigated with acid solution over many weeks, and then recovering the uranium from the resulting liquid.

All of these have different impact on the environment, the biggest one is the open cut mining where it is created big pits where there used to be ground and stone and other minerals, and it is a big operation.

The countries that are the biggest within the mining of uranium is not the same that consume the most. In 2017 Kazakhstan was the leading country with mining 23,391 tons of uranium. This is because different countries have different amount of uranium in the ground, some countries have to import a lot, but overall the amount of U-235 left in the earth is very low.

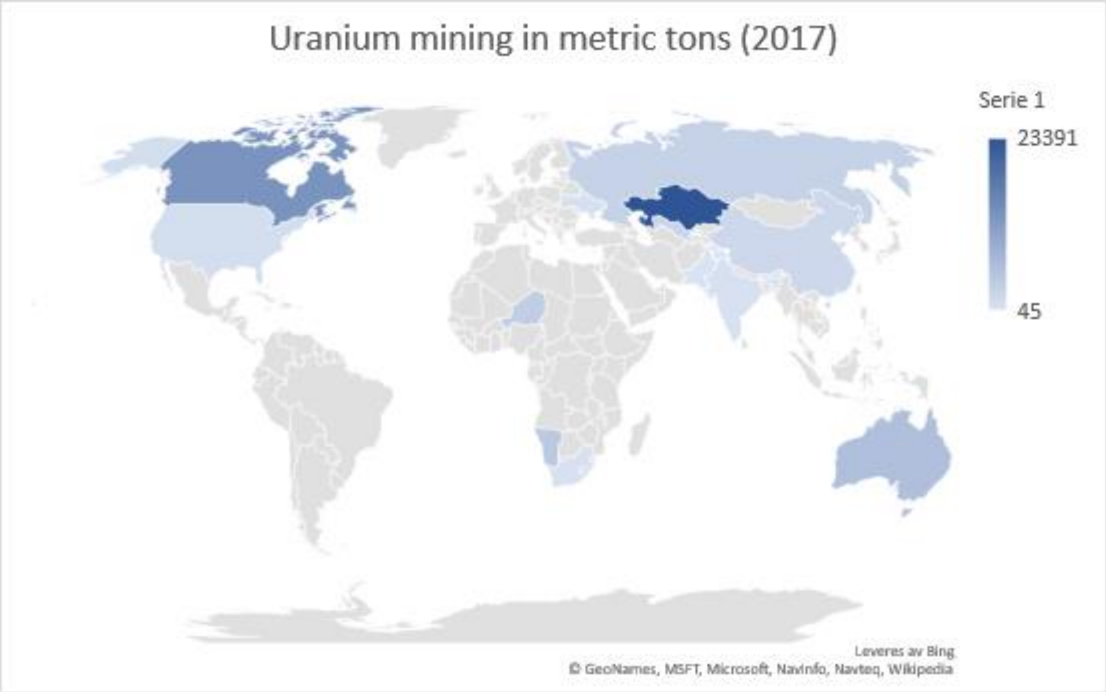

Figure 22: Uranium mining in the world in 2017

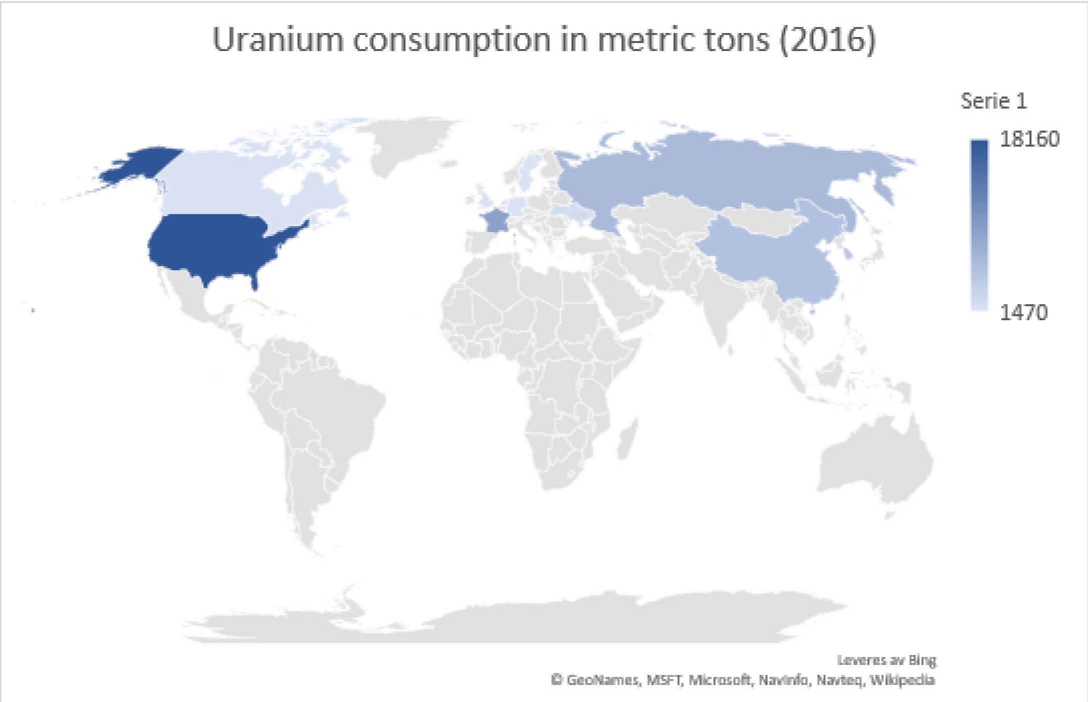

Figure 23: Uranium consumption in 2016

From stats we see that USA is the world most leading in uranium consumption, something that reflects how many nuclear reactors they have in the country, the same for the rest of the countries within uranium consumption.

After the mining and leaching the uranium needs to be cleaned up and centrifuged. The basis of being able to separate the U-235 as much as possible from the U-238 in the centrifuge is that there is the mass difference of 1%. In the centrifuge the uranium is being flung around until most of the U-238 is at the outer end of the container since it is heavier, whilst the lighter U-235 stay in the inner part, so the inner part is used for fuel and the other is depleted uranium. But it takes many times of centrifuging the uranium to be able to have a high enrichment of U235 because of the small difference in mass.

To get 1 kg enriched uranium you would need to start with 10 kg natural uranium, and with a by-product of 9 kg depleted uranium. You would therefore need to extract 10 times the amount natural uranium to get the enriched uranium.

The spent fuel coming from the PWR still has 96% of its original uranium content (whereas the U-235 content has been reduced to less than 1%), 3% is waste and the remaining 1% is plutonium-239 that is a result of U-238 absorbing a neutron, and the spent fuel still has a lot of potential energy. Therefore the spent fuel is often recycled also called reprocessing to extract the fissile materials to be put back in again as new fuel in the reactor. The main purpose is to separate the fissionable plutonium and uranium from the waste because it can be reused and therefore reduce the waste.

The finale waste created is radioactive and needs to be handled with care and in the right way. That means that the workers handling the waste needs to have the right equipment and have an idea of how much radiation is coming from the waste and cutting down working hours based on that. Since it is radioactive waste the waste needs to be safely stored, and that often means to bury it down in to the ground or stored in safe containers, so it will not give radiation poisoning to anyone or cause any damage and decay safely.

And the biggest issue is that the waste needs to be buried if it is not planned to be reused somehow. The high level waste needs to be stored for around 40-50 years to when the radioactivity has decayed to relative low levels. High level waste is where the radioactive decay increases the temperature of the waste and its surroundings, so it needs cooling and to be shielded, which happens in a storage. There is currently 250.000 tonnes of spent fuel in storage at the moment.

After 1000 years most of the radioactivity have decayed, but at 10.000 years the radioactivity is back to what the original uranium oar's radioactivity was.

6.2 Thorium:

Thorium-232 is the one used in the MSR and is the one found naturally in nature. It is three to four times more abundant than uranium in the earths crust. Even if it is more abundant in the earth crust, it has to be readily available or accessible to be used as a fuel in the future.
It will demand mining to extract enough thorium fuel for the future or as a by-product or a by-product of a by-product, but the resources available can in theory be sufficient to cover the demand for centuries to come.

Thorium is often found together with rare earth materials being mined, but at the moment thorium is put back since there is no MSR or other reactors that exist that can use it as fuel. Rare earths are a group of seventeen chemical elements often used in new technology, such as cars and batteries.

The biggest problem is the product of radioactive decay from Th232 to U232. Because U232 decay chain produces high energic, penetrating gamma rays, but just for some days, but therefore it needs to be shielded off by special metal containers, both during operation and as waste. The overall waste needs to be safely stored or sealed of for around 300 years to become safe.

6.3 Infusion of thorium

The mining would be the same as for the two others, just a combination depending on which fuel is going to be used. The radioactive waste will be reduced when adding thorium to the existing uranium fuel cycle used in the light water reactors, but if it is a lower percent of thorium the radioactive waste needs to be stored longer because of the elements created, but still not as long as the existing fuel cycle.

7. Discussion:

First off analysing what the calculations show. First it is the calculations of the heat transfer between the fuel and the second coolant in the molten salt reactor. This show that the temperature difference for the fuel is at 167 K with the Th-U fuel, and the U233 and U235 made the temperature difference in and out of the heat exchanger to be 242 K, which is an increase of 45%. The increase in temperature difference on the other side would make an increase in the heat transfer and improved turbine output. The problem is that the elements used in the fuel is just uranium and not with thorium, therefore it is not a breeder and will therefore use fuel and not create more, which is the whole point of using th-u fuel cycle in the molten salt reactor.

The second calculations looks in to how much the fissile material in the two different cycles used in the two different reactors. This show that the energy released in 1 kg of the enriched uranium (U235/238) releases 72.358×10^{12} J/kg, where the U233 is 75.224×10^{12}J per kg. The difference is around 3.4×10^{12} J, which is not small, that means that theoretically the 1 kg of U233 releases more energy than the enriched uranium. This means that the th-U233 fuel cycle theoretically can create more energy. The problem is that these numbers is just theoretically and pure fission product, but both of the fuels will have a fertile element that collects neutrons released from the fission and therefore the potential energy the chain reaction would have created don’t happen. The reactors also need to have moderators to control the amount of fission reactors, since too much energy will lead to an unstable reactor and it is more likely for accidents and will not be allowed. So there is a lot of potential energy in both fuel cycles, but there are several problems that makes it not possible to reach the full chemical potential.

Then taking a look at the overall pros and cons for all of the options:
Thorium-uranium molten salt reactor pros and cons:
Pros:

- Breeder, creates more fuel than it uses
- Abundant amount of thorium compared to uranium
- No pressurization needed and therefore less space

- Radioactive decay takes a short time to become safe, compared to current radioactive waste
- Thorium has a higher thermal conductivity and melting point, which makes the process safer and can handle more changes

Cons:

- Corrosion because of the fluoride salts used
- High energic penetrating gamma rays from U-232 decay chain
- Still just a conceptual design
- Needs to go through experiments and more research as well as development
- Low design life because of corrosion, and need to find a way to replace parts safely
- Need to build new reactors

Uranium 235 pressurized water reactor pros and cons:

Pro:

- Already running and creating energy so don't need more investment for research and development
- High design life

Con:

- Bad fuel utilization, needs to be reprocessed but still a lot of potential energy in the waste
- Less uranium oars in the earth's crust
- The radioactive waste needs to be stored for a very long time before it is safe compared to the other two options

Infusion of thorium pros and cons:

Pros:

- Th-mox can be use in 90% of existing nuclear reactors
- Th-mox use plutonium that is not being used and do not create more
- Safer than existing nuclear reactors
- Lower the time waste needs to be stored

Cons:

- Still needs more testing in a testing reactor
- Cannot be used in all reactors

These show the overall pros and cons for the different options, each of the points will weigh different in the big picture of trying to be as sustainable as possible. All of them are better than using certain existing fossil fuels that releases dangerous gases and can be dangerous to everything living depending on different scenarios. But the mining operations for uranium does create a lot of changes in the surrounding environment.

The safety point and fuel point is the biggest pros and cons between the different options. The safer it is the more people want to have it as their energy generator.
The infusion option has maybe reached further in their development because of the lucrative option of using reactors in operation today and don’t need to build new ones and having available a test reactor ready for use.

8. Conclusion:

Based on the conceptual design for the TMSR-LF it is overall better than the PWR, but the infusion of a thorium based fuel in to the existing light water reactors can be just as good and better in certain areas as the MSR, and it has come further.

The problem with the MSR is that as in the name of the report, it is conceptual, and that means it is not up and running. There has been few experiment where it was running for 9 days and six months or so, but that didn’t show what problems could come up if it was running for a longer time and how the use of thorium in the fuel could change the efficiency, because they only used single fluid with uranium, as well as how the salts long term could damage the reactor and the graphite moderator.

It makes it hard to invest for big companies, since it is uncertain if it will work and therefore the development of the technology for this MSR is at a halt. Companies that don’t have the money can’t do experiments without investments from bigger companies.

MSR has the advantage of easily available fuel since it is a bi-product or a bi-product of a bi-product of existing mining. It also is a breeder that will create more fuel than uses and will reduce the need for interfering in nature, which makes it attractive. Another huge plus is that it is a lot safer than existing reactors, which will make it a better alternative for the people living near the reactor.

The same goes for the infusion of thorium or changing the conventional uranium fuel cycle with the th-U233 fuel cycle in existing reactors. So far it seems to be going good from what the company has written and published, there still may be problems that will show up in the long run, but for now it is not any.

Thor Energy have been able to get further in their work than companies doing research in to the MSR, so this is what looks most promising as is. They have been able to manufacture the fuel pellets, same type of pellets the existing reactors use. And the use of th-mox makes the reactor safer.

Total there is a lot of unanswered questions and uncertainty, and there is still a lot of development and experiments needed, but Thor Energy's project is looking promising and could be a very good step in the direction of having reactors only running on thorium fuel in the future. It also helps put a focus on thorium and make companies and potential investors aware of that thorium exists and can be used. The more research, development and experiments done the closer we come to a reactor that can create more fuel than it uses, which can solve the growing energy demand problem caused by countries becoming industrial countries and population growth.

9. Future work:

Since there is so little experiments going on in the field of TMSR and fuel with thorium that could be infused in to nuclear reactors that are running today there is a lot of potential future work.

Some of it in regards to the MSR is to do experiments, that is the next step to see what problems that may occur in the future so problematics may be discovered so that it can become an area of technology worth investing in and help it up and running.

The infusion of thorium in to existing reactor is a very good step toward making thorium a viable option for use as fuel, and not just the enriched uranium used today.

Specific experiments could be:
How will fluoride salts affect materials in a MSR over a longer period of time.

What happens to the fuel and does it properties change the longer the MSR reactor runs.

How will the existing reactor react to thorium infused fuel and how will the reactor design affect the properties of the fuel, and does it lead to design changes.

What radioactive elements will the th-mox (90% Th 10% Pu) fuel create and how will that change possible handling of waste, reprocessing and possible reactor design.

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